TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

GLOSSARY

ABS	Acrylonitrile Butadiene Styrene
ALM	Additive Layer Manufacturing
BOM	Built Of Materials
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
DAC	Digital to Analog Converter
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMF	Electromotive Force
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
IDE	Integrated Development Environment
LCD	Liquid Crystal Display
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NTC	Negative Temperature Coefficient
PCB	Printed Circuit Board
PLA	Polylactic acid
PTC	Positive Temperature Coefficient
PWM	Pulse Width Modulation
RAMPS	RepRap Arduino Mega Pololu Shield
RTD	Resistance Temperature Detector
SHS	Selective Heat Sintering
SLA	Stereolithography
SLS	Selective Laser Sintering
SMD	Surface-Mount Device
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory
USART	Universal Synchronous/Asynchronous Receiver/Transmitter
USB	Universal Serial Bus

1. Introduction

1.1. Background

Nowadays, *RepRap* and *Arduino* communities have had an increasing progress. These terms are demarcated on the Open Source development model; the designs produced by these projects are released under the GNU General Public License, which promotes free universal access and distribution of it, allowing an exponential and rapid improvement.

RepRap project uses Fused Additive manufacturing (FDM) technology, term used to refer to processes that make solid objects from 3D computer models. In particular, the object is created by printing thin layers of fused plastic on top of one another.

The objectives of this philosophy are the creation of 3D printers which are capable of self-replicating and use an *Open Source* software for everyone. Currently, printer's control is realized by two printed circuit boards (PCB); one board is a microcontroller (*Arduino*) and the other contains the power electronics.

As regards of *Arduino*, it is an electronic platform whose purpose is having an easy-to-use hardware and software. This platform permits reading its surroundings by receiving inputs from sensors and modifying it by actuators such as motors and lights.

Therefore, this thesis consists on the design of a PCB for control a *RepRap* printer in order to contribute to the improvement of these philosophies.

1.2 Objectives

The main objective of the project is to design the electronics of a 3D printer. In particular, the aim is to design a board which holds these two parts, *Arduino* microcontroller and power electronics, and it will be done with surface mount devices (SMD). Another purpose is to improve the current design and solve overheating problems that present these devices.

It pretends to do it at more affordable pricing to bring this new technology to a larger number of users and to everyday uses.

1.3 SCOPE

The current project consists on the design and election of each part which compose the electronic system of the printer.

This thesis will only focus on:

- Study each part of the 3D printer (motors, cooling fans, heating of the bed and the extruder and control sensors).
- Design or election of the control circuit for each part mentioned above.
- PCB design in *Eagle*.
- Implementation of a *Protoboard* prototype.
- Environmental impact study.
- Economic consideration.
- Planning.

Nevertheless, it will not include the programming of software or firmware; it will be compatible with the *RepRapBCN 3D+ v.11* firmware.

Furthermore, it will also be compatible with the 3D printer design that it has been realized by Sara de la Peña García in the thesis called *'3D printer kit design'*.

1.4 MOTIVATION

The motivations for this project are based on two aspects: commercial and personal motivation.

The commercial motivations of this thesis are:

- Designing electronics on a single board in order to achieve an affordable pricing.
- This technology is booming and, it is possible that increase the sales in the future.

The personal motivations about this thesis are:

- Contributing to improve electronics for Open Source philosophy.
- Increasing the knowledge in *Arduino*.
- Increasing the knowledge in SMD technology.

2 State of Art

2.1 Rapid Prototyping

Rapid Prototyping is another term to refer to Additive Layer Manufacturing (ALM). As previously mentioned, it consists in making a three dimensional object from a 3D computer-aided design (CAD) model. Overall, this is achieved by printing thin layers of material on top of another. These machines work by transforming powder or liquid material into a solid only where the design dictates.

ALM allows a rapid prototype manufacturing without moulds and other tools and therefore, the product's development time and cost decreases.

Nowadays, prototyping is the main objective of these technologies, however there are other applications, for example it is used in aeronautic engineering for making heat protective liners inside aeroplane engines. Other currently developed functions are related with medicine field as prosthesis or human tissues. Moreover, it is possible to create objects at home.

The principal processes which are used in ALM are Stereolithography (SLA), laser sintering (SLS) and fused deposition manufacturing (FDM).

The SLA technique was born in the 80's century and it was the first marked technology in this field. This method uses a photosensitive resin which solidifies when it is exposed to UV light. The base board is situated below the surface of this resin, and after the first layer has been solidified, the board sinks into the liquid while another layer is solidified.

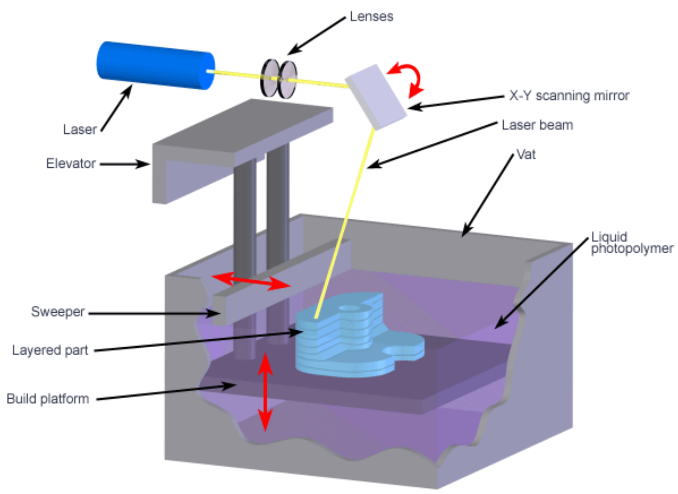


Figure 1: ***SLA diagram process. Source: [2]***

Laser sintering is used to make polymeric and metallic objects. This technique uses the same principle as SLA, although it uses a CO_2 laser and, at the beginning, the material is a powder. The laser is used for melting these particles into a solid. Each time a layer is solidified, the board moves down and a new complete layer of powder is distributed over the whole board by means of a roller. At the end, the object is buried in a vat of powder which must be cleaned after.

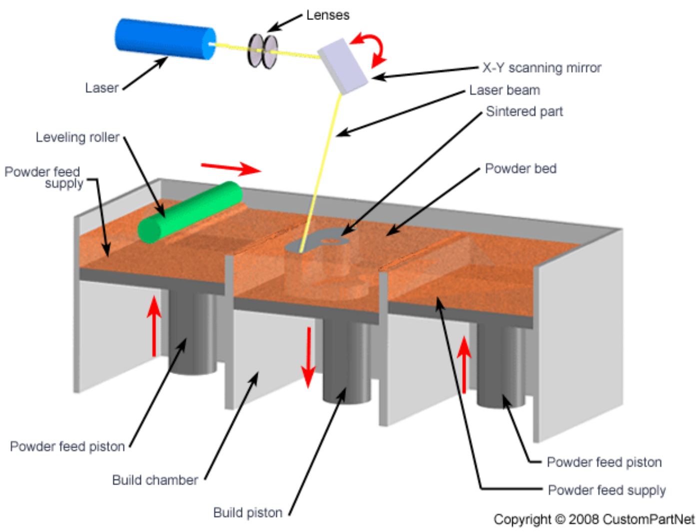


Figure 2: ***SLS Process diagram. Source: [2]***

Finally, fused deposition modeling (FDM) consists in built the layers by extrusion of a thermoplastic polymer filament and following the shape of each section. This is done with the material at 1 ° C above its melting point, so that solidifies immediately on the preceding layer.

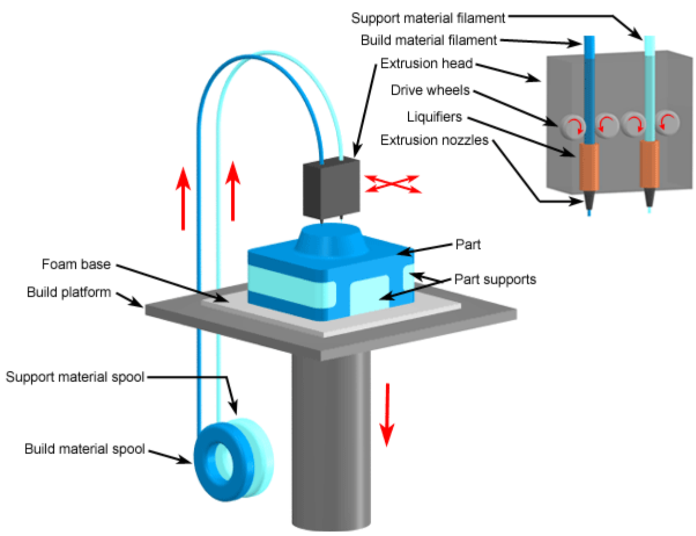


Figure 3: ***FDM diagram process. Source.[2]***

Table 1 gives an overview of this technologies mentioned above.

	SLA	FDM	SLS
Type of material	Liquid (photopolymer)	Solid (filament)	Powder (polymer)
Max. size about the piece	149,86 x 74,93 x 50,038 cm	91,44 x 60,96 x 91,44 cm	55,88 x 55,88 x 76,2 cm
Min. layer thickness	0,0254 mm	0,127 mm	0,004 mm
Tolerance	0,127 mm	0,127 mm	0,254 mm
Surface	Smooth	Rough	Medium
Construction rate	Medium	Slow	Fast
Applications	Fit Tester Functional Tests Patterns of rapid tooling Very detailed parts High temperature applications	Fit Tester Functional Tests Patterns of rapid tooling Very detailed parts High temperature applications Applications for food and medicine	Fit Tester Functional Tests Patterns of rapid tooling Less detailed parts High temperature applications Parts with hinged or pressure settings

Table 1: ***Technologies' comparative***

2.2 Fused Deposition Modeling (FDM)

As previously mentioned, the thesis has been based on control electronics of a FDM printer. Therefore, it has been considered relevant a detailed description of this technology. For this reason, it has been done a functionality study of the machine.

As briefly mentioned above, the FDM system consists in form a piece by melting a thermoplastic material, which builds up layers for the solid creation.

In brief, the steps of the printing process are:

1. Obtaining the material (thermoplastic filament) from a coil.
2. Heating the material in the extruder.
3. Solidifying the material on a Surface/base.
4. Three dimensional movements in order to be able to reproduce an object.

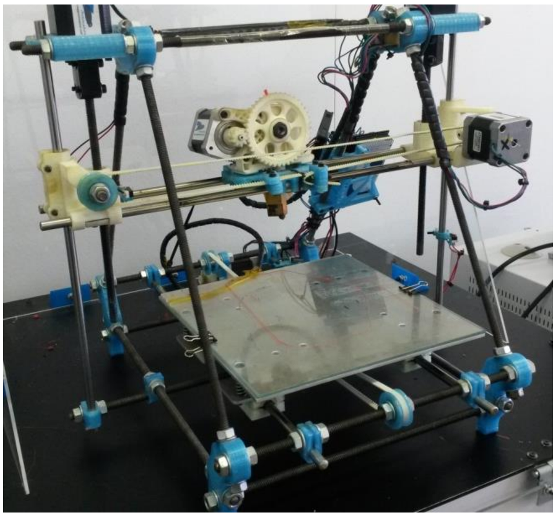


Figure 4: ***3D RepRap printer. Source [10]***

The following figure shows the main functions and sub-functions of a 3D printer. As mentioned earlier, the purpose is to analyse each printer part in order to understand the machine functioning.

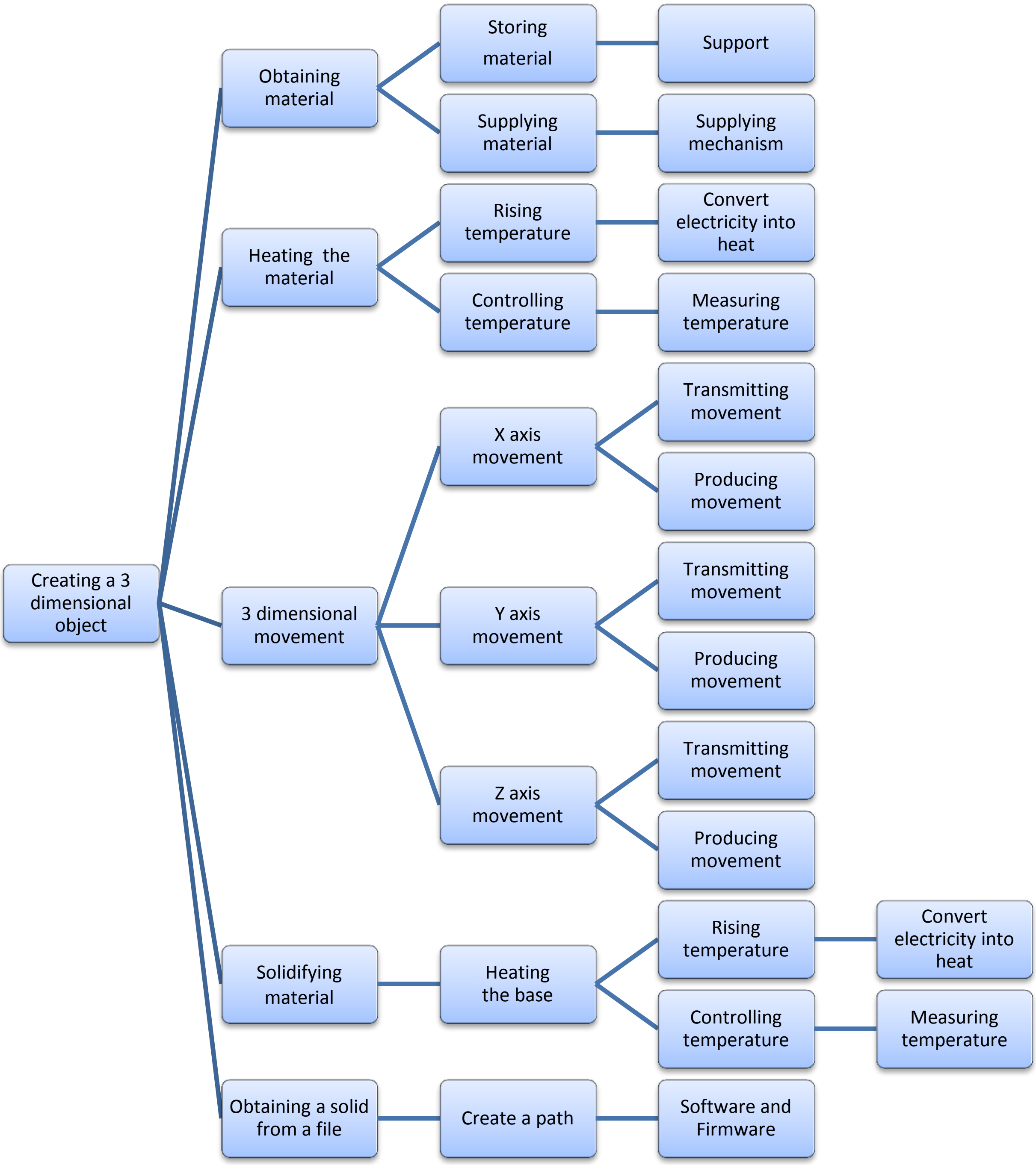


Figure 5: ***Functionality diagram.***

2.2.1 Obtaining material

First of all, it is mandatory to store and supply material to the printer. On the one hand, thermoplastic filament is stored in a coil.

On the other and, in order to feed the machine, the filament is led to the extruder by means of a torque. The mechanism which generates this force is situated on the extruder and is moved by a stepper motor; which allows accuracy.

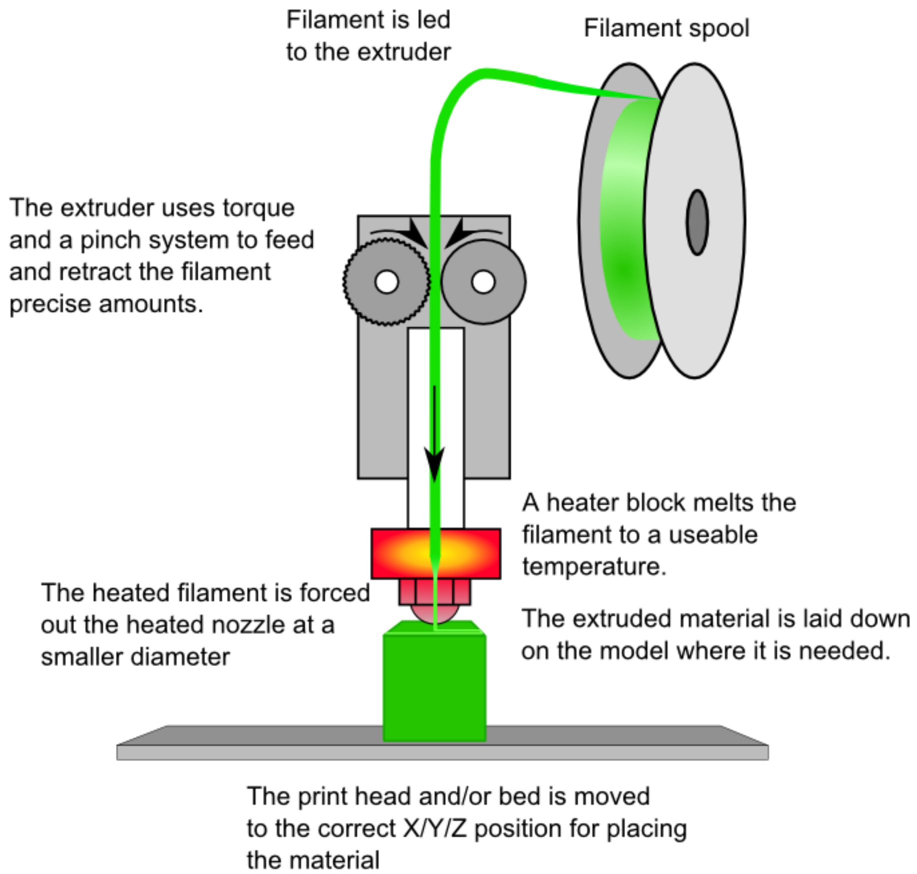


Figure 6: ***Printer diagram process.***

2.2.2 Heating the material

As stated in the figure above, when the filament is in the heating area, a heater block melts the filament, and then the heated filament is forced out to the nozzle at smaller diameter.

This process takes place at the extruder which has the following areas:

- Heating area: the material fuses on the nozzle (see figure part 6), part which is heated by piece 5 and where the extruded material melts.
- Temperature control zone (part 7) where is situated a temperature sensor.
- Cooling area: it allows the extruder not obstruct and block the nozzle.

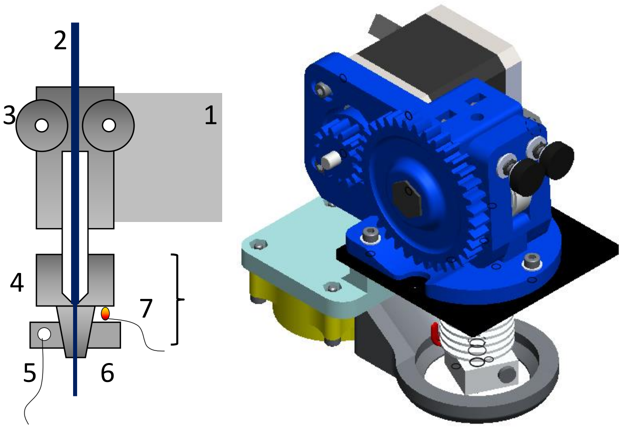


Figure 7: ***Schematic and parts of extruder.***

2.2.2.1 Electronics of the extruder

Since this project focuses on the study of 3D printer electronics, devices that compound the extruder are detailing below [8]:

- 1 x 100K Semitec NTC thermistor
- 12v 40W Heater Cartridge
- 1 x 12v 30x30x10mm fan
- 1 x High Temperature Fiberglass Wire - for Thermistor (150mm)
- 2 x 0.75mm Ferrules - for Solder-Free Wire Joins

Figure 8: ***Electronic components of the extruder Source: [8]***

These electronic components are essential for printing process. Each one has a function:

- The thermistor is a transducer which enables the measurement of temperature of the extruder. With this piece, it is possible to control the heating process.
- The heater cartridge is used to transform electricity into calorific energy to perform the extrusion process.
- The fan allows cooling a part of the extruder and to avoid the obstruction.

2.2.3 THREE-DIMENSIONAL MOVEMENT

Printer movements are those that carry out printing process. For performing this process, the movements of the printer are produced by Cartesian coordinates. This coordinates have three axes (X, Y and Z) which perform the movements necessary for the 3-dimensional object. These movements are generated by stepper motors which, in turn, are controlled by a microcontroller that sends electrical signals to the motors.

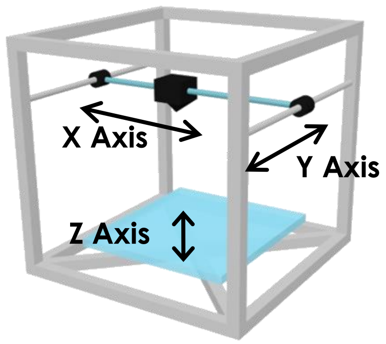


Figure 9: ***Cartesian coordinates.***

2.2.4 SOLIDIFYING MATERIAL

In order to solidify the thermoplastic filament, it is necessary a platform or base where the material is supported and cooled. If it is not pre-heated, it will shrink that provokes the lifting of the solid lateral edges due to the large temperature difference between the base and the filament. This phenomenon is called warping (Figure 10). To prevent material shrinkage, the base must be heated at an elevated temperature and is called *heated-bed*.

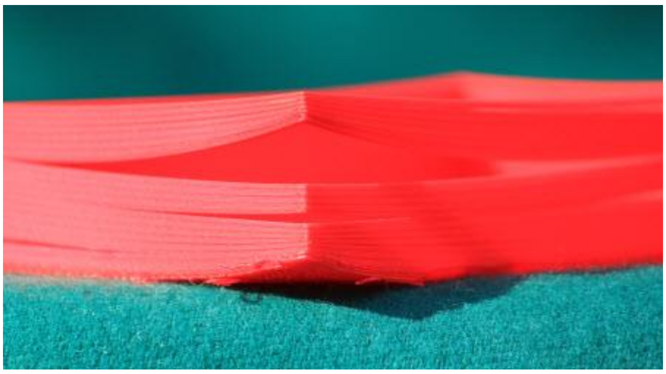


Figure 10: ***"Warping" phenomenon. Source [5]***

2.2.4.1 Heated Bed PCB

The *heated bed* is an elemental piece for the printing quality and the prevention of warping phenomenon.

Currently, there are two methods to heat the base. The first one consists in a metal board with welded resistors which allows energy transmission. The second method is the most innovative and used, because it is most efficient system. This is a PCB with a printed circuit as the figure bellow that helps rapid distribution and uniform of the temperature. As will be shown, this base is not necessary for some types of thermoplastics. However, the platform must maintain a temperature range around 100 and 130 ° C to print ABS.

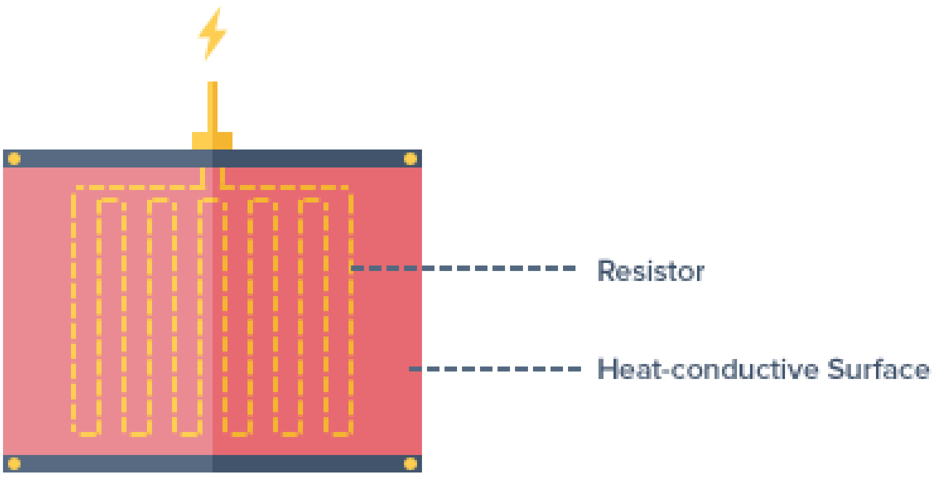


Figure 11 ***Heated bed diagram Source [5]***

There are different types of boards. In this project it has chosen the MK2 platform because it has the requirements for temperature and dimensions.

The maximum temperature which supports the PCB is 180 ° C. This value is higher than the maximum required, which is 130 ° C. As for the dimensional requirement, this is due to the necessary characteristics dictated by Ms. De la Peña. The following image shows the board and measures.

Figure 12: ***MK2 PCB. Source [7]***

For the study, is necessary to know some of its properties, which are shown below.

MK2b Dual Power Technical Details [7]

- Total dimensions 214x 214mm
- Heat conductive dimensions 200x200mm
- Laminate FR4 1.6+-0.15mm
- 2 layer, 35µm copper
- Red Soldermask - both sides
- White Silkscreen - both sides
- Power Input: 12V or 24v
- Copper boardd holes
- Resistance between 1.0-1.2 Ω (12V) or 3-3.4Ω (24V)
- EPCOS 100k thermistor hole
- Functioning current PLA 8-9A, ABS 10-12A

It has to be emphasized that, on the one hand, it must be taken into account the input voltage, as well as the resistance value and the current performance of the board. On the other hand, it should contemboard that the PCB MK2 is ready to host 100k thermistor (in particular, EPCOS brand), which will suppose a limitation in the experimental phase.

2.2.5 Obtaining a solid for a file

Once thermoplastic melts and is creating layers, it would wait for the solid. But, how design passes to a real solid? Roughly, the printing process consists of; solid design, adapted this design print file and finally printing. These steps could be seen in the diagram on the next page and tool chain used

First, to print an object, it has been proceed to design it. This design begins with CAD (Computer Aided Design) software such as *SolidWorks* or *Sketchup*, which creates a parametric model of the solid. Owing to the fact that the design is based on parameters such as dimensions, shapes, textures, colors, etc. it should change the file format.

This format must be exported to STL (Stereo Lithography)[1] file that converts the solid to a model based on triangles.

Sometimes, it is necessary to optimize the object for manufacturing; this is done by specialized program as *Netfabb*, consequently, the solid can be correctly printed.

Second, must be prepared the object for printing. Therefore, it must adapt the STL file to commands which are understood for the printer.

G-code is a set of commands, which give specific orders to the computer or device. These commands define what to do and how to do it. Namely, it indicates speed, path and path shape. Some CAM tools which allow passing the design to G-code are *Cure* or *Slic3r*.

Once it has been passed the file to G-code, it will start the preparation for printing. To do this, it must take into account some considerations about the characteristics of the print process and the printer (ex. printing temperature, dimensions of the machine, etc…).

To carry out these orders, it is uses *Repetier-Host* program which indicate what the characteristics of each print are used. These commands are communicating directly with the printer while printing the 3D model.

[1] This file has been called STL by 3D Systems enterprise, when has been created the first rapid prototyping technology, theStereo Lithography.

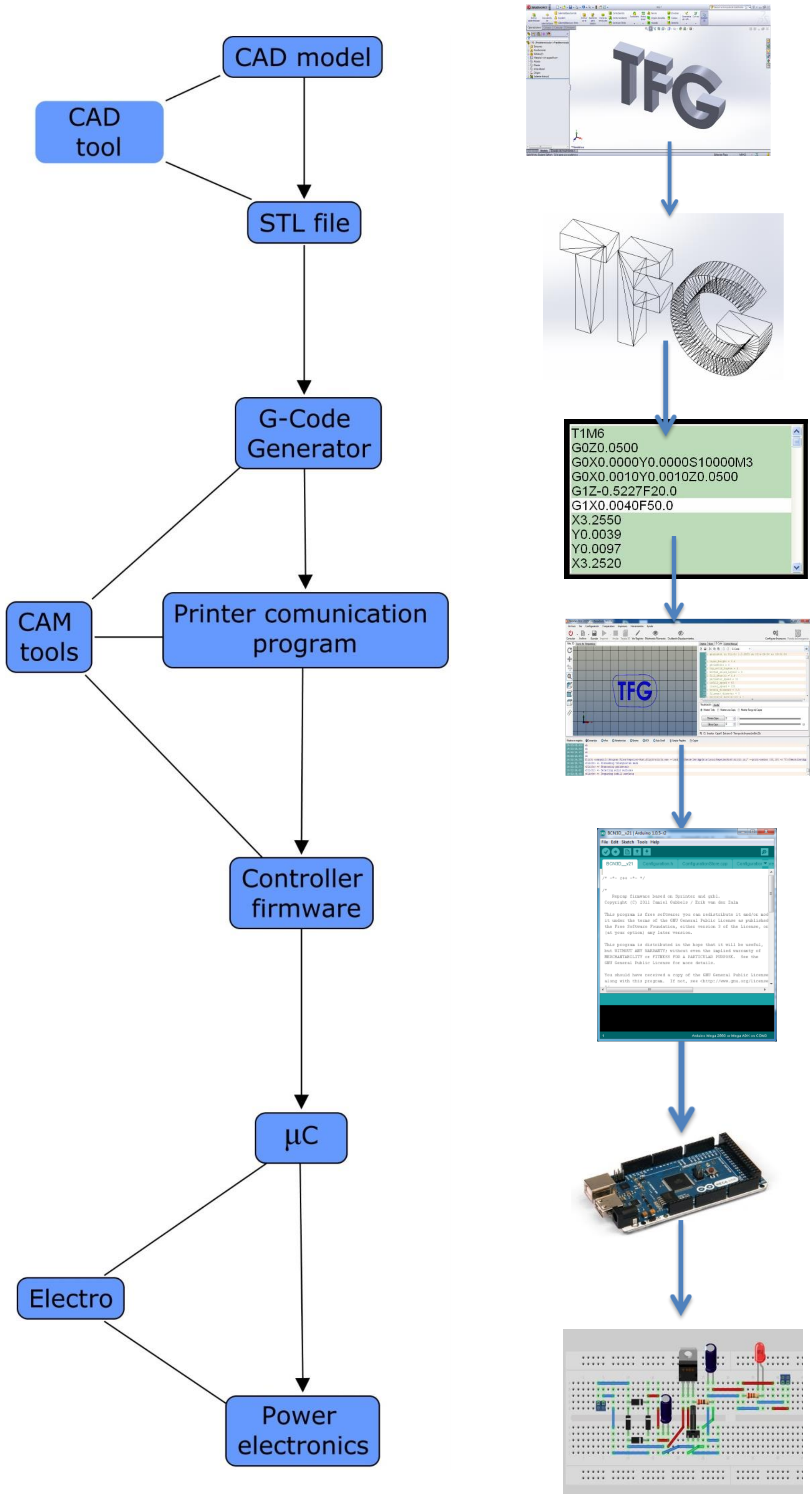


Figure 13: ***Printing process Flowchart.***

Repetier sends instructions to the firmware, which controls the electronic components for the operation of the printer.

Finally, through the firmware, the electric components convert the commands in electrical signals that generate movements and appropriate actions to begin the printing process. Currently, the most commonly used electronic assembly is *Arduino* more *RAMPS*, which the microcontroller is *Arduino and RAMPS* is power electronics. These characteristics will be studied in more detail in section 4 of this document.

2.2.6 MATERIALS

As noted before, it used plastic filament to print the solid. In particular, plastics used for the design of the printer are the Acrylonitrile Butadiene Styrene (ABS) and polylactic acid (PLA). Table 2, shows a comparative between each material and emphasize some of their properties. ABS is a very common plastic and very impact resistant. As a main feature, this material is very tough even at low temperatures. Because of this, solid manufactured is possible. To printing the pieces, this item requires a print temperature between 230 and 260 ° C depending on their properties. Once made, you can sand, polish, drill, etc, easily without losing quality finish.

As for limitations, it is noteworthy that this type of plastic need a base of print hot about 120°C and is sensitive to temperature changes. With this limitation it's possible to cause the phenomenon "warping" mentioned and explained above.

Another limitation about the ABS is that emits a lot of harmful gases that harm the environment. Furthermore, if it has printers working in the same space, is needed ventilate this space due to gases.

Instead, the PLA is a plastic derived from renewable resources. Specifically, this material comes from corn. Therefore, this polymer is biodegradable and does not produce noxious gases so is ecologically and environmentally sustainable.

The PLA is a tough and strong material that having well finishes at the end of printing. Due to the characteristics of this thermoplastic, it could be used for thin-walled hollow parts.

To perform printing, this plastic requires a lower temperature on the base and can even be printed without overheat.

The temperature of printing of this material is performed at 210 °C but as negative point, this material not resists high temperatures one time produced.

That is, the maximum temperature that can endure are about 50-60 ° C. This results that elements in the manufacture are somewhat less resistant than ABS.

Notably on these two types of plastics printers designed to print ABS also support printing PLA. However, this does not happen in the reverse direction due to the properties of the materials, since the ABS requires a higher temperature for melting. This is the reason for use hot printing platform, which supports and ensures stability and adhesion of the piece during printing because of design a printer capable of printing both materials.

It is important to keep this in mind because, as it will see later, one of the main problems in electronic is the heating platform.

	ABS	PLA
Description	Plastic very common, very tough and rigid. With great tenacity.	Hard and durable plastic. With good finish.
Printing temperature	230-260 ºC	210 ºC
Platform temperature	100-120 ºC	50-60 ºC
Environmental impact	- Emit harmful gases. - Recyclable but not for create filament.	- Not emit harmful gases. - Biodegradable.
Utility	For solid, dense and resistant parts.	For hollow parts with thin walls.
Colours	Variety	Wider range (fluorescent, transparent, semitransparent, etc.).
Post-process	Can be machined, polishing, sanding, shaping, paint, paste, etc.. Easily, and the finish is still good.	More complicated. This makes it difficult for do large pieces
Limitations and characteristics	- Ventilation is required when are more printers running in an enclosed space, due to the gases given off. - Sensitive to temperature changes. - Better finish	- It is possible to print without base. - Not resistant to high temperatures (up to 50 - 60 ° C). - It is more fragile, but more stable and easier to print

Table 2: ***Printer materials comparative***

2.3 REPRAP

The main objective of the present work, as described in the first chapter, is creating a 3D printer in order to be compatible with all the free software available. In particular, this thesis is based on RepRap project. This consists creating a 3D printer with Open Source philosophy able to reproduce it by printing your own pieces.

RepRap was born in 2005 at the hands of Adrian Bowyer, professor of mechanical engineering at the University of Bath in the UK. A year later, revisions and modifications to the first prototype, permit develop parts of this printer for later playback, but not was until February 2008 when the first RepRap gets reproduce itself. Currently there are over 100 different models created in various countries.

These printers use technology fused deposition manufacturing (FDM) explained above, but even still the same concept. However, it is called FFF (Fused Filament Fabrication) because of the copyright. Similarly, the pieces are made by melting a filament and drawing layer by layer until develop the object you want.

The main objectives of this project are:

- Create a 3D printer that it be able to self-replicate them.
- Use free software that it could be used for worldwide.

Both software and hardware of the printer are Open Source. In hardware, the electronics RepRap uses Arduino, a free platform for controlling the printer.

About the software, the system includes a computer-aided 3D modeling as design-aided manufacturing (CAM tool) and drivers that allow hardware to give instructions to physical objects.

As regards of the hardware, the most used solution is *Arduino Mega* plus *RAMPS*. The following figure shows the RAMPS wiring.

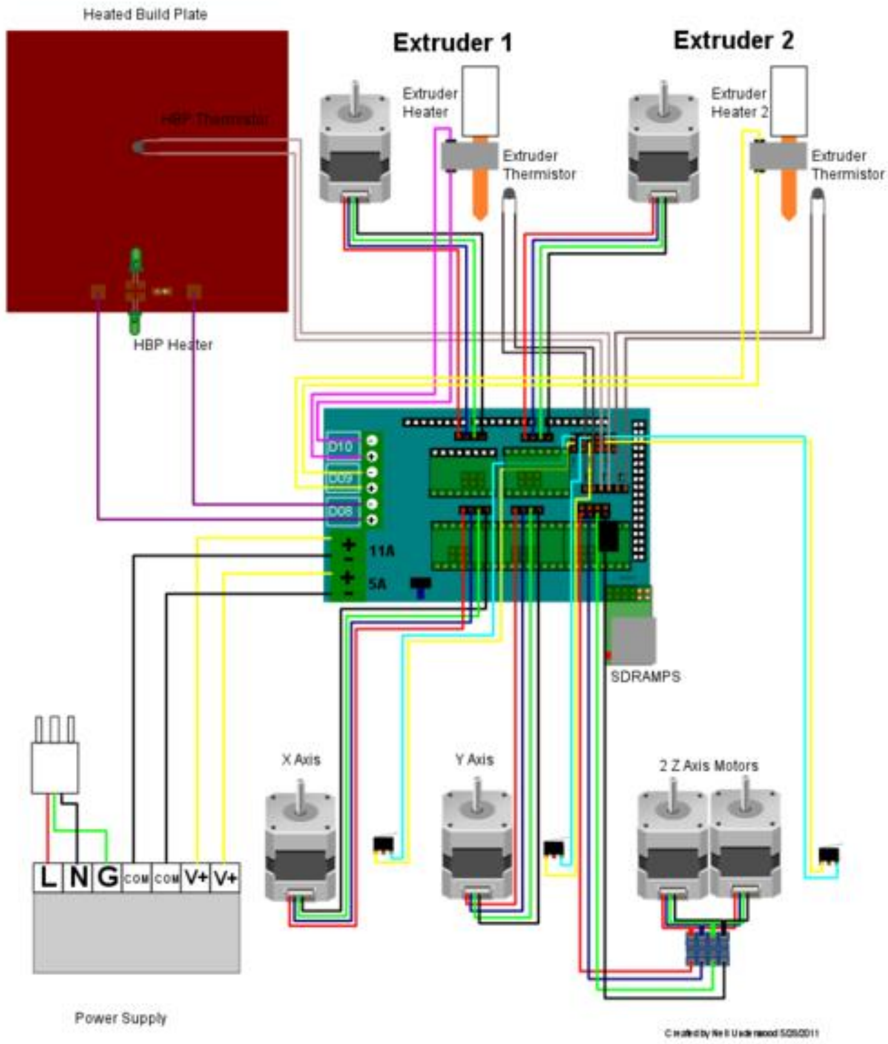


Figure 14: ***RAMPS wiring. Ref [19]***

RAMPS more *Arduino* is not the only option for carrying out the control of the printer. The following table shows different types of solutions for controlling the machine.

All devices shown in the table allow the control printer movements in all three axes, determining coordinates origin, control the extruder and bed. Also, other characteristics it listed:

- Number of extruders
- Number of fans and heaters.
- If these boards are an integral solution or, contrary, are two or more boards.
- If it can remove the drivers.
- If the boards included an SD card, without other characteristics.
- Type of microcontroller.

Board	PCB qty.	Extruders	Fans	Heaters	Endstops	Temp sens	CPU	CPU Speed (Mhz)	Stepper driver	Other features	Price
RAMPS	2 (+Arduino Mega)	1-2	3 (maximum, shared w/ Heaters)	3 (maximum, shared with Fans)	6	3	Arduino Mega 8 bits ATmega1280, ATmega2560	16	A4988,Pololu boards	-	32€
Sanguinololu	1	1	3	2	3	2	8 bits ATmega644P (or ATMEGA1284)	16	A4988,Pololu boards	TH	36,30€
STB_Electronics	1	1	1	2	3	2	8 bits ATmega1284P	20	A4988,Pololu boards	Built in SD-Card, 128x64 graphic LCD, clickwheel, USB	Nd.
Melzi	1	1	1	2	3	2	8 bits ATmega1284P	16	A4982*	-	53,48$
Megatronics	1	1-2	1	2	6	4	8 bits ATmega1280	16	A4988,Pololu boards	-	80€
Printrboard	1	1	1	2	4	2	8 bits AT90USB1286	16	A4982*	-	46,38€
Generation 7 Electronics	1	1	0	2	3	2	8 bits ATmega644 (P), 1284P	20	A4988,Pololu boards	-	46,38€
R2C2 electronics	1	1	1	2	3	2	32 bits ARM (LPC175x)	100	A4988*	-	Nd.
RAMBo	1	2	2	2	6	4	Atmega2560, Atmega32u2	16	A4982*	all-in-one RAMPS board, marlin FW, digipot, extra ports	65,71€

Table 3: ***Electronic printer controls comparative. Source: [6]***

(*) Removable drivers

It can see that all these drivers can control the three Cartesian axes of the printer, including one extruder or more, as well as heated-bed and 3 End-Stops at least. However, it has to be emphasized that the control is different for each board. First, for drivers, in some of these boards, this are removable and some not (marked with (*)). The fact that drivers aren't removable is negative for their function.

Most boards use a type of *Atmega* microcontroller, which are based on *Arduino*, excepting *R2C2 electronics* and *Printrboard*. The features that vary from these microcontrollers are memory and the inputs and outputs present, as will see in section 4.3.

Another aspect is the temperature control. In all boards, the control circuit is made for add a thermistor, except *Megatronics* that also has a thermocouple circuit.

Apart from this study of existing plaques and their characteristics, were two visits to determine those aspects that need improvement for 3D printers: one of them was in "*Fundació CIM*" and other in "*Aula d'impressió RepRap*"[2]. After asking and studying the characteristics of the printer, it was concluded that it should make the following improvements over the *RAMPS* + *Arduino* solution:

- When any part of the electronic fail, is very difficult to find where the fault is, therefore, a possible solution it would be to include a LED indicator on each circuit to see where the error is and what has been the component that caused it.
- One of the main problems is the overheating of the circuits that control the bed and extruder.
- The drivers of the engines that are currently used (*Pololu A4988*) have problems in the design. This causes high temperatures and promotes its destruction. Therefore, alternatives are explored to change.
- *RAMPS* have some fuses and unsuited connectors (they spoil easily).

[2] For further information about the visits, see the annex I.

2.4 Arduino

.

The board layout for the 3D printer is based on *Arduino*. This is an electronic platform that, like the *RepRap* project is part of the Open Source philosophy of both software and hardware. This system was created for students, professionals, designers and / or staff who were interested in creating interactive objects. For this reason, *Arduino* software is very intuitive and easy.

Arduino was born in 2005[3] in Italy as an economical solution for electronics students due to the high cost of microcontrollers that were used. It was pretend to do an economic platform System and at the same time was complete enough to work.

Arduino captures information from the environment through sensors, which allow getting information in order to process, execute or perform the actions that are planned for use.

To accomplish all this, the platform has on the one hand, an IDE (Integrated Development Environment) that allows *Arduino* programming using the programming language C + +, and on the other, the hardware.

This hardware consists of two main components; a microprocessor Atmel that by its inputs and outputs makes possible the reading of sensors and modification of actuators, such as a temperature sensor and an LED; and USB-Serial converter, which converts a communication protocol to another, thereby facilitating the programming of the microprocessor, and consequently its use.

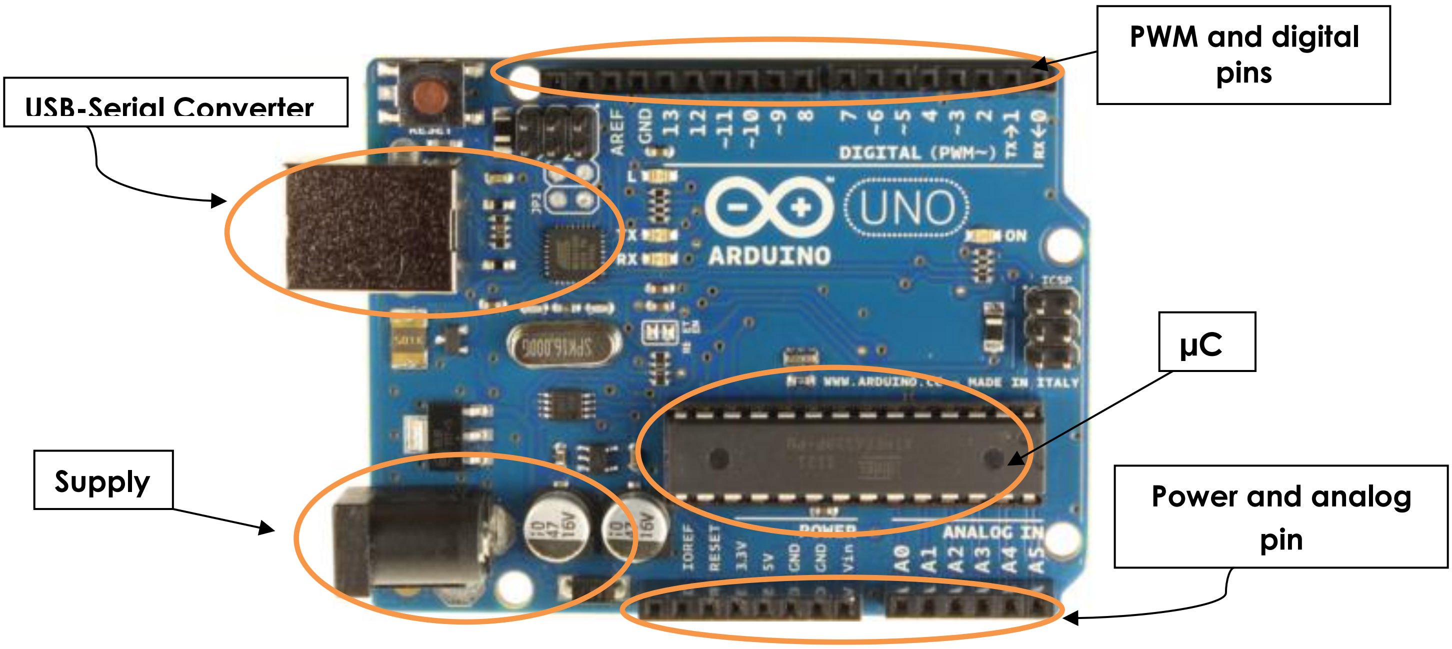


Figure 15: ***Arduino UNO board. Source: [1]***

[3] Source [1]

2.4.1 MICROCONTROLER CHARACTERISTICS

As mentioned before, *Arduino* use microcontrollers from trademark Atmel. This µC have in common a set of inputs and outputs (pinout), which are essential for controlling the printer. Below, it is described explicitly for the study and design:

First, **Power** and **GND** pins. All electronic component needs to be feed, but the value of it depends on the device. The Atmel microprocessor is able to feed another device to 3.3 V, 5V or both.

Second, it has the control pin. The control output, or **RESET,** is used to reset the device when necessary.

Third, the Port Pin; these are the most important for the proper functioning of the printer. The types are:

- Digital pin

By default, entries are in high impedance state, it is, any small signal activates it (HIGH). Therefore the use of resistors pull-up or pull-down[4] is necessary, to set its value to high or low. This pin can also use as output. For this it's necessary activate it via firmware. This makes them low impedance state and can provide high or low (HIGH / LOW) output and up to a certain intensity. These values depend on the microprocessor. The HIGH value can be 3.3 or 5V and the current can reach 40 mA.

- Analog pin:

These pins function in the same way that digital. The difference is that carry an analog to digital converter (DAC). Because of this feature, let you read or provide intermediate values between HIGH and LOW. The number of values that could be interpreted differs depending on the number of bits of the DAC (Digital to Analog Converter), which in the present case there are 8 therefore may interpret 256 values (2^8).

- PWM pin:

The PWM pin comes with Pulse Width Modulation. This simulates an analog output having only a digital output. This generates a periodic square wave which can modify the duty cycle, which consists basically in commute the signal switch on and off. This allows simulating values between LOW and HIGH, varying the proportion of time on and off.

[4] Pull-up resistance is raising the output voltage of a logic circuit.

Switch on duration (ON) is called pulse width and the duty cycle is the pulse width divided by period time. The frequency of *ATmega*, if not altered, usually about 500Hz, it be, a period (T) of 2ms.

The main use of these ports is the possibility to vary the power supplied to a device. To do this, it is effected by an arduino function, *analogWrite()* that allows 256 values, it is, use a scale of 0-255, 255 being 100% duty cycle (always on), the value 127 is 50% of cycle (half the time on) and 0 always off.

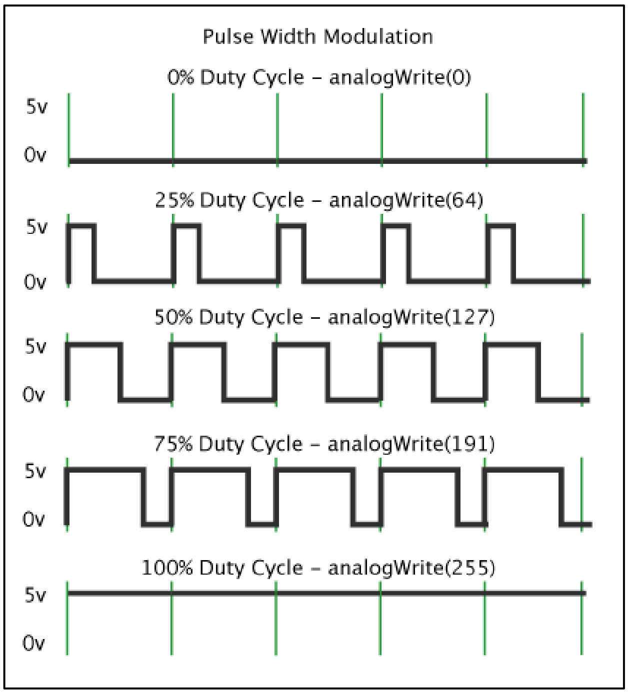


Figure 16: **PWM. *Source: [1]***

Finally, there are a set of pins for **communication protocols**. The *Atmega* have three types of serial communication (USART, SPI and I2C), which provide a variety of functionalities to the microcontroller, allowing interaction with a variety of devices, such as displays or even other microcontrollers.

Other aspects of the microcontroller are the memories; this contains different types and each of these memories has characteristics and functions of which are described below:

- Memory FLASH: Is the memory for save the firmware.
- SRAM (*Static Random Access Memory*): where the program stores and manipulates variables to run.
- EEPROM *(Electrically Erasable Programmable Read-Only Memory)*: is an area of memory that could be used by programmers to store information of long-term.

Below it can see a picture of the microcontroller pinout and then a table with a summary of their characteristics.

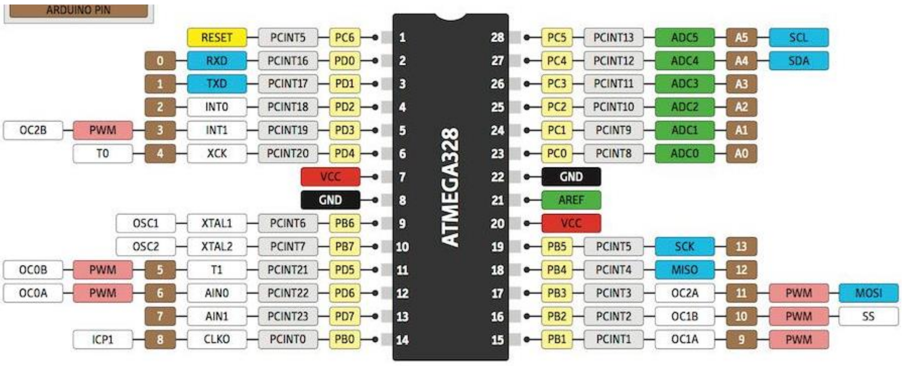


Figure 17: ***Atmega 328 pinout (Arduino UNO microcontroller). Souce: [6]***

Pin type	Nomenclature	Qty.
Analog pin	A0-A7	8
Digital pin	0-13	14
PWM pin	3,4,12-15	6
Serial	TXD, RXD	2
SPI	MISO,MOSI,SCK	3
I2C	SCL,SDA	2

Table 4: ***Atmega 328 pinout summary.***

2.4.2 Printer Firmware

As mentioned in the introduction, a noteworthy aspect is that it is used an existing firmware. In order to perform the design and testing is necessary to understand its functioning broadly.

As already said, the firmware is the code that governs electronics. On the one hand, it understands the G-code commands, and on the other hand, it performs other actions.

This firmware it is compose by three types of files:

The first is ". ino", an Arduino file that controls and contains other files. This file allows building or uploading a firmware to a device and easily creating new projects. The ".h" is a library. These decode / interpret the functions or commands that could be understood by the program. Finally, the register ".cpp" is the file that contains the code itself and functions taking place in the device.

ETSEIB

The firmware used, *RepRapBcn 3D v.11* [4], consists of 41 files. The following table summarizes the files and their function. From these files, the most relevant are the configuration file, the pin and Marlin[5].

File names	Function
BCN3Dv11.ino	Mean file that control and contain the rest of the files.
Configuration.h and Configuration_adv.h	Printer settings (minimum and maximum values of temperature, PIDs values, print size, speed ...)
EEPROMwrite.h	Library that allows write in the permanent memory.
Marlin.h and MarlinSerial.cpp/.h*	Understand g-Code
Fastio.h	Translate pins in "Arduino language"
Language.h	Allow choose language
Motion_control.h/.cpp, Planner.h/.cpp and Speed_lookuptable.h	Define types of movements
Pins.h	Contain info pins related board
Stepper.h and .cpp	Stepper control
Thermistortable.h	Read the thermistors
Temperatura.h and .cpp	Control the temperature (with PID) of the extruder and de heated bed.
Ultralcd.ino/.h	Allows viewing of printer status via an LCD
18 SdCard files	To read files from a SdCard

Table 5: ***Firmware files description***

[5] For further information see annex II.

3 REQUIREMENTS

The requirements of the PCB depend on printer characteristics; its easy usability and other technical aspects.

As regards printer features, which were mentioned before, the printer technology is fused filament fabrication (FFF) and the printing materials are polymers, namely, ABS and PLA.

Owing to this fact, firstly, it is necessary to realize the following aspects:

- Controlling 3 stepper motors so as to print in 3 dimensions.
- Controlling 1 extra stepper motors to supply the extruder.
- Heating printer's base at 120 °C to avoid imperfection of printed objects.
- Heating extruder to fuse the plastics. Consequently, the temperature peak must be 260 °C in order to print ABS.
- Controlling the temperature due to the necessity of adjusting both base and extruder temperatures
- Cooling an extruder part with a fan.

As far the easy use is concerned, it is recommended to connect easily the printer to a computer; for this reason, the connection is by means of the USB port. Besides, it is advisable easy-wire connection to ensure user´s comfort.

Other preconditions have been contemplated, which are related with design programmes. On the one hand, the highest PCB size must be 80x100 mm because of the *Eagle* programme. On the other hand, the printer should use a pre-design *firmware* which results in a need of a 90-bytes minimum memory.

Three extra points has been pondered. To begin with, it compulsory to achieve the main objective this is an integrated board. Then, the board should be eco-friendly, hence it should accomplish with European regulation. Furthermore, it is important to be profitable and, in order to that, the selling price must be around 80 € to be competitive.

The following table summarizes the stated data:

Printer characteristics	
Technology	FDM/FFF
Materials	ABS and PLA
Temperature maximums	Extruder 260 °C Base 80 °C
Motors	Steppers (4)
Extruder heating	10-12 A / 1-1,2 Ω
Base heating	3 A / 3,6 Ω
Temperature sensor	Thermistor 100K EPCOS
Requirements	
Compatible software	Arduino
Microprocessor	ATMEGA serie
Compatible Firmware	Marlin (G-code)
Connection	USB
FASH Memory	Minimum 90 bytes
Dimension	Maximum 100 x 80 mm
Maximum selling price	80 €

Table 6. Technical Requirements

4 COMPREHENSIVE STUDY OF THE ELECTRONICS

In this section, it has been detailed each printer electronics part to the proper functioning of the machine. For this, the problems and the solution have been studied and finally the design of the PCB has been realized.

The following diagram shows these parts:

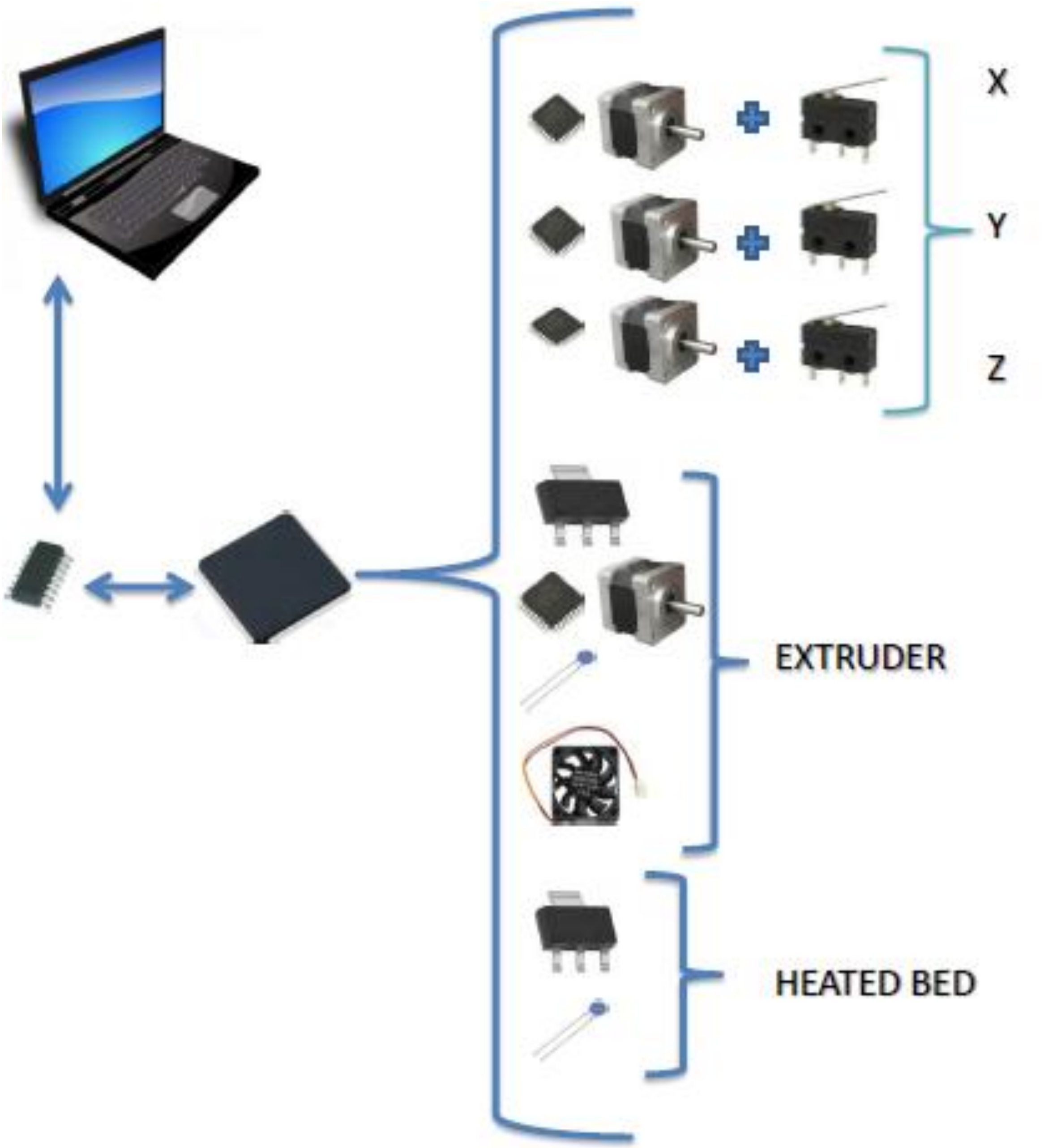


Figure 18: ***Control-parts diagram***

On the one hand it has the control part. On the other hand, it has the power part. The control is done by the *Arduino* microcontroller, which, as was stated throughout the document, will be integrated into the PCB. In addition, to make the communication between the computer and the microcontroller, a USB-Serial converter is required to send commands to each device.

These devices are the power section, these are:

1. <u>Drivers (+Steppers):</u> Permits the movement control of 3 axes (X, Y and Z) and the extruder mechanism.
2. <u>End-Stops</u>: Permits determinate the position of the coordinates origin.
3. <u>MOSFETs</u>: Allows the warming of heated-bed and extruder.
4. <u>Thermistors</u>: Allow the temperature controlling of the heated parts.
5. <u>Fan</u>: Avoid the obstruction of the material in the extruder.

4.1 Heated Bed and Extruder Control

As mentioned before, the control for heating the extruder and the heated bed is performed by MOSFETS that are activated and deactivated by PWM signals that alter the power applied to each of the parts. In other words, the MOSFET intensity driving is turned into heat by the bed or cartridge.

The currently problem involved is the overheating of the MOSFETS, because they work in a commutation and, also, a high frequency.

As it can see below, when the square PWM signal switches from high to low, a voltage peak is generated in the MOSFET and destroys this piece. To avoid this, it has installed a freewheeling diode and the lowest possible frequency it has been used because, against higher the frequency, the switching per second is lower.

It has to be emphasized that, although the temperature control does not require such continuous monitoring, is possible that this is not the optimal solution. However, in the firmware used, the control is done in this way, and then it has been consider the commentated solution.

4.1.1 MOSFET Overheating

As said, the main problem about the MOSFETS circuits is that it overheats and ends up hurting. For realize the control of the printer, a power MOSFET (N-channel) which is controlled by a PWM signal is used.

The PWM allows variable control over the current flowing through the circuit, allowing modifies the heat delivering, and consequently the temperature.

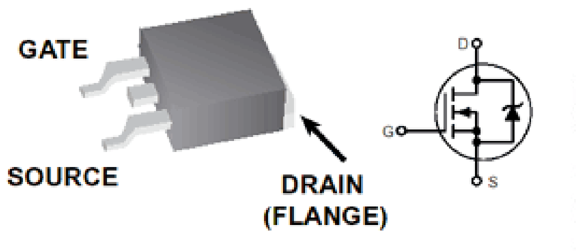


Figure 19: ***MOSFET device and symbol [25]***

The power MOSFETS are electronic components that allows to control high currents. This has three output terminals that are called: *Drain, Source* and *Gate* (D, S y G). The main current passes between *Drain y Source* (I_{DS}) while the control of this current is obtained by applying a voltage on the Gate terminal (relative to the Source terminal), known as V_{GS}. Minimum voltage is required to start driving a MOSFET. This definition is called "threshold voltage" or V_{th}.

As it will see in this section, there are 4 factors that adversely affect the operation of these devices:

- **Signal Resistor**: This resistance (R2) is situated at the Gate terminal and its value allows the MOSFET dissipates in greater or lesser extent, and consequently more or less heat.
- **R_{DS_ON}:** This is the resistance of the MOSFET conduction and generates losses by the Joule effect.
- **Parasitic Inductance**: Devices that are connected to the MOSFET (heated-bed, cartridge and wires) generate parasitic inductances which, in turn, generate voltage peak destroying the power component studied.
- **Frequency**: One of major cause of the overheating of these devices is the switching from state high to low, in other words, de move from one state in which you are driving at high intensities one in which stop driving. When this happens, all the energy stored in other components is transformed into heat.

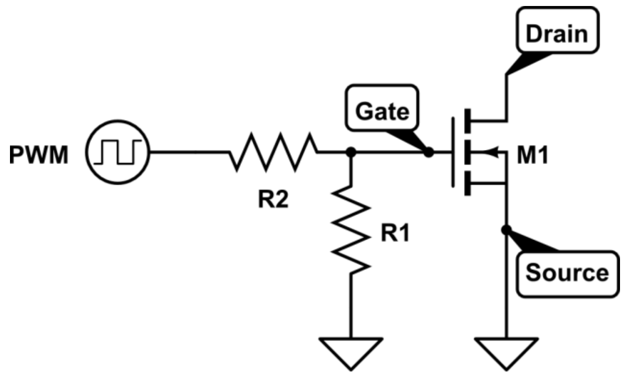


Figure 20 ***PWM control circuit diagram***

Before discussing these aspects, as seen in the picture above, when a MOSFET is connected to a microcontroller is necessary to implement two resistors: Resistor signal (R2), which will detailed below and is a source of problems, and the pull-down resistance.

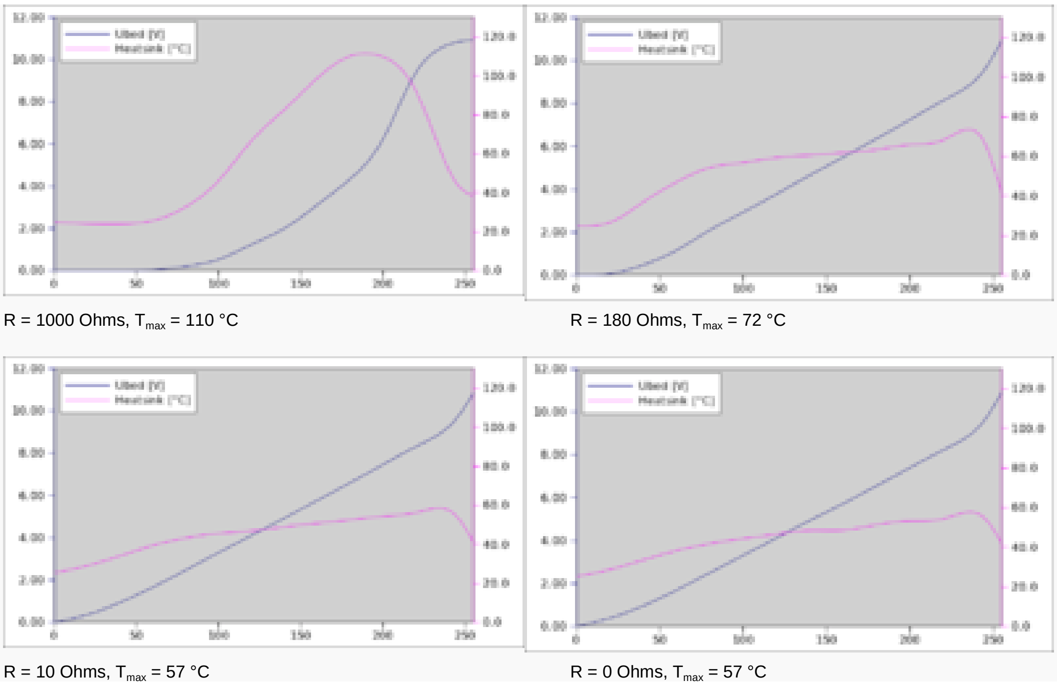
This last resistance of 100kΩ value is used to define a logic "LOW" state, which is necessary for the initialization of the microcontroller. In other words, to prevent the MOSFET is activated (conduction) while μC is switching on, it is used a high value resistance, thus maintaining the Gate voltage to 0V.

SIGNAL RESISTOR

The signal resistance (R2) is required to regulate the intensity coming through the Gate terminal. This is one of the reasons that cause heating, which is due to the phenomenon explained below:

When the control logic changes, for a brief moment of time the MOSFET absorbs current which charges the internal capacitor of the Gate terminal. The signal resistor limits this current; a low value allows rapid charging of the capacitor and therefore a faster switching which is very useful for regulating power pulse (PWM).

In this type of regulation, if the MOSFET commutation was "slow", it would find long time in the linear region and, therefore, would increase the power dissipation in it. Therefore, as stated above, a low value could be around 1kΩ, but after seeing the Gen7 Research study shown below, it was decided by a resistor of10Ω because as can be seen, it significantly reduces the operating temperature of the MOSFET.



R = 1000 Ohms, T_{max} = 110 °C

R = 180 Ohms, T_{max} = 72 °C

R = 10 Ohms, T_{max} = 57 °C

R = 0 Ohms, T_{max} = 57 °C

Figure 21: ***Heat vs signal resistor. Source: [20]***

FREQUENCY

In switching from state high to low, the energy stored in other components is transformed into heat. Therefore, the higher the frequency, the greater the heat dissipation, since the number of operations per second is also higher.

As to the value of the PWM frequency, this depends on the microcontroller used and their configuration. The *Arduino* microcontroller allows an approximate frequency from 500Hz to 32 kHz. These values will be used to study the following subsection.

R_{DS_ON}

Not only influences the frequency and signal strength in heating device. When a MOSFET is switched on, has a resistance between Drain and Source, which encourages the heat. This resistance is referred Rds_on, and is a parameter which is dependent on the component.

In other words, when a MOSFET is in the ON state, it behaves like a resistor (R_{DS_ON}). As a result, it is produced heat and this power dissipation is I^2x R_{DS_ON}. Therefore, against larger it is this resistance; greater is the increment of temperature.

PARASITIC INDUCTANCES

These are the problems derived from circuit design, but there is another problem leading to destruction of MOSFETs; these problems are the parasitic inductances that are created on the cable into the extruder and heated-bed.

These parasitic inductances cause for a moment a very high voltage and provoke the destruction of the device. This is because that the inductors store energy during the on-time of the process, so when the MOSFET switches from high to low state, this energy is converted into a voltage spike.

Parasitic inductances are created for different reasons: On the one hand the complex construction of the heated-bed creates an inductance of about 650nF, a little bit value. Instead, the heated cartridge generates a 3µF value. Furthermore, it must take into account the inductance generated by the wires between themselves and the heated-bed or extruder. For the following simulations it will take the experimental values obtained on references [9] and [10].

Part	Value
Wire (1m)	1µF
Heater Cartridge	3,6 Ω 3 µF

Table 7: ***Parisitic inductances Source [9] and [10]***

4.1.2 Simulation

In order to observe one of the problems discussed above, in particular peak voltage generated by parasitic inductances. Then, a circuit of cartridge heated is illustrated. The values of this are firstly resistance of 3.6 Ω and on the other, a parasitic inductance 3 μF. In addition, it also represent the cables which have a 1 μF inductor and MOSFET circuit mentioned at the beginning of subsection 4.1.1.

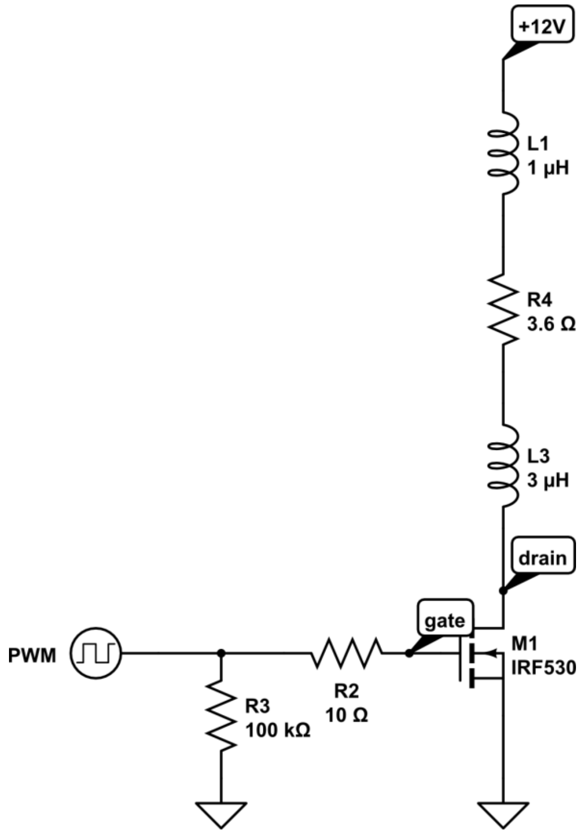


Figure 22 ***MOSFET circuit designed***

It has been developed two simulations. The one was a higher frequency of the *Arduino* (32kHz) and another was to the lower (500Hz), with a duty cycle of 0.5. The simulation MOSFET is IRF530.

To make these two simulations in the time domain it is to consider the following aspects:

- Total time simulation: This varies depending on frequency of simulation.
- Increase in simulation time: several tests it was conducted to obtain the optimum value (one that shows in enough detail values obtained with a time not very long simulation).

SIMULATION 32kHz

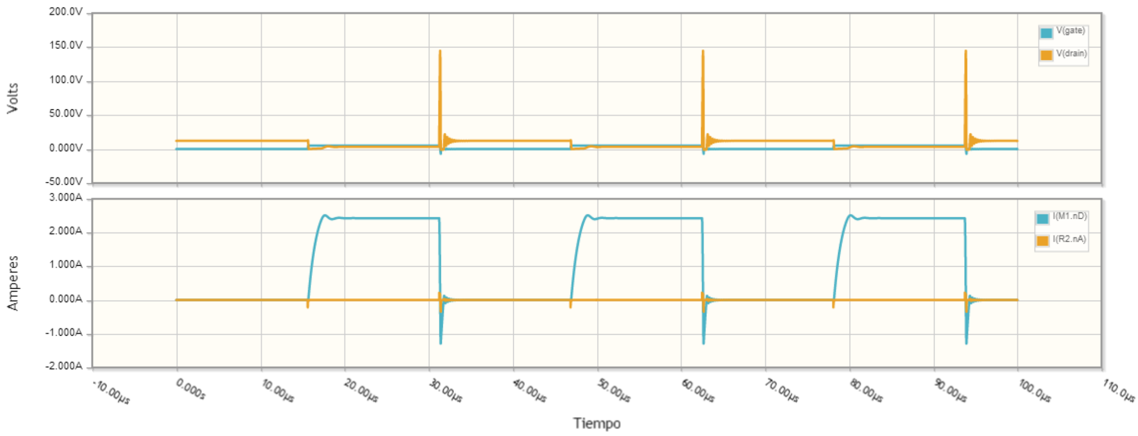


Figure 23: ***32kHz MOSFET circuit simulation***

As it could be observed, since the frequency is 32Hz, the cycle has a period of 31.25 microseconds. These may also notice that the ignition timing is about 15 microseconds, since the duty cycle is 0.5 (this could be seen in the voltage Gate, in blue in the top graph, and the current flowing through the MOSFET (Ids = 2.43 A)).

Another important aspect that it could be seen is that when switching from ON to OFF, inductances generated by a moment (about nano seconds) almost 150V voltage (149.7 V), which had said that it is a factor destroy the MOSFET, and that applies a high voltage repeatedly.

In addition, this simulation has been repeated for different values of duty cycle, and verifies both of the value of the maximum voltage and the value of the intensity do not vary significantly in terms of this.

SIMULATION 500Hz

This simulation shows that the period is lower than before, 2 ms, and it can see that the duty cycle is 0.5 also, since this the same time off as on. Finally it can see the same phenomenon happens in the previous frequency, although the value of the voltage is lower, although this is still high.

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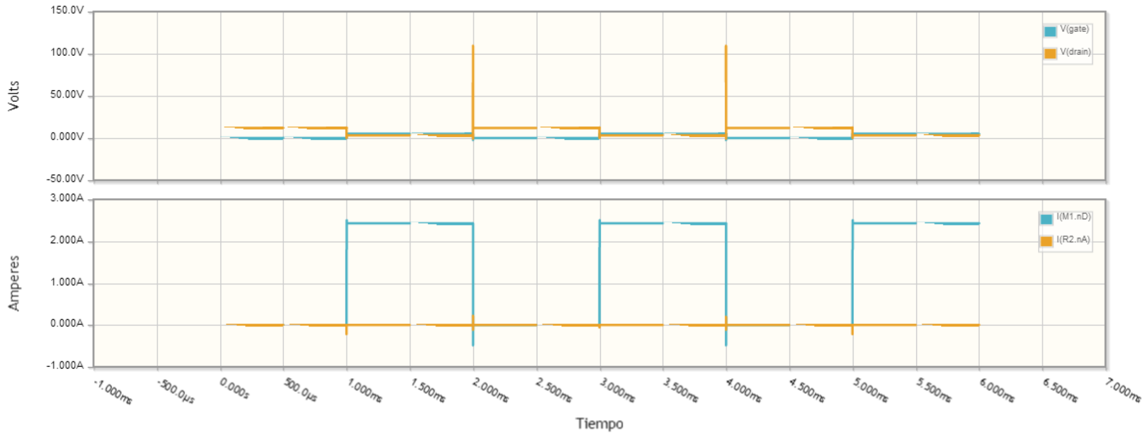


Figure 24: ***500Hz MOSFET simulation***

Features simulations are shown, as well as, the most relevant values:

	T simulación	Incremento	Vmax	Ids
32kHz	0,1ms	5ns	149,7V	2,43
500Hz	6ms	50ns	110V	2,43

Table 8: ***Simulation values***

4.1.3 Solution

In the previous sections it has been observed the main problems are the circuits. In summarizing:

- Overheating due to high signal strength.
- Overheating due to Rds_on.
- High voltage generated parasitic inductances.
- Overheating due to the frequency (which is greater the higher this).

On this basis, the solution is:

- Implement low signal strength, specifically 10Ω.
- Choose a MOSFET with lowest RDS_ON possible action to be taken at the end of the paragraph.
- Avoid the voltage with a freewheeling diode.
- Choose lowest possible frequency.

As mentioned above, first, the new circuit will have a resistance of 10 Ω. Secondly; to prevent the reverse voltage freewheeling diode is required.

Freewheeling diode: these are often used specially for motor circuits (Figure 25), to facilitate the passage of current when the input signals to amplifiers cease to apply, or when sudden direction reversals of motor rotation is performed (the current and voltage in the motor are of opposite direction). In this case, the diode it will be used by the energy accumulated in the inductors (which is equivalent to a motor) is dissipated through it and not the MOSFET.

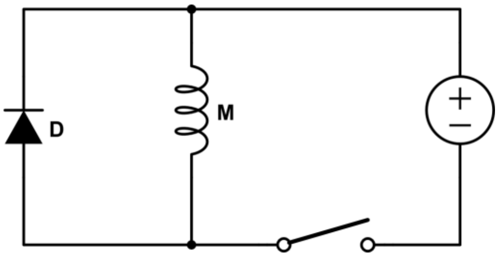


Figure 25: ***Motor with freewheeling diode***

Third, frequency of 500Hz it will be used since, as it has seen before, how much more frequency, worse consequences are obtained. In addition, since a high frequency does not provide an improvement in any other field (as with any frequency you can get a variable power control) it could use low-frequency.

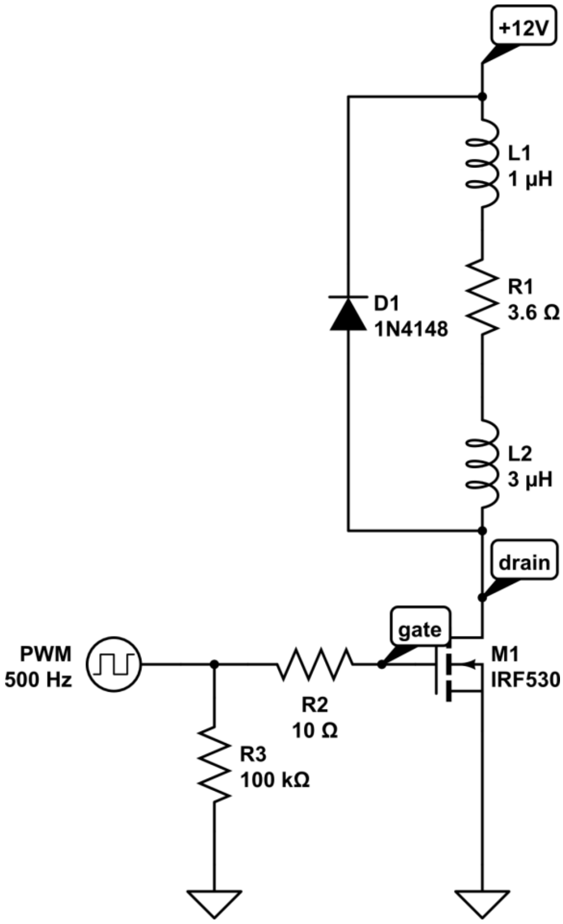


Figure 26: ***MOSFET circuit with diode***

With these parameters, a final simulation was realized:

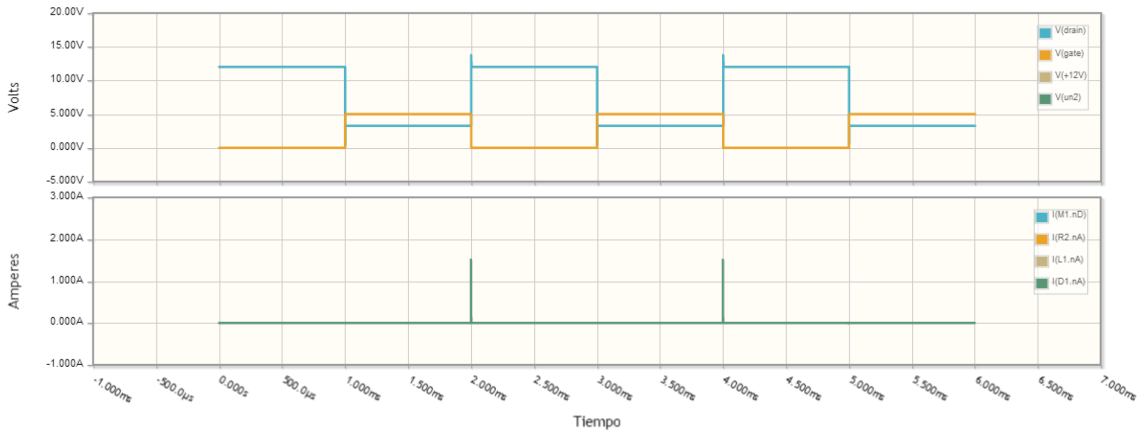


Figure 27: ***500hz simulation with diode***

The graphs can be seen as discussed above. Firstly, in the second graph can be seen as now the peak voltage has decreased to 14V.

Secondly, in the first graph shows how the diode absorbs the intensity generated by the parasitic inductances. Note that for the correct display of this intensity chart does not show intensity of driving the MOSFET, which is identical to the figure 24.

MOSFET SELECTION

Finally, for the choice of MOSFETs, besides what has been said, it has had to take into account resistance of the MOSFET driving (RDSon) is as small as possible to avoid the Joule heating effect.

Another aspect to consider is that meets the appropriate requirements to operate with an input voltage (VGS) of 5V and able to provide adequate strength for the devices. These devices are the bed, which requires 12 A o intensity, and heated cartridge, which needs 3A.

Finally, for the choice has been taken into account other aspects, besides those already mentioned:

- Voltage Rating (VDS max)
- RDS_ON
- VGS needed to switch on device sufficiently It
- Package type (through hole or surface mount)
- Package thermal Characteristics
- The maximum power dissipation
    - Maximum operating temperature.
    - Peak current rating

The table below shows the selected MOSFETs for each case and their corresponding features:

Part	MOSFET	Channel	Vds	Vgs	Id	Rds_on	Tmax	Pd
Cartridge	STP55NF06	N	60V	20V	50A	18mΩ	175ºC	110W
Heated bed	IRFB3004PBF	N	40V	20V	340A	1,4mΩ	175ºC	380W

Table 9: ***MOSFETs characteristics***
Source: [21]

4.2 TEMPERATURE MEASURE

Another aspect considered is the way to measure temperature. Measuring is an easy task; however it is difficult to make accurate and repeatable measurements. Currently, thermistor is used to determine the temperature of the extruder and heated bed, but in this project we have tried to study if there was a more efficient way of measuring. Therefore, it has been studied the different transducers to measure its shape and its advantages and disadvantages.

To introduce and clarify some doubts about these concepts, a temperature transducer is any device that converts heat into electrical signals received that could be processed by an electronic device.

There are four types of temperature sensors: thermistors, RTDs, IC sensors and thermocouple sensors:

- First, the thermistors are sensors base their operation on the variable resistance of semiconductor according to the temperature. Its temperature coefficient can be positive or negative, that is, the resistance increases or decreases as the temperature increases. The measuring range is between -50 ° and 150 ° C although some of them may exceed 300 ° C. Their behaviour is nonlinear.
- Second, the RTD (Resistance Temperature Detector) are sensors base their operation on the change of resistance of a conductor with the temperature, which is linear. The measuring range of the sensor ranges from -200 ° C to 800 ° C.
- Third, the IC sensors are those integrated circuits (hence come short) and offer high levels of performance. These sensors have a range of 5-30 VDC. Therefore, supplying the output is proportional to temperature. The drawback presented is usually accurate only at room temperature.

- Lastly are thermocouples. They base their operation on the Sbeeck effect, which union of two dissimilar metals creates an EMF (Electro Motive Force). When the two metals are joined and touching, this small contact point produces an open-circuit voltage which is function of temperature. This part is effective for the measurement of temperature because it is economical, exchangeable, presents standard connectors and can measure a wide range of temperatures.

As seen above, the RTC and the thermistors base their operation on the change of the resistance, either a conductor or a semiconductor. The main drawback is that required to operate a current for reading the associated voltage and thus be captured by a microcontroller. Therefore, this current provokes self-heating.

However, within these two transducers, the thermistor is most accurate when the RTDs measured temperature range is narrow, since the latter have a linear behaviour over a wide range of temperatures. Therefore, better response thermistors provide small changes in temperature. This characteristic is what has allowed decant the study of these transducers, as for the temperature of the bed and the extruder will be required to observe the changes in temperature over a small range.

In addition, as discussed in section 2, the heated bed is prepared to contain a thermistor, therefore, since it is difficult to adapt the design to another solution, this section will study possible improvements to realize.

As for the ICs and the thermocouples, as mentioned, only the former is accurate at room temperature. Although thermocouples solve the problem of self-heating of the thermistor, otherwise, they are more difficult to implement.

The thermocouples would be a better solution to measure temperature as the thermistor does not have self-heating, but due to its difficult implementation, finally it is not used.

4.2.1 THERMISTOR

A reason that this transducer is finally implemented it will be studied in detail.

As already mentioned, the thermistors are sensors which base their operation on the variation of resistance of semiconductor.

Figure 28: ***Thermistor***

There are two types of thermistors:

- The **NTC** (Negative Temperature Coefficient) thermistors are nonlinear resistor in which the resistance decreases according to the temperature.
- The thermistors **PTC** (Positive Temperature Coefficient) resistors are increasing their resistance versus temperature.

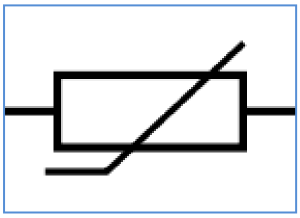


Figure 29: ***Thermistor symbol***

In this project an NTC thermistor will study. The operations of these thermistors are based on the heat receiving and measuring the electrical impulses. Therefore, there must be a relationship between the resistance of the temperature and ambient catching.

To understand the relationship between temperature and resistance, apply the following expression:

$$R_T = R_0 e^{\beta\left(\frac{1}{T_s}-\frac{1}{T_o}\right)}$$

Where:

- $\mathbf{R_T}$ is the resistance in ohms at the absolute temperature of the environment.
- $\mathbf{R_0}$ is the resistance at the reference temperature T_0.
- **β** is the constant that appears in a moderate temperature range and depends on the material.

As you can see the temperature-resistance relationship is not linear and it depends on the thermistor.

There are different types of thermistors. For the study of this project, has carried out to study the *Epcos* thermistor 100K, because it is the device to which the MK2 PCB is ready. This thermistor has the following features[6]

- **Thermistor Type:** NTC
- **Resistance:** 100kohm
- **Thermistor Tolerance:** -1% to +1%
- **Beta Value (K):** 4036K
- **Thermistor Case Style:** Radial Leaded
- **No. of Pins:** 2
- **Operating Temperature Min:** -55°C
- **Operating Temperature Max:** 300°C

4.2.3.1 Circuit

Then the circuit used most boards for measurement thermistor and disadvantages explained:

First, it must observe the difference of heat resistance (thermistor) versus temperature for the above model, which could be observed which is a nonlinear:

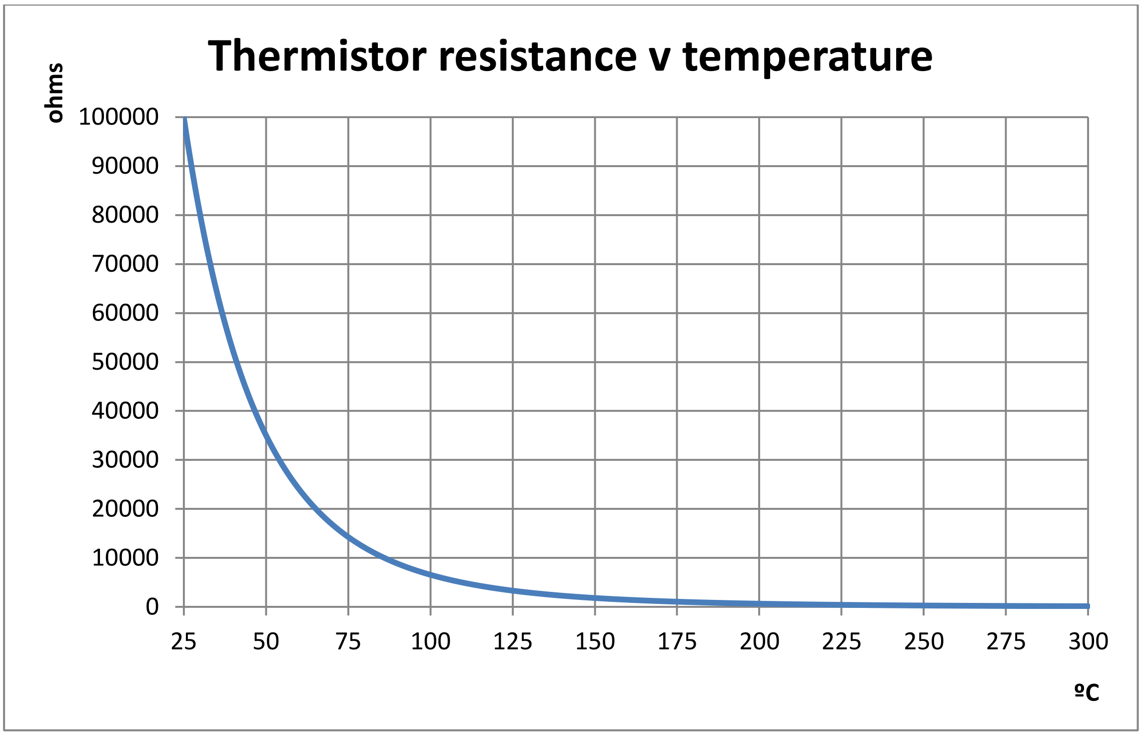


Figure 30: ***Thermistor resistance v temperature***

[6] Source [11]

The control circuit used it is shown below. The resistance 4.7kΩ reads the temperature causing this voltage between 5 and 0V for all temperatures as shown in Figure 32. Electrolytic capacitor (tantalum) it is used to smooth the signal and avoid noise.

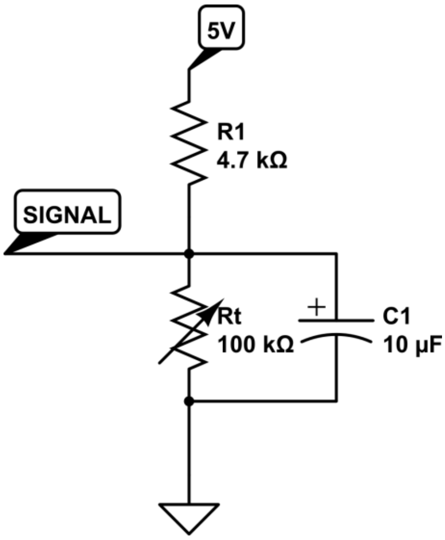


Figure 31: ***Thermistor circuit***

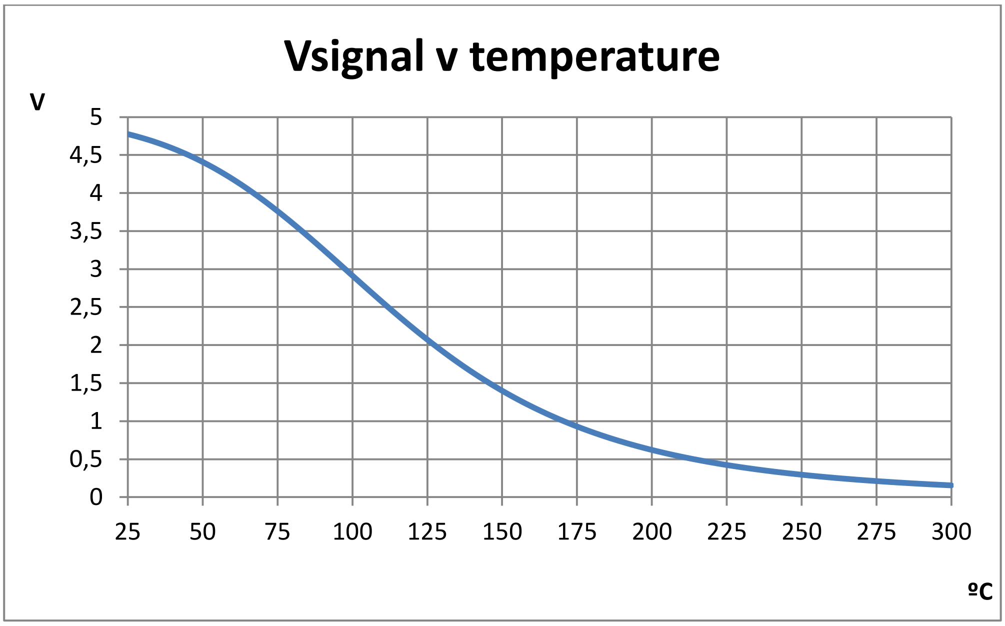


Figure 32: ***Vsignal v temperature***

In the picture it could see that the voltage decreases as temperature increases, because, as mentioned early, is a NTC thermistor.

Another important consideration is to know what errors induced intensity step by the thermistor, for it has made the following calculation:

First you must know the maximum power, which occurs when the two resistors (R1 and RT) are equal. Therefore:

$$Pmax = V \cdot I^2 = 1{,}33mW$$

Finally to know what temperature increase there, look for the value of the dissipation coefficient device (Source [11]).

$$\Delta T = \frac{Pmax}{\partial_d} = \frac{1{,}33}{1{,}3} = 1ºC$$

Finally one could observe that the overheating is not significant. Therefore, it could conclude that this measurement may it be acceptable for your application.

4.3 Driver

One of the problems with all printers is overheating of drivers, which are it used to control the stepper motors. Next, introduce what is a stepper and a comparison to see which the best alternative is will it be performed.

4.3.1 Stepper

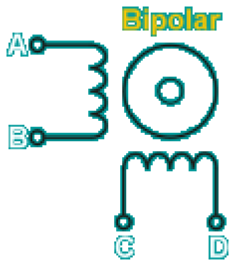
The stepper motor is an electromechanical device that converts electrical impulses from a microcontroller in discrete angular displacements.

This type of motor consists of a rotor with permanent magnets and a number of coils on the stator. There are different types of stepper motors. In this case, the design of the printer it has been studied engine performance bipolar[7] stepper, which has two windings inside.

Figure 33: *Stepper*. *Source [21]*

Bipolar motors have 4 output wires; these correspond to the outputs and the inputs of two separate windings (Figure 34). To control the motor is necessary to reverse polarity of each of the coils in the proper sequence. Then a sequence table are used to make 1 step, 2, 3 and 4 steps:

[7] This device has been the model chosen by Sara de la Peña to perform the project.



Paso	A	B	C	D
1	**+Vcc**	**Gnd**	**+Vcc**	**Gnd**
2	**+Vcc**	**Gnd**	**Gnd**	**+Vcc**
3	**Gnd**	**+Vcc**	**Gnd**	**+Vcc**
4	**Gnd**	**+Vcc**	**+Vcc**	**Gnd**

Table 10 ***Stepper steps Source [12]***

Figure 34: ***Stepper diagram***

Each investment in polarity causes the movement of the shaft, this one step forward. The direction of rotation corresponds to the sequence of steps: for example to move clockwise sequence 1-2-3-4, 1-2-3-4 serious ... and serious for counter-clockwise; 4-3-2-1, -4-3-2-1...

The main property is the motor step angle. The total rotation of 360 ° stepper grades divided by the angle step that provides the number of steps per revolution it is obtained. That is, if the step angle is 1.3 °, the stepper motor will be equal to 277 steps per revolution.

Another property of a stepper motor is the micro stepping. This consists to increase the number of steps that occur with these engines for greater positional accuracy.

4.3.2 Driver Pololu A4988

For the control of a stepper it is required a driver. The most used is Allegro A4988 breakout board, which allows intensity up to 2A per coil, which could be adjusted by a potentiometer.

Figure 35: ***Pololu A4988 breakout board. Source [13]***

It also allows micro-stepping 5: full-step, half-step, quarter-step, eighth-step and sixteenth-step.

The following figure shows how to connect the driver for proper operation. On the right side it could see the connections to the motor and the motor power (which requires a 100 µF electrolytic capacitor for decoupling) and power microcontroller. As the motor connections, it could be seen that as a bipolar motor connected on the one hand a coil (yellow) with each terminal (1A, 1B), and similarly for the second coil.

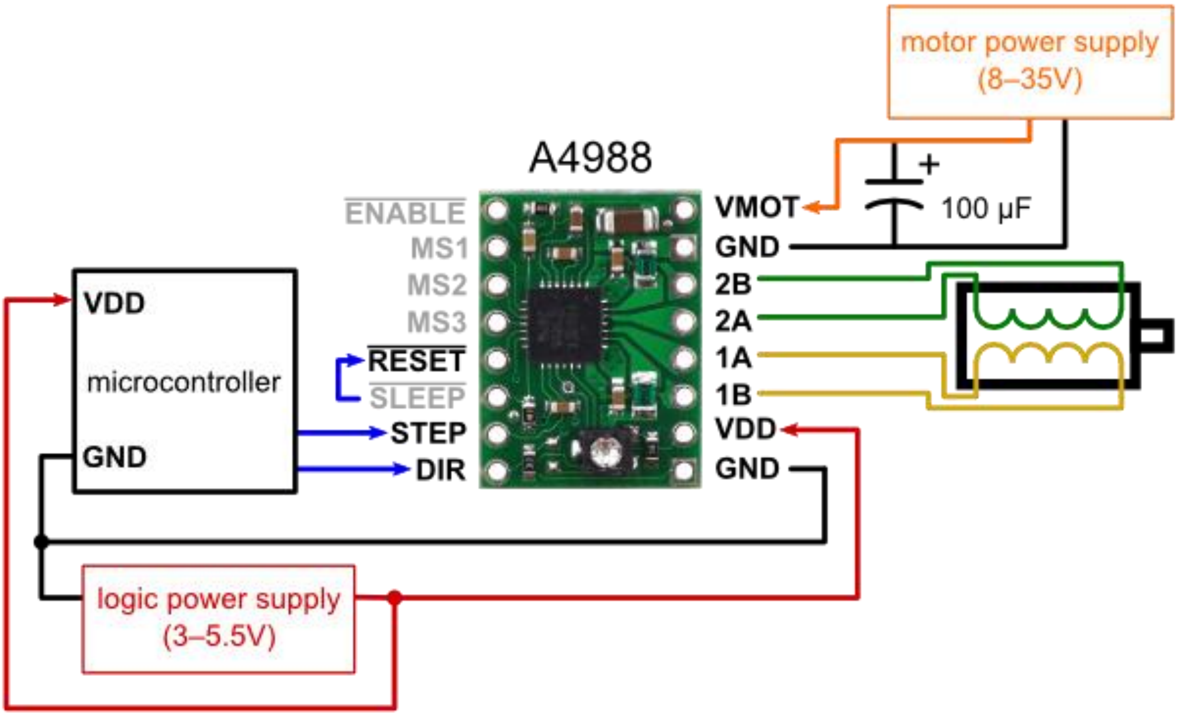


Figure 36: ***Driver A4988 connection. Source [13]***

On the left side, the driver has 8 controls inputs, which it is described below:

- ENABLE: as the name suggests, enables the board but with negative logic, in other words, it must be logical LOW state.
- RESET and SLEEP: These should it be connected by board construction (see datasheet in Annex IV).
- STEP: Each pulse on this pin corresponds to one microstep.
- DIR: This marks the direction that the motor turns.
- MS1-MS3: as the logical value of these terminals, the motor will rotate at 1, ½, ¼ 1/8 and 1/16 step, as indicated in the following table (all these terminals have a pull-down resistor, therefore could be left unconnected and move to full step).

MS1	MS2	MS3	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	Quarter step
High	High	Low	Eighth step
High	High	High	Sixteenth step

Table 11 ***Micristep Resolution. Source: [13]***

Another important aspect is the heat dissipation. The manufacturers recommend that this driver will incorporate a heatsink.

Finally, sample explained, when connected to Arduino with the aim of obtaining a microstepping 1/16, the pins it should be:

Control input	Arduino pin
Enable	Digital pin
STEP	PWM pin
DIR	Digital pin
MS1	HIGH (5V)
MS2	HIGH (5V)
MS3	HIGH (5V)

Table 12: ***Arduino pins for A4988 driver.***

4.3.3 Comparative

As written in the project scope, the driver would not be designed but will change the current one most suitable. Below is a comparison of potential drivers is to choose.

First of all allow the control to 5V (value of Arduino pin).

Secondly, it could be seen that all feeding are 12V except DRV8834.

Regarding A4988, as normal as voltage regulation, has overheating[8] problems. However the black edition is an improved driver, which it is mounted on a 4 layer PCB version, which facilitates heat dissipation.

The DRV8824 not allow the passage of sufficient intensity, and the maximum is 1,2A, and it is required an intensity around 2 A.

Therefore, the decision has between the A4988 and the DRV8825 black edition. Both share the characteristics listed in the table, and as both are mounted on a 4-layer PCB, making better dissipate heat. The only difference is the microstepping as the DRV8825 also permits in addition commons, 1/32, that is, could provide a more accurate.

Finally, for these reasons the DRV8825 choose which connection is identical to that discussed in the previous section, except mircoestepping as shown in Annex IV.

[8] See annex I

Product	Unit price	Size	Weight	Minimum operating voltage	Maximum operating voltage	Continuous current per phase	Maximum current per phase	Minimum logic voltage	Maximum logic voltage	Microstep resolutions	Reverse voltage protection?
	USD		oz	V	V	A	A	V	V		
A4988 Stepper Motor Driver Carrier	9.95	0.6″ × 0.8″	0.046(1)	8	35	1(2)	2(3)	3	5.5	full, 1/2, 1/4, 1/8, and 1/16	N
DRV8825 Stepper Motor Driver Carrier, High Current (8)	13.95	0.6″ × 0.8″	0.056(1)	8.2	45	1.5(2)	2.2(3)	2.5(4)	5.25(4)	full, 1/2, 1/4, 1/8, 1/16, and 1/32	N
A4988 Stepper Motor Driver Carrier, Black Edition (8)	11.95	0.6″ × 0.8″	0.0561)	8	35	1.2(2)	2(3)	3	5.5	full, 1/2, 1/4, 1/8, and 1/16	N
DRV8834 Low-Voltage Stepper Motor Driver Carrier	9.95	0.6″ × 0.8″	0.056(1)	2.5	10.8	1.5(2)	2(3)	2.5(5)	5.5(5)	full, 1/2, 1/4, 1/8, 1/16, and 1/32	N
A4988 Stepper Motor Driver Carrier with Voltage Regulators	19.95	0.7″ × 1.4″	0.12(1)	8	35	1(2)	2(3)	3(6)	5.5(6)	full, 1/2, 1/4, 1/8, and 1/16	Y(7)
DRV8824 Stepper Motor Driver Carrier, Low Current (8)	10.95	0.6″ × 0.8″	0.056(1)	8.2	45	0.75(2)	1.2(3)	2.5(4)	5.25(4)	full, 1/2, 1/4, 1/8, 1/16, and 1/32	N

Table 13: *Stepper control drivers comparative. Source [13]*

(1) Without included optional headers.
(2) Without a heat sink or forced air flow.
(3) With sufficient additional cooling.
(4) This driver does works with 2.5 to 5.25 V logic. It does not take an external logic power supply.
(5) This driver does works with 2.5 to 5.5 V logic. It does not take an external logic power supply.
(6) Logic voltage can optionally be supplied from integrated voltage regulators.
(7) On motor supply voltage (VMOT) only.
(8) 4 layer P

4.4 End Stop

Another essential part of the printer parts are the End-Stops. As mentioned earlier in this chapter, the control of three End-Stops is necessary to determine position of the Coordinate origin.

Figure 37 ***Mechanical End-Stop Source: [14]***

The End-Stop used is a mechanical one, because they are simpler and more affordable than others (ex. optical). This is an electromechanical device such as image, and it functions as a switch, in other words, has two states corresponding to logic HIGH and LOW level (5V and 0V).

To carry out operation of this Part, shall be connected to a digital pin, which requires a pull-up resistor to read the data obtained.

In addition, meeting the targets, to verify its operation it is added an LED to indicate when power is on and therefore find out if it works or if there is some mistake.

The following image shows the designed circuit. As you can see the device has a pull-up resistor of 10k and an LED in parallel.

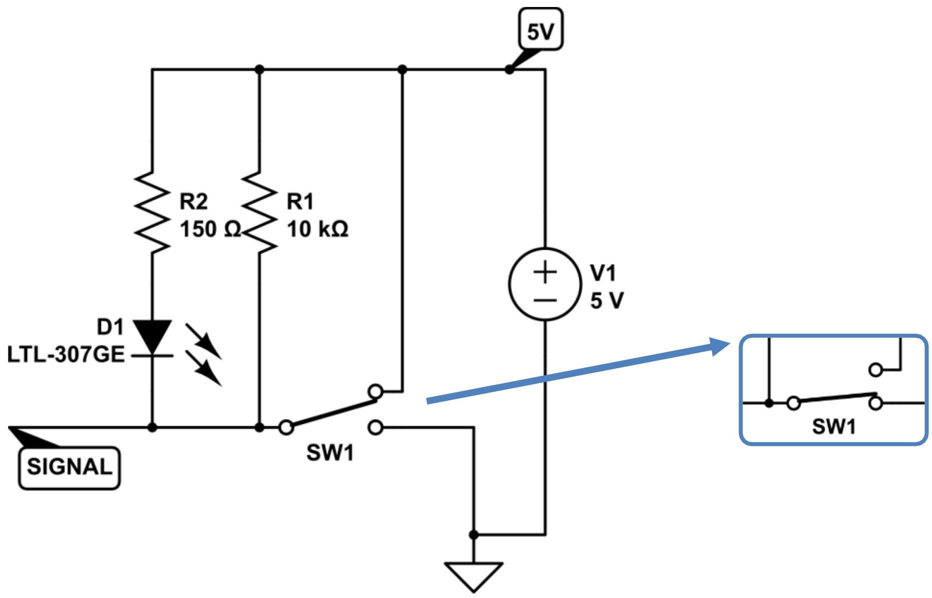


Figure 38: ***End-Stop Circuit***

To find resistance of the LED required for proper operation, apply the simple formula described below that takes into account the voltage and current operation of this:

$$R = \frac{Vcc - Vd}{Id}$$

Where:

- R is the resistance
- Vcc is the amount of voltage applied to the diode
- Vd is the operating voltage of the LED.
- Id is the operating current of the diode Led.

The LED that LTL-370GE it is used (see Annex IV). This has a voltage 2.1 v and 20mA current. With these data discussed above formula applies:

$$R = \frac{Vcc - 2{,}1V}{0{,}02A}$$

For to seen, to obtain the strength necessary to know the voltage, it being applied to the diode itself.

The voltage provided by the microcontroller is 5V, so:

$$R = \frac{5 - 2{,}1}{0{,}02}$$

$$R = 145$$

The resistance shown is 145, but if that is not a standard value, it wills used150Ω.

Once these calculations have it been performed in current simulation *CircuitLab* and have obtained the following results:

Value	Open	Close
SIGNAL	5 V	0V
I diode	0 A	19.10mA
V diode	0 V	2.135V
I pull-up	0 A	500 µA

Table 14: ***End-Stop Simulation values***

It can see the difference in the results of the values when the switch is open and when closed. If the circuit is open the signal has a high (HIGH) and therefore the LED (zero intensity) is not illuminated, and on the other hand, if the circuit it is closed the value it provides is low (LOW) and led illuminated with an intensity close to the nominal.

4.5 MICROPROCESSOR

For the choice of microprocessor must take into account different parameters. Firstly this should it be enough terminals with the right features, for it below is a table summary that indicates the type of pin control required by each part:

Printer part	Qty.	Control pin (type)
MOSFET Heated bed	1	PWM
MOSFET Hot-End	1	PWM
MOSFET fan	1	PWM
Drivers	4	1 PWM, 2 digital pins
Thermistors	4	Analog pin
End-Stop	3	Digital pin

Table 15: ***Printer Control pin***

Therefore, in total 4 analog pin 7 PWM and 11 digital pins are needed. The table below it is observed, one can see that the first two columns are it discarded and do not meet the minimum PWM pin.

Another aspect that it has been discussed in the initial requirements, it was that the board has to be compatible with the *RepRapBcn* firmware. Therefore, it takes into account two aspects; one hand, the sketch occupies about 90 bytes (see next image). Therefore, the microcontroller must have an equal or higher FLASH memory. On the other hand, for compatibility must also be implemented in the firmware and the table they are it shown only the first 4 microcontrollers[9].

[9] See annex II

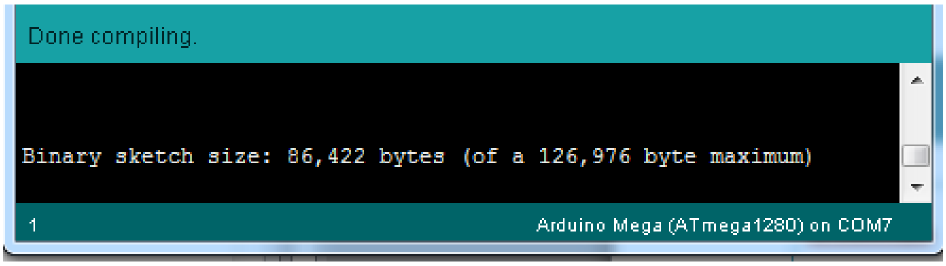


Figure 39: ***Arduino sketch compiling.***

To summarize, the devices that meet all of the features are only ATmega1280 and ATmega2560. It could be seen that share all features except price and memory and, since more memory is not precise, the first is chosen because it is more affordable.

Feature	ATmega 328P	ATmega 664P	ATmega1280-16AU	ATmega2560-16AU	ATmega32U4	AT91SAM3X
Price	$2.99	$4.66	$10.03	$11.28	$12.24	$13.21
Architecture	8 bit AVR	8 bit AVR	8 bit AVR	8 bit AVR	8 bit AVR	32 bit ARM Cortex M3
Speed	16MHz	16MHz	16MHz	16MHz	16MHz	84MHz
SRAM	2k	16k	8k	8k		96k
Flash	32k	64k	128k	256k	32k	512k
EEPROM	1k	2k	4k	4k		250k
UART	1	2	4	4	1	3
I2C	1	1	1	1	1	2
SPI	1	3	5	5	2	6
USB Host	(*)	(*)	(*)	(*)	1	1
IO Pins	23	32	86	86	26	103
ADC	6	8	16	16	12	12
PWM	6	6	15	15	7	12
DAC	-	-		-	-	**2**

Table 16: ***Microcontroller comparative. Source [16]***

4.6 SUPPLY

For operation of any device the aliment it is required. First, as it has seen the power section operates at 12V and 5V digital, which are fed separately.

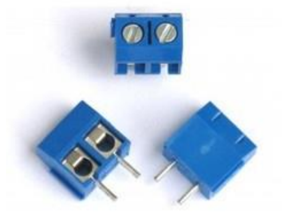


Figure 40: ***Term Block Connector. Source [24]***

For the digital part, in other words, the ATmega microcontroller, it will use the reference circuit *Arduino* Mega (see Annex IV) and fed by USB.

To feed the power electronics it is divided into two parts the heated bed, which requires 12A and 7A rest. In addition, to protect the circuit surge fuses previously mentioned values and a diode it is used to prevent reverse polarity.

Finally, it has to be emphasized that the connectors these are used for food are Term Block type PCB, which support up to 16A and a voltage of 250V. Also withstand high temperatures (105 ° C) [24].

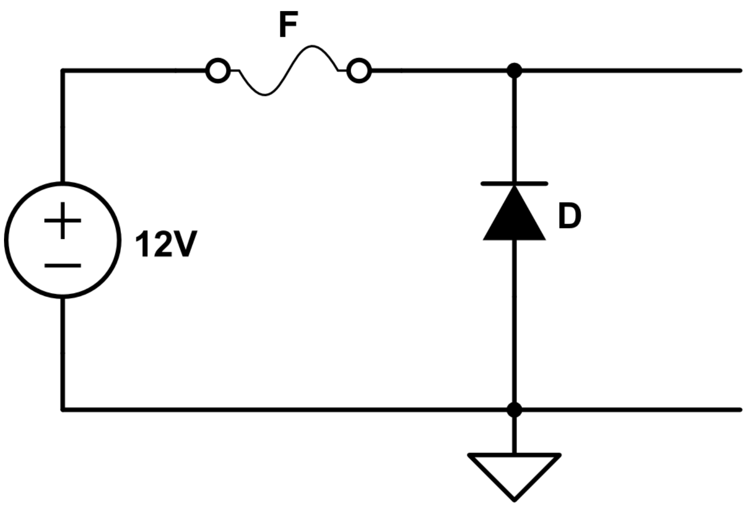


Figure 41. ***Supply Circuit.***

4.7 HEAT DISSIPATION

The thermal study of the power devices is essential to prevent overheating thereof. Ejecting heat certain components causes an increase in temperature. If this increase is very high, it may cause overheating in the device and, therefore, its destruction.

Since the devices that generate more heat energy are MOSFETs, to carry out the study of dissipation it is taken into account two main factors for cooling: On the one hand the number of layers of the PCB, and secondly a heatsink for the MOSFET.

Cooling the MOSFET through the layers of the PCB is sufficient to cool the devices as discussed in the following sub paragraph art. Instead, the sink it is considered a complementary mechanism and this it is explained in Annex III with corresponding calculations.

4.7.1 PCB LAYER

Since the MOSFETs are SMD, these are located on the PCB; accordingly, they transmit some heat causing heating of the motherboard. Although it may seem inconvenient, actually, if done a good board layout, this can help to dissipate the heat generated by the power device.

Therefore, a study of the PCB design it was made in terms of temperature variation depending on the layer having the PCB, as well as this variation depending on the number of MOSFETs and finally, variation of copper area and the space between MOSFETs.

First, this study should consider the following thermal considerations for the use of MOSFETS:

- This dissipates energy, which will lead to temperature increases elsewhere in the board
- If the device temperature is too high, this will cause damage to the MOSFETS and, in general, across the board.

One proposal for cooling and prevent overheating of MOSFETS is to add more layers on the board to dissipate heat faster. Then it will be exemplified this annotation to clarify this concept:

First studied how the temperature affects the number of layers for a MOSFET having a copper area as that of Figure 42.

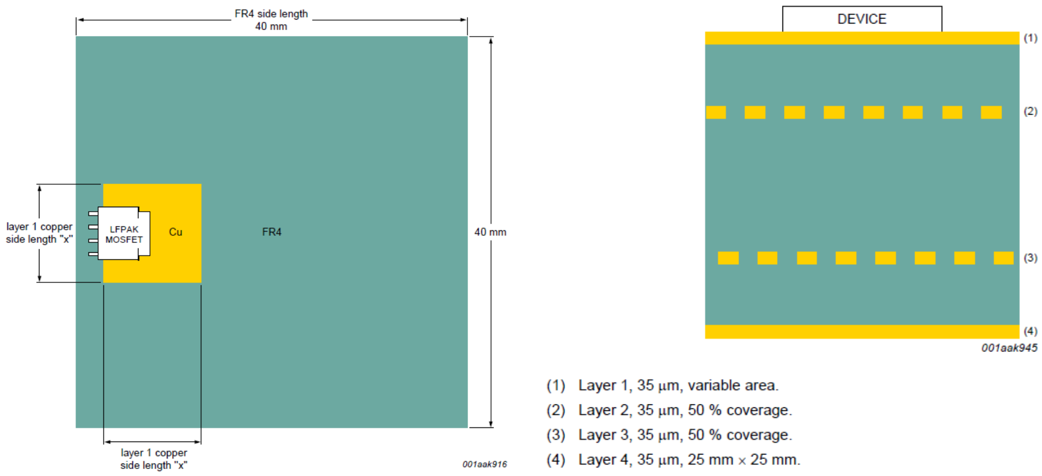
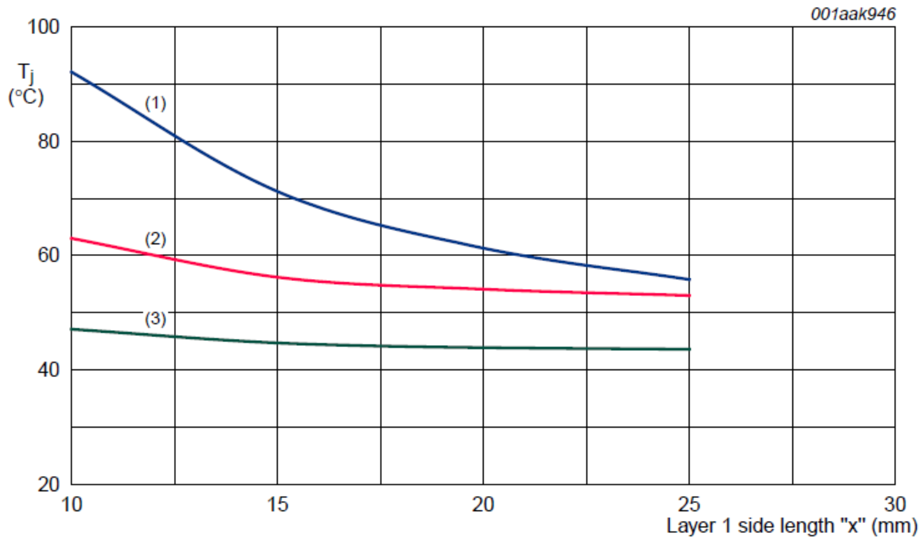


Figure 42 ***Copper area of a single device and 4 layer stack-up. Source: [18]***

On the one hand, the graph shows variation of the junction temperature as a function of number of layers. If it is observed, the value given for copper area of 20 mm side, it could be seen that temperature for 1, 2 and 4 layer is about 60, 55 and 45 ° C. It could see, therefore, that on greater the number of layers, lower the temperature. Furthermore it can be seen that the difference between layers 1 and 2 is less than the difference between 2 and 4 layers, which are 5 and 10 ° C respectively, that is, decreases in the second case double.

Moreover, if it pay attention to the temperature variation, depending on the area of copper it is provided, it could see that, against larger this, better conduct heat and reduced temperatures. Still, this effect varies depending on the number of layers. For one layer, variation of 10 mm side and 25 represents a reduction almost 40 ° C. In contrast, 4 layers of temperature variation are negligible.

It could be concluded, therefore, that it is necessary to pay attention to thermal aspects of the PCB, since as discussed above, add MOSFETS on different layout or add another layer on board, are factors that can help reduce overheating of MOSFETs and prevent destruction of these.



(1) Layer 1 only.
(2) 2-layer.
(3) 4-layer.

Figure 43: ***Device juction temperatura v copper side length for the 1,2 and 4 layer PCB stack-ups. Source: [18]***

Second, if behavior of the temperature for 4 MOSFETs in a same PCB studied with different configurations are it studied (see image below), comparing the relative distance of these, the results shown in figure 45 are obtained.

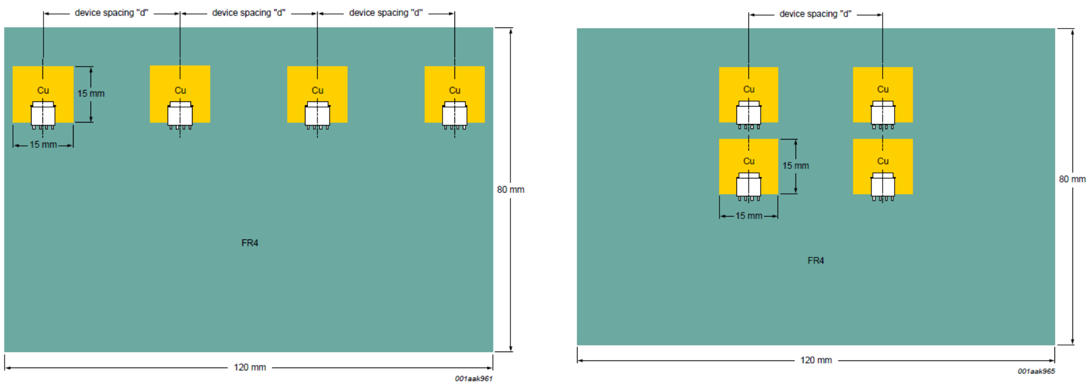
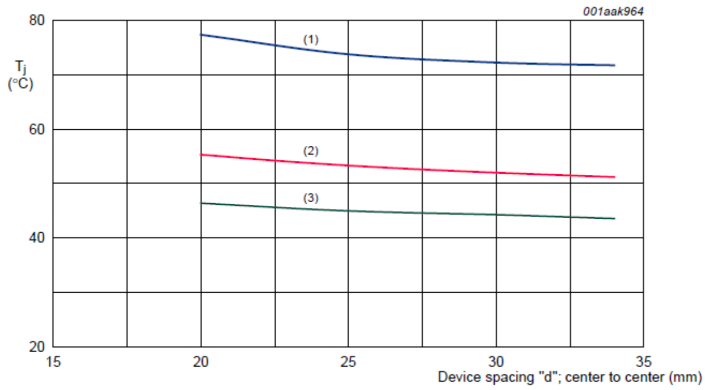
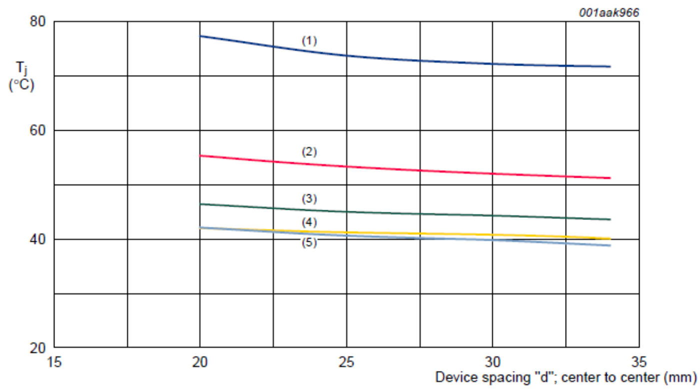


Figure 44 ***Four devices: PCB top copper configuration a and b. Source: [18]***



(1) Layer 1 only.
(2) 2-layer.
(3) 4-layer.



(1) Layer 1 only.
(2) 2-layer.
(3) 4-layer.

Figure 45 ***Simulation results for four devices of varying separation d for configuration a and b. Source [18]***

In these graphs it could be seen that the gap does not significantly affect the temperature, as it only decreases by less than 5 ° C. In contrast, the number of layers yes, as the temperature difference between one layer and 4 layers is 30 ° C in both cases.

As has been observed, using 4 layers in the PCB can be seen that MOSFETS dissipate enough energy to prevent overheating. For this reason, it has been using a sink as a complementary alternative, although it could be said that it is an appropriate solution to avoid these problems.

Finally, it is concluded that:

- The distance between the devices does not significantly affect the temperature.
- The copper area affects more significantly for layers 1 and 2; but not for 4.
- The number of layers significantly helps heat dissipation, being higher for 4 layers.

4.8 PCB DESIGN

Lastly, is has been designed the PCB. For this design, it has taken into account a number of regulations (UNE 20-621-84/3 and UNE 20-621-85/3) to carry out the correct elaboration of this circuit.

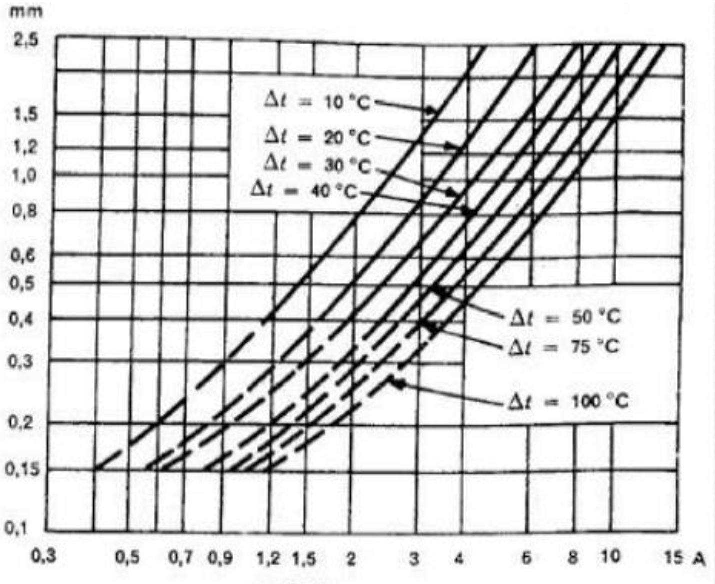


Figure 46: ***Track width v current Source for a 35 µm track [30]***

Other considerations or rules have been followed for the development of the board has been established by Eurocircuits. The document called '*design guidelines*' located in Annex III, describes the rules to be followed in the design of the board to correct fabrication, commenting concepts as the minimum separation between board drills, minimum silkscreen size, etc.

In general terms the rules and considerations that have been made are as follows:

- Simple design, tracks as short as possible, and therefore components sharing relationship situate near each other.
- Track width depending on the intensity.
- Track pitch depending on the voltage (0.4-0.8 mm).
- Distance between edges of the board and the tracks and / or components.
- Size of the holes.
- Do not put pints at right angles. (to make two turns of 45 degrees)
- Components parallel to the PCB edges.
- Do not pass the tracks between the terminals of a component.
- Provide support PCB holes.

It is noted that, more considerations are needed for board design, but these have been considered for the project. It has to be emphasized that should improve the design and layout of the tracks supply and make a design that avoids electromagnetic interference.

To the PCB design, it has been used Eagle software, it is an Open Source program for the development of boards. This is composed by a Schematic editor and layout editor. To perform design has performed the following steps:

First, it has been edited the *schematic* and has implemented the ATmega1280 microcontroller with *Arduino* reference circuit (see Annex IV) at Eagle program.

Once inserted, the circuits designed in the previous section are added. To facilitate this process, the editor can add cross cables (cross reference for nets) references. To accomplish this, it must take into account characteristics of each component (footprint, power resistor, a capacitor voltage, etc.). Then it designed each circuit control parts of the printer.

The following figures show these implemented circuits:

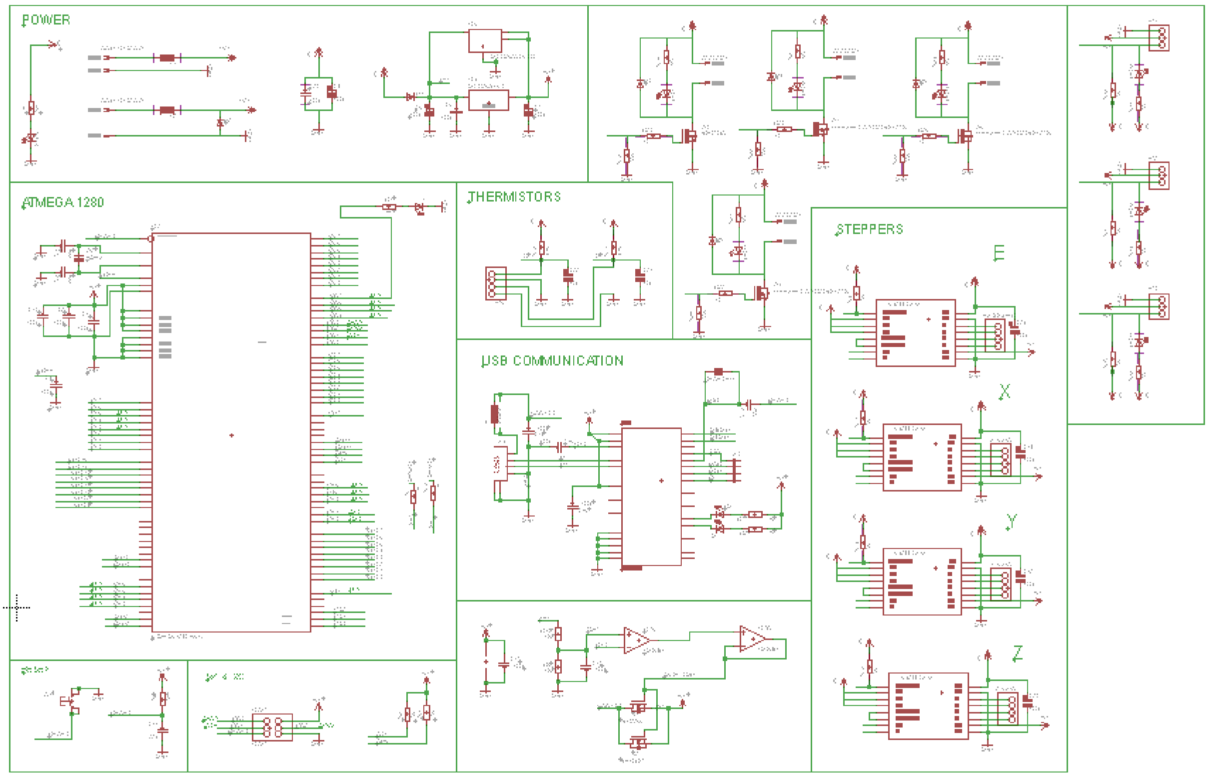


Figure 47: ***Schematic PCB circuit in Schematic Editor***

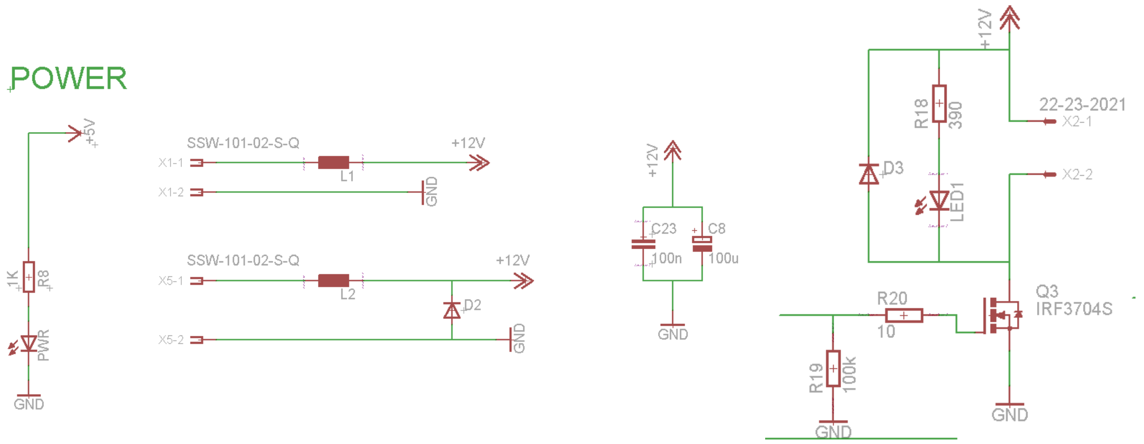


Figure 48: ***Power and MOSFET circuit in Schematic editor***

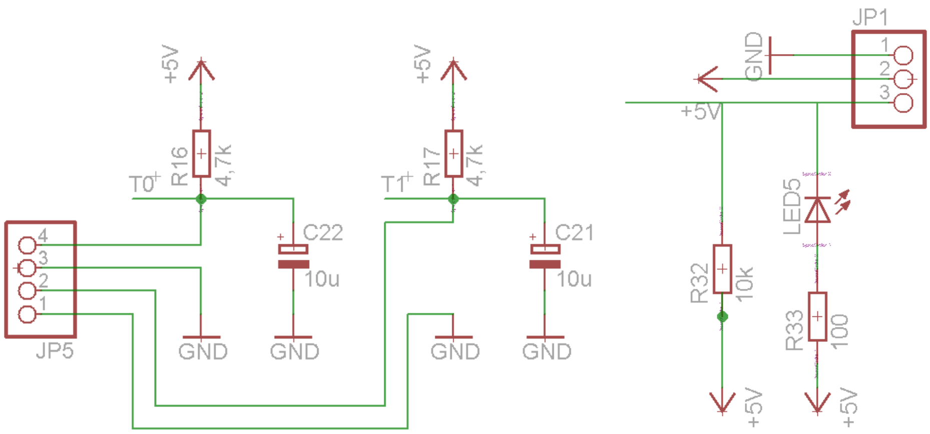


Figure 49: ***Thermistors and end-stop circuits in Schematic Editor***

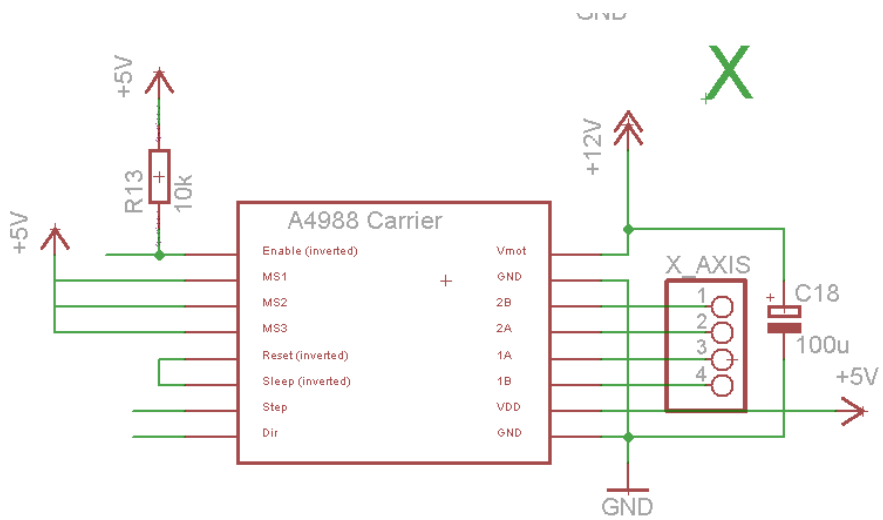


Figure 50: ***Driver circuit in Schematic Editor***

Finally, it has been edited the layout taking into account the considerations commented before. As it could see in the following figure:

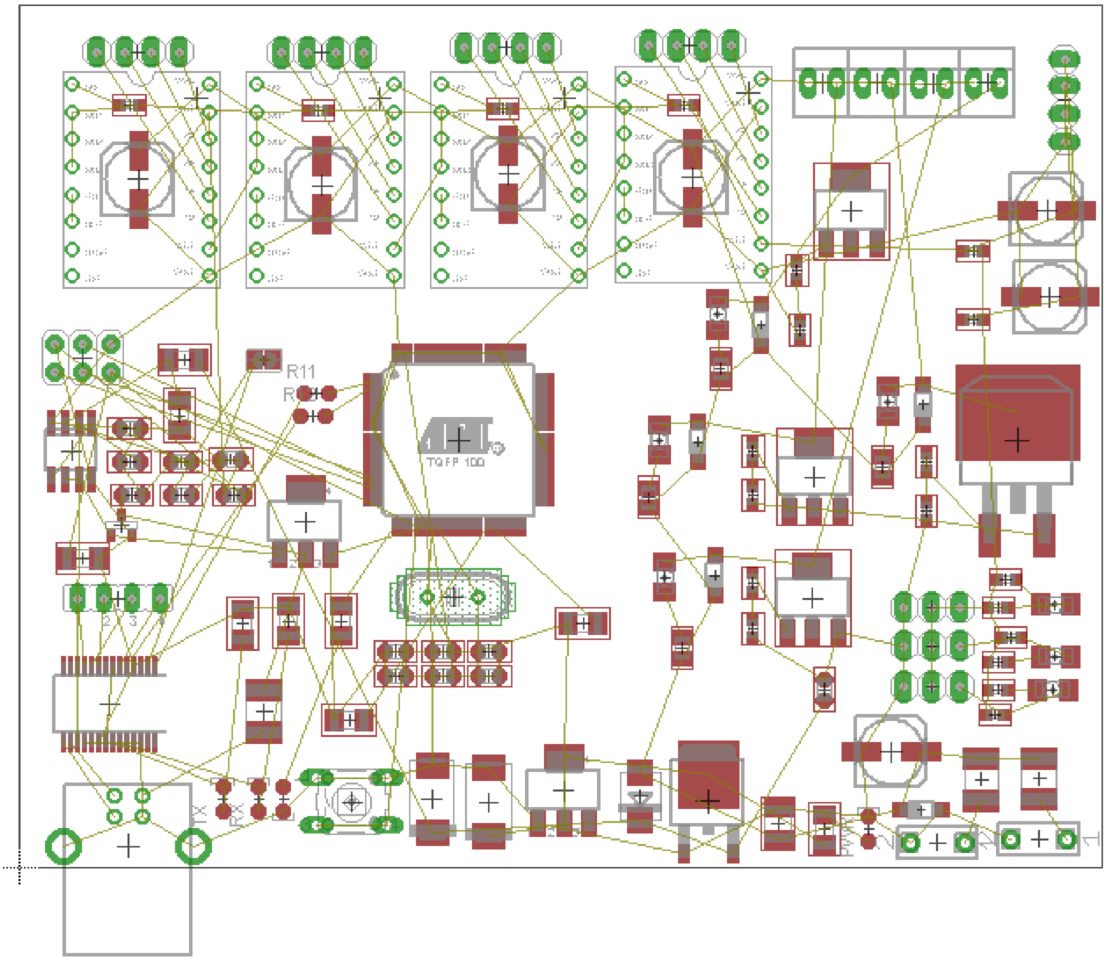


Figure 51: ***PCB design in layout Editor***

5 TESTING

To demonstrate the accuracy of the results obtained on the study of this work, experimental tests were performed. These were achieved from a prototype consisting of an *Arduino Mega* and circuit try on *Protoboard*.

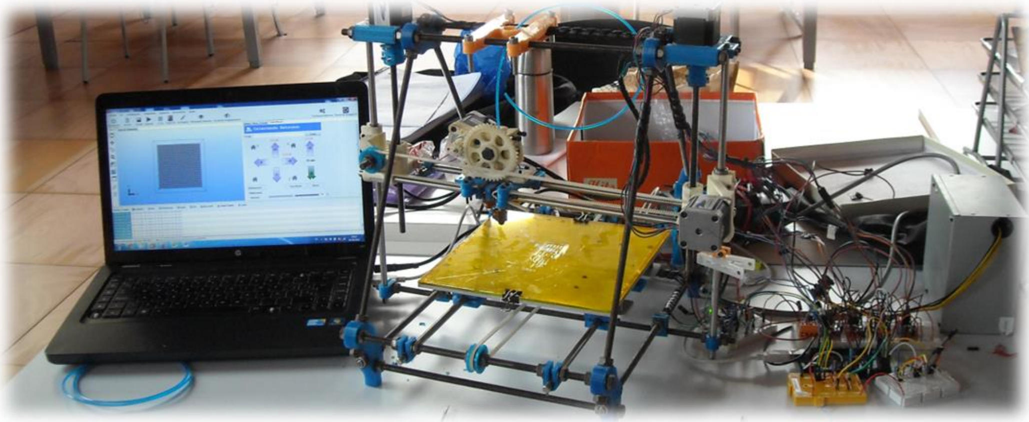


Figure 52: ***Material used for testing.***

It should be added that these tests only verify the board functioning, but has not been able to verify a continued operation ad nor have been able to take measurements with an oscilloscope so could verify the correct operation. Therefore, it has been proved that all the parts of the printer worked, in other words, have verified the following aspects:

- 3 axes movement and extuder mechanism.
- Merger of two PLA and ABS plastics.
- Warming of heated-bed to 60°C.
- Correct operating of end-stops.

The tests it was made with the first version of the RepRap printer Bcn Citilab[10] center (Figure 52).

[10] The printer belongs to the company Citilab, in Cornellà de Llobregat (Barcelona). Citilab "***exploits and spreads the digital impact on creative thinking, design and innovation emerging from digital culture.*** *Citilab is a mix between a training center, a research center and an incubator for business and social initiatives."* Source: [22]

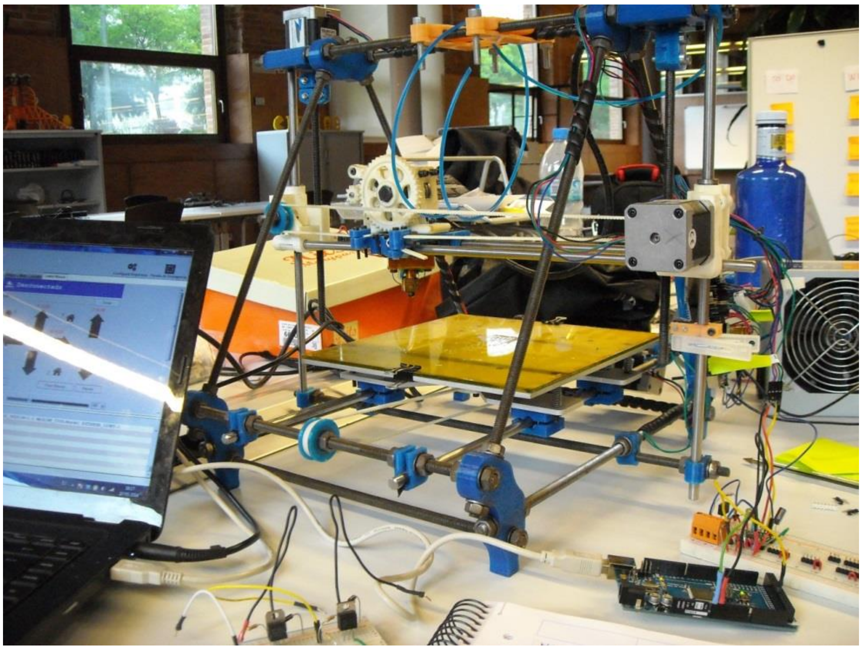


Figure 53: ***RepRapBCN printer***

The printer was only available during 2 hours, three days a week. Given these circumstances, it was a small order to test all components of the printer time, since there is a complexity to change all connections and also if any failed connection was very difficult to find the problem.

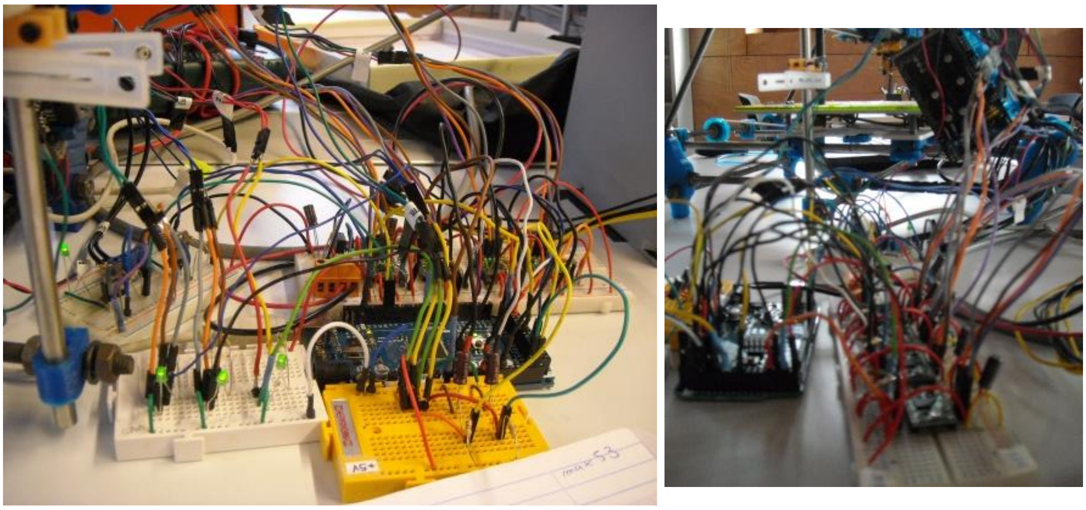


Figure 54: ***Printer RepRap connections in Protoboard.***

In one of the tests that it were conducted, due to a bad cable connection, it was produced a short-circuit that caused the failure of a fuse and the diode, causing everything to stop work.

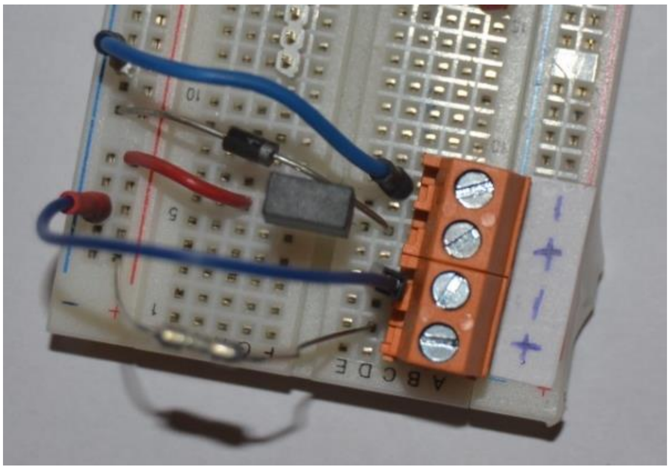


Figure 55: ***Supply prototype in protoboard***

Other problems that it has arisen to test the results have been that the maximum intensity of the *Protoboard* was 5 A. However, the precise intensity bed 10 or 12 A to reach 120 ° C. Therefore, it was not possible to raise the temperature of the bed at high temperatures. Consequently, to avoid damage to its operation, merely board and only reached 60 ° C.

Figure 56: ***Temperature monitoring with Repetier-Host***

The following image it could be shown as temperature decreased after being disconnect.

As has been discussing throughout the document, the firmware that it was used *RepRap 3D Bcn* v.11 + [3] and to control the printer it was used Repetier-Host software, which allows control of every part of the printer it is used manually, as, for example, temperature control as shown as in previous image.

As for the firmware, configuration 33 it was used to determine the *Arduino* pins used for these tests. This setting is the same as that used for the RAMPS [11].

With these tools it could make relevant checks of each component of the board. The following sections, the steps taken for development of the tests and the results that it were made will be explained are it discussed.

[11] For more information, see annex II.

5.1 FIRMWARE COMPILATION

As mentioned above, the firmware was used for the realization of the test was *RepRap BCN 3D+ v.11* from CIM Foundation.

The steps that have been made to add the firmware to the Arduino Mega board have been (See Figure 57):

1. To get the firmware to be added to the board, first, download the IDE of the microprocessor on the website[12]. Select the operating system to work with a computer (in this case has been made with Windows 7) and install corresponding drivers.
2. Once downloaded, open *Arduino* program.
3. First, choose the file is going to work, in this case, v.11 firmware.
4. It proceeds to verify that it hasn't failures in the code.
5. Once verified, begin the steps to proceed with the compilation. To do this, it must access to Tools, and choose the Microprocessor Board with which the tests are performed. In this case it has selected *Arduino Mega 2560.*
6. Thereafter, select the USB port.
7. Finally, it compiles the firmware to the microprocessor

[12] Source[1]

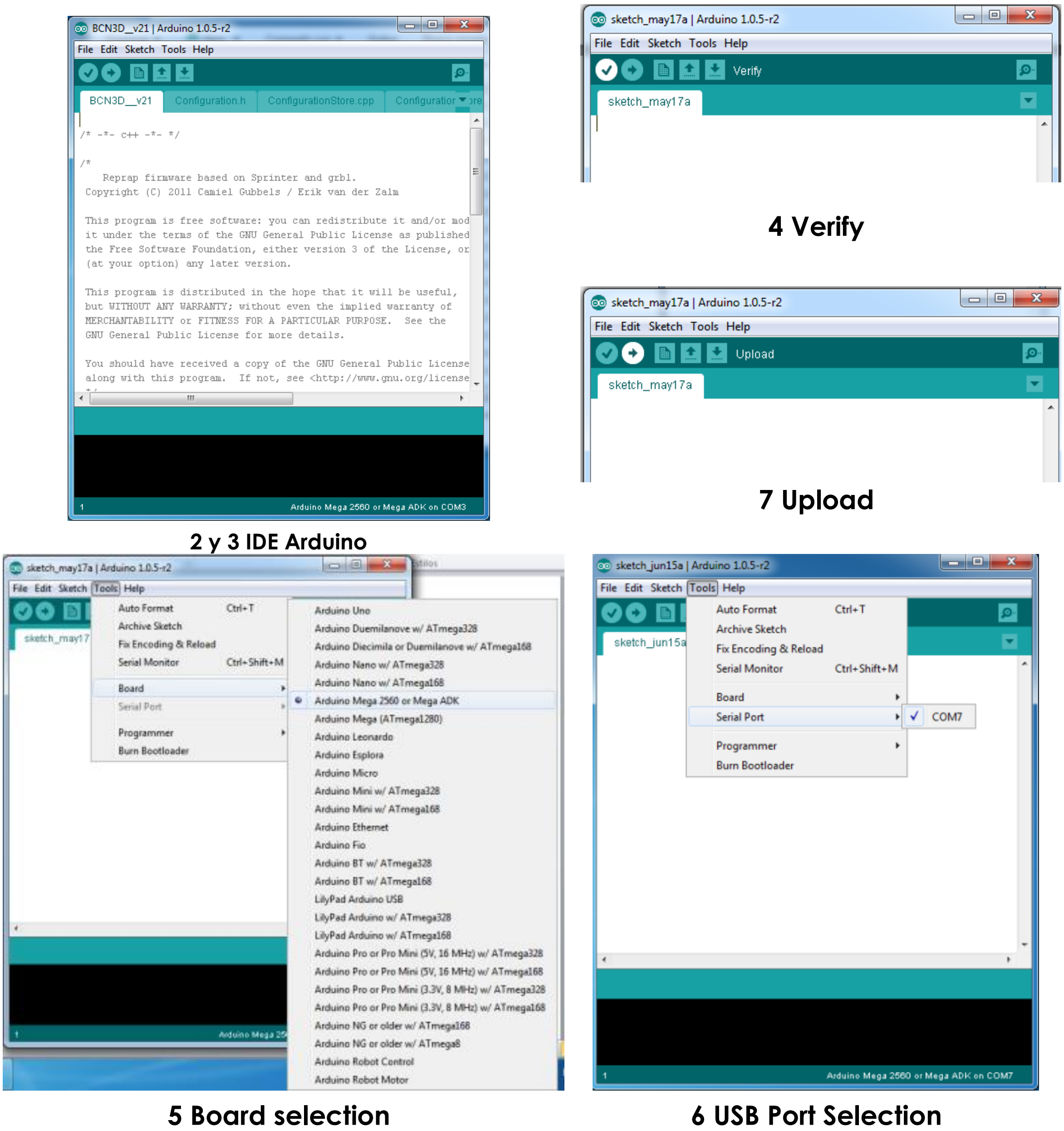


Figure 57: *Firmware compiling.*

5.1 PROBES

5.1.1 AXIS MOVEMENT

Once the firmware is installed in the microprocessor, tests are done on Protoboard to test separately the movements made by the printer. This study is realized for the tool Repetier. This process can be seen in image 46. This tool allows move the axe in steps of 0.1, 1, 10 and 50 mm.

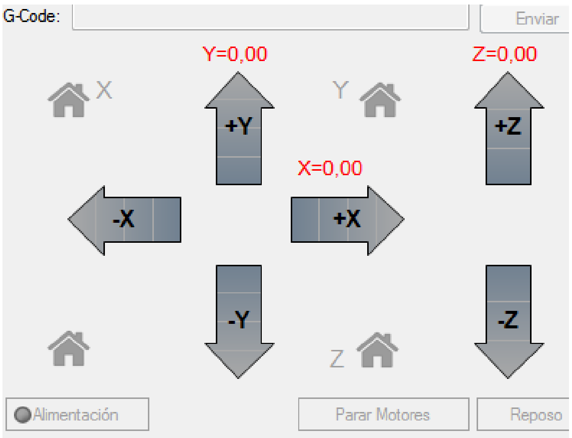


Figure 58: ***Manual control of Repetier.***

The following image shows the drivers that control the X and appear, and Z. To test each is checked if the pins 1A, 1B, 2A and 2B, are properly connected, or vice versa, making the direction of the axis it is correct.

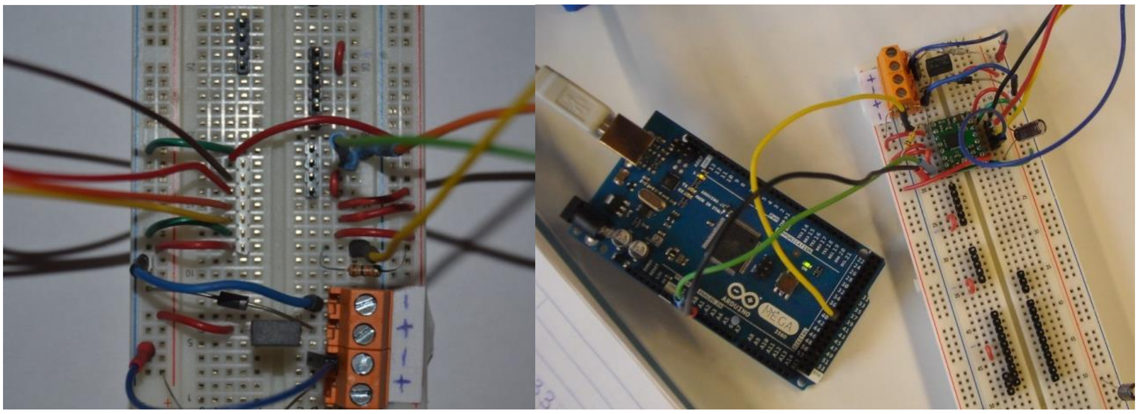


Figure 59: ***Stepper drivers.***

It has to be emphasized that the *RepRap* printer is identical to the prototype printer who control the manufactured board, except that in the printer with which you have performed these tests has two engines on the z axis, while the printer to be done in this project would have a single engine. Therefore it was necessary to add two groups of wires to control the Z axis.

5.1.1 Heating and temperature

In the next process it proceeds to evaluate the temperature and heating about heated bed and extruder, two printers *RepRap* parts that perform printing.

To check this warming of both parties had to install temperature sensors. By Repetier CAM tool was programmed that heating the extruder was 200 ° C and the base platform (heated bed) was a 55°C. The following image shows this first step.

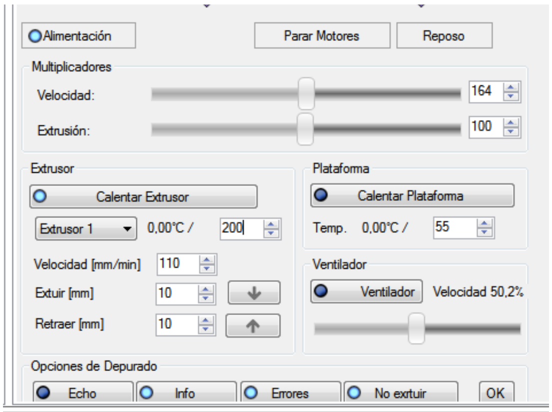


Figure 60: ***Programming extruder temperature.***

While both parts are heated, in the screen can be seen temperature increase of the two sections. This it has allowed know and study the processes for perform the heating of this pieces.

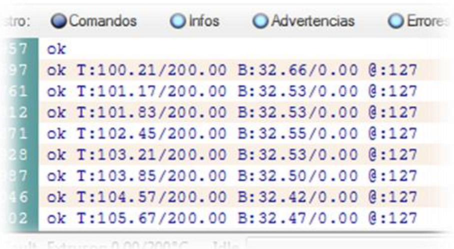


Figure 61: ***Temperature monitoring of Repetier***

It was checked that the heating about the extruder and the base carried out in a short part of time appropiate for the time of printing. In image 62 it can see the increase of extruder temperature as time passes.

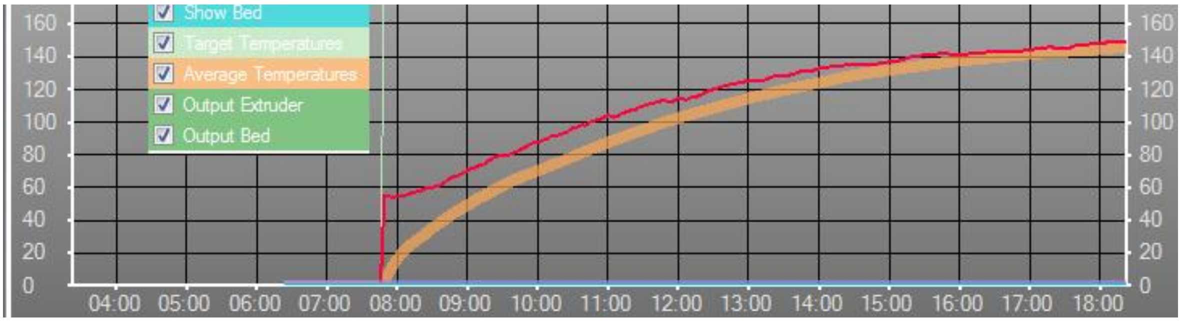


Figure 62: **Temperature monitoring of Repetier**

Another form for to can visualize that MOSFETS are in functioning are through a led that it was installed in a Protoboard, which it blinked when was executed the function at PWM.

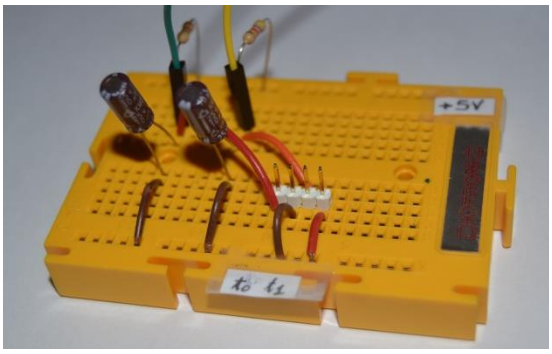


Figure 63: ***Thermistors prototype circuits***

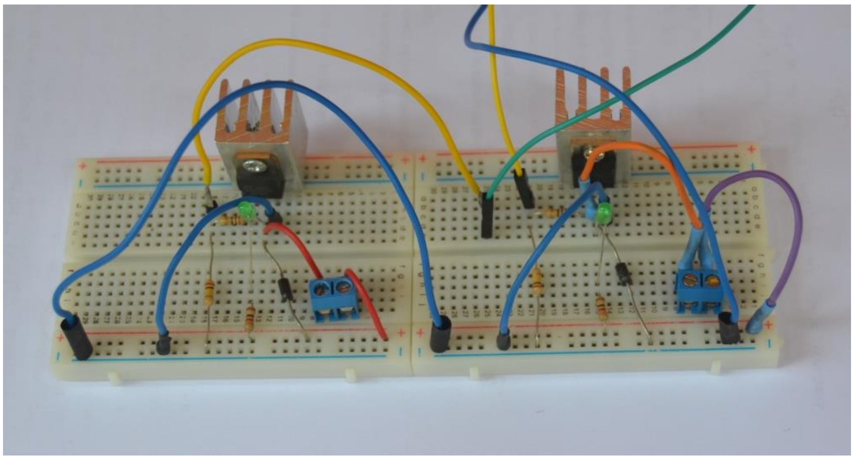


Figure 64: ***MOSFET circuit.***

5.1.1 END-STOP

As already discussed in this document, the use of End-Stop is necessary to determine the origin coordinates of the printer, since it is not possible to know the position of the engines with other data acquisition.

To perform verification, it was implemented three End-Stops on *Protoboard* to verify properly operation of the axes. To find out, the control circuit contains an LED that is off when the End-Stop was activated. In the next picture it can see circuits End-Stop corresponding to 3 axis.

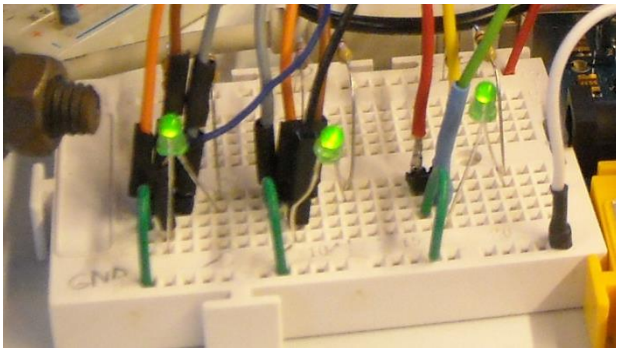


Figure 65: ***End-Stop Circuit for axes X, Y and Z.***

6 Economic Analysis

For the economic study of the project it have been referred two concepts; on one hand the costs associated with engineering and design and, on the other, the estimated cost of the product including material and manufacturing.

First, as to the cost of research it was considered the hours spent and invested in developing the prototype. It is estimated that a total of 300 for 25 € / h and the amount has it been spent 200€[13].

In order to carry out the total cost of the investigation, it has been multiplying the dedication hours for the study of the project for 25€ per hour. Investigation dedication study has been 300 hours plus a cost of 200€ derived from the first *Protoboard* prototype. Therefore, this cost generated 7.800€ for development and investigations.

Concept	Quantity	Cost	Import
Engineering	300 h	25 €/h	7500 €
Prototype	1	200 €	200 €
Program		0€	0€
TOTAL			7.800 €

Table 17: ***Engineering cost estimation***

However, it would be necessary to invest about 500 hours and make a new prototype or two that are not based on *Protoboard*, so summary a cost of 170€ per prototype and finally making a total of 12.900€.

Concept	Quantity	Cost	Import
Engineering	500 h	25 €/h	12.500 €
Prototype	2	200 €	400 €
Program		0€	0€
TOTAL			12.900 €

Table 18: ***Engineering cost estimation II***

[13] See annex II.

In these hours, it will carry out the next actions:

1. Testing with an oscilloscope the actual prototype.
2. Modifying the prototype on PCB.
3. Testing with an oscilloscope the modificated prototype.
4. Modifying this prototype on PCB.
5. Testing this modificated prototype with an oscilloscope.

It has to be emphasized that there is no cost associated with the software used and that they are all Open Source program, as not as has generated no cost investment in welding equipment which is used for the assembly of boards these prototypes discussed above.

7.1 Product estimation cost

For the product cost estimation, it was divided on three differentiated parts. At the first it was propels the price that printed circuit of the motherboard across the 'Price Calculator' of 'Eurocircuits[14] .at the second one, the cost of the spreadsheet the materials it will elaborated one BOM (bilt of materials) and it was sought the import of the one components at the distribution Mouser. Finally, just knowing the assembly it was demanded a budget on the business Insercard. For the old spreadsheet might add for elaborate the costs it was not adapting VAT.

Next, it shows the general disaggregation of this is shown, calculated for different amounts of orders:

		1	10	100	250	500	750	1000
PCB	Total cost	92,22 €	216,50 €	610,30 €	1.024,57 €	1.534,30 €	1.948,37 €	2.477,31 €
	Unity cost	92,22 €	21,65 €	6,10 €	4,10 €	3,07 €	2,60 €	2,48 €
Material	Total cost	77,44 €	432,70 €	2.927,00 €	6.882,00 €	12.619,00 €	18.937,00 €	24.198,00 €
	Unity cost	77,44 €	43,27 €	29,27 €	27,53 €	25,24 €	25,25 €	24,20 €
Assembly	Total cost	na	na	1.000,00 €	1.900,00 €	3.400,00 €	4.900,00 €	6.400,00 €
	Unity cost	na	na	10,00 €	7,60 €	6,80 €	6,53 €	6,40 €
TOTAL	Total cost	169,66 €	649,20 €	4.537,30 €	9.806,57 €	17.553,30 €	25.785,37 €	33.075,31 €
	Unity cost	169,66 €	64,92 €	45,37 €	39,23 €	35,11 €	34,38 €	33,08 €

Table 19: ***Estimation cost of the product***

[14] See Source [23]

In the above table it could be seen that as unit both as 10 is not considered the assembly cost because it will do manually. From 100 it takes into account the cost of assembly and later, is detailed calculation.

From this information, it can be seen that the price of the board it is reduced to exceed quantity of 100, as the price of assembly, since its initial cost is 10 € or less and will shrink considerably.

The following graph shows the cost of the board according to the unit that are manufactured. As is natural and has been discussed in the previous table, the price decreases as more units are produced. Another feature observed is that from 500 units, the price of the board stabilizes at a lower figure than 35€.

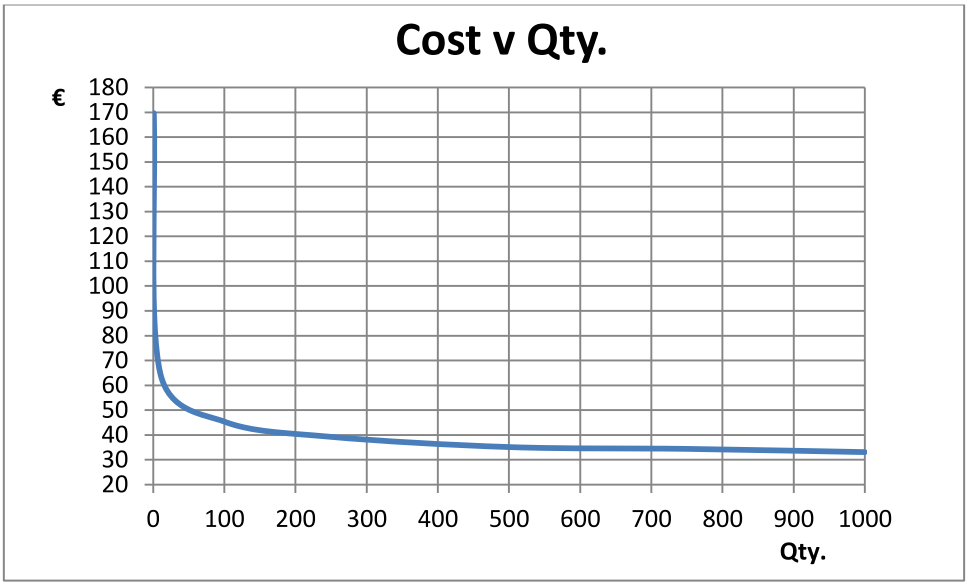


Figure 66: ***Product Cost v Quantity.***

7.1.1 PCB Cost

In this section would see the specific cost of the PCB. This calculating it is made by Eurocircuits Price Calculator tool, taking into account all properties of each material.

The costs obtained are shown in table below and in Figure 67 you can see the values in calculation tool discussed.

	1	10	100	250	500	750	1000
Total cost	92,22 €	216,50 €	610,30 €	1.024,57 €	1.534,30 €	1.948,37 €	2.477,31 €
Unity cost	92,22 €	21,65 €	6,10 €	4,10 €	3,07 €	2,60 €	2,48 €

Table 20: ***PCB cost estimation***

Delivery term (working days)	PCB quantity 100 Net	Gross*	PCB quantity 250 Net	Gross*	PCB quantity 500 Net	Gross*	PCB quantity 750 Net	Gross*	PCB quantity 1000 Net	Gross*
9	€ 6.41	€ 7.76	€ 4.52	€ 5.46	€ 3.57	€ 4.33	€ 3.28	€ 3.97	N/A	N/A
	€ 641.43	€ 776.13	€ 1129.12	€ 1366.24	€ 1787.50	€ 2162.87	€ 2459.11	€ 2975.53	N/A	N/A
10	€ 6.10	€ 7.38	€ 4.10	€ 4.96	€ 3.43	€ 4.15	€ 3.03	€ 3.66	€ 2.89	€ 3.49
	€ 610.30	€ 738.46	€ 1024.57	€ 1239.73	€ 1713.02	€ 2072.75	€ 2269.95	€ 2746.64	€ 2886.19	€ 3492.29
15	€ 6.10	€ 7.38	€ 4.10	€ 4.96	€ 3.07	€ 3.71	€ 2.60	€ 3.14	€ 2.48	€ 3.00
	€ 610.30	€ 738.46	€ 1024.57	€ 1239.73	€ 1534.27	€ 1856.46	€ 1948.37	€ 2357.53	€ 2477.31	€ 2997.55
20	€ 6.10	€ 7.38	€ 4.10	€ 4.96	€ 3.07	€ 3.71	€ 2.60	€ 3.14	€ 2.48	€ 3.00
	€ 610.30	€ 738.46	€ 1024.57	€ 1239.73	€ 1534.27	€ 1856.46	€ 1948.37	€ 2357.53	€ 2477.31	€ 2997.55
25	€ 6.10	€ 7.38	€ 4.10	€ 4.96	€ 3.07	€ 3.71	€ 2.60	€ 3.14	€ 2.48	€ 3.00
	€ 610.30	€ 738.46	€ 1024.57	€ 1239.73	€ 1534.27	€ 1856.46	€ 1948.37	€ 2357.53	€ 2477.31	€ 2997.55

Figure 67: ***Eurocircuits Price Calculator. Source [23]***

7.1.2 Material Cost

The first table shows a component list of the board as well as cost in Mouser[15] Company, mentioned above, for different quantities of buy. The cost reduces according the request increase.

The second and third columns show the needs of each component to a single board as well as its cost. The columns show the same preceding calculation considering costs but the 10, 100, 250, etc. It seen the same comment as before; the price is stabilized when the amounts exceed 500 units.

To make this calculation in detail, will be exemplified below:

It is used as an example the third component, a 22 pF capacitor. Of this component, the board requires three pieces. Therefore, observing the Table 21, if acquired from 1 to 49 parts, the cost is equivalent to the unit 0.144€. Therefore, for such a board would condenser 0,144 x 3 pieces that would be needed by the PCB.

However, if are manufactured 100 boards should buy 300 units of this capacitor. If an amount between 100 and 499 purchase price of the piece would be 0.104€ so the unit cost associated to a single PCB of this capacitor would be 0.104 x 3. Therefore, the cost is less, the more units are purchased. This calculation is used for all of the board material.

[15] Source [24]

			1	10	25	50	100	250	500	750	1000	2000	5000
C	100n	0805	0,08	0,22			0,014				0,01		0,007
C	100n	C1210	0,176			0,152	0,128		0,105		0,073		
C	22p	0805	0,144			0,12	0,104		0,064		0,042	0,04	
Cpol	100u	SMC_D	0,392	0,226			0,122				0,079	0,071	
Cpol	100u		0,392	0,226			0,122				0,079	0,071	
Cpol	10u		0,392	0,226			0,122				0,079	0,071	
D		SMB	0,16							0,16			
D		SOD123	0,176	0,15			0,053				0,036		
Pinhead	8	8	8,13	7,78	6,71		6,54	5,83	5,47		4,84	4,59	
F	500mA	L1812						1,250	1,220		1,000		
F	5	L1812	3,260	2,610		2,380	1,910	1,860	1,590		1,490		
F	12	L1812	3,260	2,610		2,390	1,920	1,860	1,600		1,500		
Atmega			14,710	13,380	9,360		8,360						
MC33269D-5.0		DPACK		0,720	0,557			0,359				0,287	
MC33269ST-5.0T3		SOT223		0,752	0,585			0,378				0,302	
FT232RL		SSOP28	3,660	3,290		3,130	2,970	2,640	2,310		2,150		
LM358D		SO08	0,456	0,268			0,126				0,094		
LED		0805	0,080	0,037	0,035	0,034	0,033	0,031	0,030		0,029	0,028	
LED		1206	0,080	0,046	0,044	0,042		0,039	0,038		0,035	0,034	
Reloj			0,390	0,330			0,300		0,280		0,250		0,240
MOSFET1			3,430	1,980			1,860	1,750	1,670		1,610		
MOSFET2			0,780	0,590			0,470		0,428		0,327		
R	1k	M1206	0,080	0,029			0,022				0,008		
R	10k	M1206	0,080	0,029			0,022				0,008		
R	10k	0603	0,064		0,053		0,046	0,042	0,038		0,034		0,030
R	4,7k	0603	0,064		0,053		0,046	0,042	0,038		0,034		0,030
R	390	M805	0,064		0,053		0,046	0,042	0,038		0,034		0,030
R	100k	0603	0,064		0,053		0,046	0,042	0,038		0,034		0,030
R	10	0603	0,064		0,053		0,046	0,042	0,038		0,034		0,030
R	100	0603	0,064		0,053		0,046	0,042	0,038		0,034		0,030
Jumper SMD													
RESET													
T1	**NDT2955**	SOT223		0,488	0,327			0,216				0,167	
T2	**FDN340P**	SOT-23		0,344	0,230			0,128				0,096	
Conector power	2		0,632	0,552		0,480	0,448	0,424	0,400				
Conector molex	2		0,632	0,552		0,480	0,448	0,424	0,400				
USB conector		B		1,290	1,220	1,160	1,100	1,010	0,985	0,950		0,916	

Table 21: ***Components cost v quantity***

		1 PCB		10 PCB		100 PCB		250 PCB		500 PCB		750 PCB		1000 PCB	
		piezas	€												
C	100n	11	2,42	110	1,54	1100	11	2750	27,5	5500	38,5	8250	57,75	11000	77
C	100n	1	0,176	10	1,76	100	12,8	250	32	500	52,5	750	78,75	1000	73
C	22p	3	0,432	30	4,32	300	31,2	750	78,75	1500	63	2250	90	3000	120
Cpol	100u	2	0,784	20	4,52	200	24,4	500	32	1000	79	1500	118,5	2000	142
Cpol	100u	5	1,96	50	11,3	500	61	1250	98,75	2500	177,5	3750	266,3	5000	355
Cpol	10u	2	0,784	20	4,52	200	24,4	500	61	1000	79	1500	118,5	2000	142
D		1	0,16	10	1,6	100	16	250	30,5	500	80	750	120	1000	160
D		5	0,88	50	7,5	500	26,5	1250	200	2500	90	3750	135	5000	180
Pinhead	15*	103	4,4	1030	4,4	10300	13,2	25750	26,4	51500	48,4	77250	70,4	103000	92,4
F	500mA	1	3,26	10	26,1	100	191	250	312,5	500	610	750	915	1000	1000
F	5	1	3,26	10	26,1	100	191	250	465	500	795	750	1193	1000	1490
F	12	1	3,26	10	26,1	100	192	250	465	500	800	750	1200	1000	1500
Atmega		1	14,71	10	133,8	100	836	250	2090	500	4180	750	6270	1000	8360
MC33269D-5.0		1	0,72	10	5,57	100	35,9	250	89,75	500	179,5	750	269,3	1000	287
MC33269ST-5.0T3		1	0,752	10	5,85	100	37,8	250	94,5	500	189	750	283,5	1000	302
FT232RL		1	3,66	10	32,9	100	297	250	660	500	1155	750	1733	1000	2150
LM358D		1	0,456	10	2,68	100	12,6	250	31,5	500	63	750	94,5	1000	94
LED		4	0,32	40	1,4	400	12,4	1000	29	2000	56	3000	84	4000	112
LED		7	0,56	70	2,94	700	26,6	1750	61,25	3500	119	5250	178,5	7000	238
Reloj		1	0,39	10	3,3	100	30	250	75	500	140	750	210	1000	250
MOSFET1		1	3,43	10	19,8	100	186	250	437,5	500	835	750	1253	1000	1610
MOSFET2		3	2,34	30	17,7	300	141	750	321	1500	490,5	2250	735,8	3000	981
R	1k	6	0,48	60	1,74	600	13,2	1500	12	3000	24	4500	36	6000	48
R	10k	5	0,4	50	1,45	500	11	1250	10	2500	20	3750	30	5000	40
R	10k	7	0,448	70	3,71	700	26,6	1750	59,5	3500	119	5250	157,5	7000	238
R	4,7k	2	0,128	20	1,28	200	9,2	500	19	1000	34	1500	51	2000	68
R	390	4	0,256	40	2,12	400	16,8	1000	34	2000	68	3000	102	4000	136
R	100k	4	0,256	40	2,12	400	16,8	1000	34	2000	68	3000	102	4000	136
R	10	4	0,256	40	2,12	400	16,8	1000	34	2000	68	3000	102	4000	136
R	100	3	0,192	30	1,59	300	12,6	750	28,5	1500	51	2250	76,5	3000	102
T1 NDT2955		1	0,488	10	3,27	100	21,6	250	54	500	108	750	162	1000	167
T2 FDN340P		1	0,344	10	2,3	100	12,8	250	32	500	64	750	96	1000	96
Conector power	2	2	1,264	20	11,04	200	89,6	500	200	1000	400	1500	636	2000	800
Conector molex	2	4	2,528	40	22,08	400	169,6	1000	400	2000	800	3000	1200	4000	1600
USB conector		1	1,29	10	12,2	100	101	250	246,3	500	475	750	712,5	1000	916
Trasnport cost			20		20		n.a.		n.a.		n.a.		n.a.		n.a.
TOTAL cost			77,44		432,7		2927		6882		12619		18937		24198
1 PCB cost					43,27		29,27		27,53		25,238		25,25		24,2

Table 22: *Components cost and quantity*

7.1.3 Assembly cost

Assembly costs have been divided into two distinct parts; the first part covers the initial costs of production and the second part covers the production costs. The Assembly budget has been obtained via e-mail with *Insercard* Company.

In the initial manufacturing expenses, the total cost is 400 € divided into different costs:

- Cost of silk screen: 250 €
- Cost programming silkscreen 30 €
- Programming automatic inserter 120 €

It might add that these expenses are only generated in the first production of the board. If it gets to make another board (without changing the design) these expenses are not included.

Within production costs there is a price in the indicative mounting (SMD and THT) representing a value 5 or 6 € per unit. For this reason, this initial cost must be into account.

To associate a cost to each PCB, has divided the initial manufacturing cost (400 €) by the number of boards that were to be manufactured and it was added you 6 € per unit. For example:

- If it make 100 every board has to pay 4 € manufacturing cost (400:100) plus 6€, in other words; assembly costs amount to 10€/board (See Table 19).

7 PLANNING

This project includes 12 instructional credits, which corresponds to a commitment of 300 hours. These hours are divided in 5 months, from February to July 2014, as shown below in Figure.

The planning is divided into 3 main phases. These are the previous phase, the design phase and the final phase.

Previous phase

The previous phase of the Project corresponds to the first 5 points that are shown in the planning. This period, approximately one month, consists in making the objectives and defining the technical specifications to be considered for the design of the 3D printer. For this purpose, it is necessary to search some general information about printers, its operation and the applicable regulations.

Furthermore, to examine the chosen theme and to inquire the difficulties, it is convenient to visit specialized centres. For this purpose, two visits will be realized to centres that use this technology: one to the *RepRap print room* and the other one to the *CIM Foundation*.

The design phase

In the second phase, the possible solutions will be studied and the viability will be evaluated. This stage is divided into 20 parts, in which each component of the machine is discussed in detail. At the end, the most suitable solution for each element has been chosen.

In these two months, the mechanics and the electronics part have been developed. These aspects will be elaborated separately by Mrs. De la Peña and Mrs. Cañete, respectively, but both parts are dependant so that one part complements the other.

Final phase

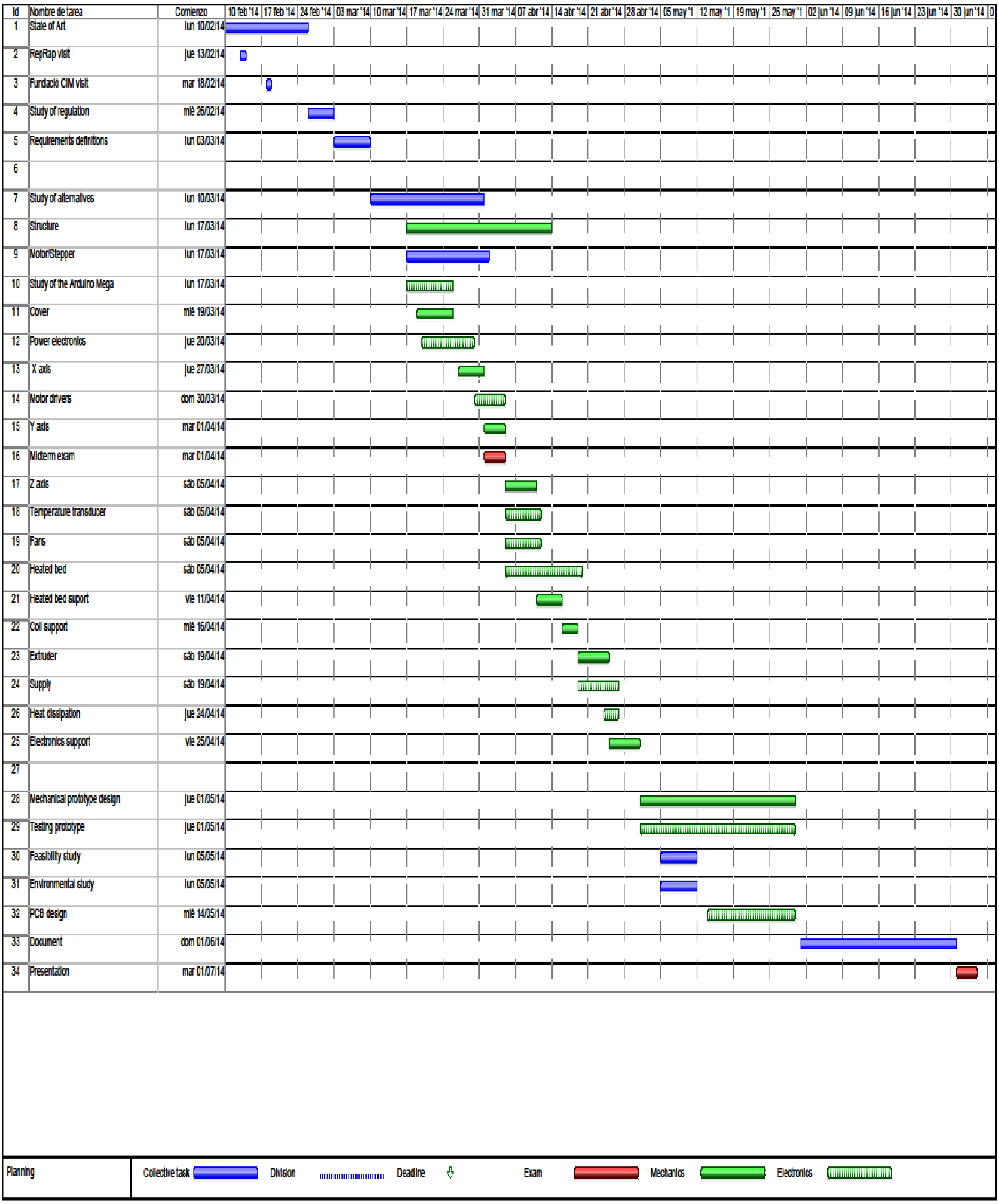
Finally, once the detailed research has been realized, the final phase has been started. On the one hand, a 3D model of the printer has been made. On the other hand, on the electronic part, its operation has been checked empirically and the PCB design has been made.

Also, environmental and viability studies have been made, analysing the costs and the profitability of the Project. Lastly, the corresponding documentation has been made.

Below, on the table, tasks contained in each phase mentioned are shown. Following that, the Schedule is shown in Table 23.

Id	Task	Duration (days)	Start	Finish
0	**PREVIOUS PHASE**			
1	State of Art	12	10/02/2014	25/02/2014
2	*RepRapVisit*	1	13/02/2014	13/02/2014
3	*Fundació CIM* Visit	1	18/02/2014	18/02/2014
4	Study of regulation	2	26/02/2014	02/03/2014
5	Requirements definitions	5	03/03/2014	09/03/2014
6	**DESIGN PHASE**			
7	Study of alternatives	17	10/03/2014	31/03/2014
8	Frame	24	17/03/2014	13/04/2014
9	Motor/Stepper	13	17/03/2014	01/04/2014
10	*Arduino Mega*	7	17/03/2014	25/03/2014
11	Cover	5	19/03/2014	25/03/2014
12	Power electronics	7	20/03/2014	29/03/2014
13	X axis	4	27/03/2014	31/03/2014
14	Motor drivers	6	30/03/2014	04/04/2014
15	Y axis	4	01/04/2014	04/04/2014
16	Midterm Exam	4	01/04/2014	04/04/2014
17	Z axis	5	05/04/2014	10/04/2014
18	Temperature transducer	6	05/04/2014	11/04/2014
19	Fans	6	05/04/2014	11/04/2014
20	Heated bed	14	05/04/2014	19/04/2014
21	Heated bed support	5	11/04/2014	15/04/2014
22	Coil support	3	16/04/2014	18/04/2014
23	Extruder	5	19/04/2014	24/04/2014
24	Supply	6	19/04/2014	26/04/2014
25	Heat dissipation	2	24/04/2014	26/04/2014
26	Electronics Support	5	25/04/2014	30/04/2014
29	**FINAL PHASE**			
30	Mechanical prototype design	24	05/05/2014	30/05/2014
31	Testing	6	05/05/2014	11/05/2014
30	Feasibility Study	6	05/05/2014	11/05/2014
31	Environmental Study	6	05/05/2014	11/05/2014
32	PCB Design	14	14/05/2014	30/05/2014
33	Document	22	01/06/2014	30/06/2014
34	Presentation	4	01/07/2014	11/07/2014

Table 23: ***Schedule***


Id
Nombre de tarea
Comienzo
10 feb '14
17 feb '14
24 feb '14
03 mar '14
10 mar '14
17 mar '14
24 mar '14
31 mar '14
07 abr '14
14 abr '14
21 abr '14
28 abr '14
05 may '1
12 may '1
19 may '1
26 may '1
02 jun '14
09 jun '14
16 jun '14
23 jun '14
30 jun '14
1 State of Art lun 10/02/14
2 RepRap visit jue 13/02/14
3 Fundació CIM visit mar 18/02/14
4 Study of regulation mié 26/02/14
5 Requirements definitions lun 03/03/14
6
7 Study of alternatives lun 10/03/14
8 Structure lun 17/03/14
9 Motor/Stepper lun 17/03/14
10 Study of the Arduino Mega lun 17/03/14
11 Cover mié 19/03/14
12 Power electronics jue 20/03/14
13 X axis jue 27/03/14
14 Motor drivers dom 30/03/14
15 Y axis mar 01/04/14
16 Midterm exam mar 01/04/14
17 Z axis sáb 05/04/14
18 Temperature transducer sáb 05/04/14
19 Fans sáb 05/04/14
20 Heated bed sáb 05/04/14
21 Heated bed suport vie 11/04/14
22 Coil support mié 16/04/14
23 Extruder sáb 19/04/14
24 Supply sáb 19/04/14
26 Heat dissipation jue 24/04/14
25 Electronics support vie 25/04/14
27
28 Mechanical prototype design jue 01/05/14
29 Testing prototype jue 01/05/14
30 Feasibility study lun 05/05/14
31 Environmental study lun 05/05/14
32 PCB design mié 14/05/14
33 Document dom 01/06/14
34 Presentation mar 01/07/14
Planning
Collective task
Division
Deadline
Exam
Mechanics
Electronics

8 ENVIRONMENTAL IMPACT

In order to carry out the development of the board, this project has taken into account the RoHS legislation to ensure the reduction of environmental impact and health and exposure to hazardous substances in factories.

The RoHS 2011/65/EU law entered into force in July 2006 and the objective of the policy is to adapt its range of electronic products to reduce the use of certain hazardous substances such as lead, mercury, cadmium, chromium IV (called also hexavalent chromium), PBB and PBDE.

To comply with the Act, the maximum values of concentration of substances that are currently restricted by weight in homogeneous materials are:

- Cadmium and her compound 0,01%
- Hexavalent chromium and her components 0,10%
- Lead and her components 0,10%
- Mercury and her components 0,10%
- Polybrominated biphelyns (PBBs) 0,10%
- Polibrominated Diphenylethers (PBDEs) 0,10%
    - Included decabromodiphenyl (Deca-BDE) 0,10%

Figure 68: ***Logotipe of RoHS. Source [23]***

In order to comply the requirements of the RoHS, it has been made a search on Mouser distribution, which indicates whether the component has a lower percentage established by this legislation. Therefore, the board designed, permits in large quantities reduce environmental pollution.

9 CONCLUSIONS

Based on the introduction, the main objective of this thesis has been the study and improvement of electronics and the PCB design that works with SMD technology. Through this study it has been observed that these objectives have been fulfilled, although it not could make a real board, it has been checked by means of testing results that it may be a correct design.

Then the achieved points of the thesis have been:

- Studying each printer part.
- Studying each problem of electronic circuits.
- Studying alternatives for each circuit.
- Design a prototype compatible with the existing firmware.
- Improving some aspects:
    - As for motor control, drivers have been improved by installing a new driver and the DRV8825, more robust than the previous (A4988) design because this allowed for a greater microstteping.
    - Overheating MOSFETs problem has been fixed by means of the designed circuit.
- Designing a new PCB.
- Accurate cost estimation of the PCB (and competitively cost).

Even with all these improvements applied to the design, this project covered is broad and complex to work in different branches of engineering, therefore, one can say that there are things that have not worked and have been left.

For future study and improvement of this same design it should consider the following aspects:

- Study in depth the more designs and elaborate tests with thermocouples.
- Try more drivers to find out what is the most optimal.
- Improve the silkscreen.
- Doing more tests and discusses them with an oscilloscope.
- Improve supply printer.
- Realise and study of heated bed.

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