Universidad de Córdoba

Escuela Politécnica Superior

DEGREE IN COMPUTER ENGINEERING
COMPUTER SPECIALIZATION

FINAL DEGREE PROJECT

Hardware modification of a 3D printer to make prints by means of using two extruders in parallel

Technical manual

Author:
Antonio Jurado Caballero

Directors:
Prof. *Dr.* Peter Glösekötter
Prof. *Dr.* José Manuel Palomares Muñoz

Münster, August 2016

Certificate

Prof. Dr.-Ing. Peter Glösekötter, full professor of the Department of Electronics and Computer Engineering at the University of Applied Sciences of Münster and Prof. Dr.-Ing. José Manuel Muñoz Palomares, associate professor in the Department of Computer Architecture, Electronics and Electronic Technology at the University of Cordoba.

INFORM

That they have guided the Final Degree Project of the Degree in Computer Engineering called "Hardware modification of a 3D printer to make prints by means of using two extruders in parallel", made by D. Antonio Jurado Caballero at the University of Applied Sciences of Münster, collecting, in their opinion, all the conditions established in this kind of projects.

Therefore, according to the above exposed, this report is signed in Münster at 18 of August 2016.

Licenses

Documentation License

The technical manual and the user's manual of this final degree project is licensed under the GNU Free Documentation License version 1.3 or superior. A copy of the license can be found at the Free Software Fundation web site: http://www.gnu.org/copyleft/fdl.html.

Code License

The code of this final degree project is licensed under the GNU Free Documentation License version 1.3 or superior. A copy of the license can be found at the Free Software Fundation web site: http://www.gnu.org/licenses/gpl-3.0.html.

"Nuestra recompensa se encuentra en el esfuerzo y no en el resultado. Un esfuerzo total es una victoria completa".
Mahatma Gandhi

"El esfuerzo y la constancia son las claves del éxito."
Anonimo

Acknowledgements

Hace 6 años comenzó una nueva etapa en mi vida, una etapa llena de esfuerzo, sacrificio, trabajo y constancia pero también de buenos e inolvidables momentos. Durante estos años siempre he tenido algunas personas a mi lado, personas que confiaron en mí, personas que no dudaron en ningún momento de mis cualidades y me apoyaron a lo largo de este recorrido. Por ello aprovecho esta ocasión para agradecérselo :

A mis padres y hermanos por darme la oportunidad de estudiar y formarme, por haber estado siempre ahí. Sin su apoyo y ánimos no lo hubiera logrado. Este logro pertenece a los cinco.

A mis abuelos, por mostrarme el verdadero significado de las palabras esfuerzo y sacrificio. Por animarme constantemente a seguir y luchar por lo que quiero, para así ser alguien el día de mañana.

A María Jesús, por hacerme ver que todo es posible en esos momentos en que perdía toda esperanza. Tú me animabas a seguir, a coger confianza en mí mismo y me hacías ver que se podía y que era capaz. Solo tú sabes verdaderamente lo que esto me ha costado, por eso y porque siempre estas cuando te he necesito, te estaré eternamente agradecido.

A mis compañeros de universidad y a mis grandes amigos de ”Birras Everywhere”, porque siempre que he necesitado ayuda no han dudado en prestármela. Porque de la carrera, estas amistades es lo que más valoro. Por muchas quedadas juntos, espero que sigamos en contacto estemos donde estemos.

A mis amigos de toda la vida, que siempre se han preocupado por mí. Aunque con los años la relación se haya distanciado un poco, espero que recuperemos todo este tiempo.

A mis compañeros del laboratorio de Münster, ahora grandes amigos, por todo el apoyo y ayuda prestada.

A mis directores de proyecto, Peter Glösekötter y José Manuel Palomares por la ayuda recibida y su involucración, además darme esta gran oportunidad.

A todas esas personas que me han acompañado a lo largo de este viaje.

MUCHAS GRACIAS

Contents

List of Figures

List of Tables

Part I

Introduction

Chapter 1

Introduction

A 3D printer is a device capable of making replicas of 3D designs, creating pieces or volumetric models from a computer design, called CAD file.

The beginning of 3D printing dates back to 1976, when the inkjet printer was invented. In 1984, Chuck Hull, carried out some adaptations and developments on the concept of inkjet printing technology, changing the way of printing, including new materials instead of the ink.[1] The name of this method was *stereolithography.* In 1988 the company founded by Chuck Hull, 3D Systems, markets the first stereolithography machines. This method was used for creating models in a layer by layer fashion using photopolymerization, a process by which light causes chains of molecules to link together, forming polymers.[2] Years later, between 1988 and 1990, new printing methods were developed: fused deposition modelling (FDM) and selective laser sintering (SLS). During these years, the impression was a process quite expensive and very slow. Until 2003 it was not improved, when a group of MIT students conceived 3D jet printing. In 2005 the Open Source 3D printing appears. Dr. Adrian Bowyer founded RepRap at the University of Bath, an open source initiative for building a 3D printer which could print most of its own components. This means a turning point in the history of 3D printing, evolving until being the most spread method. In 2009, the kits of DIY (*do it yourself*) 3D printers enter the market by MakerBot Industries, an open source hardware company for 3D printers1.1. This company starts the sale of assembly kits which allow buyers to build their own 3D printers and products. In 2014, the market of 3D printer expands, going from industrial and education fields to domestic use, arriving to many houses.[3]

There are many advantages of using 3D printers in areas such as technology, medicine or architecture. Although many pluses are found when making a design, there are some negative points as the average time that a 3D printer takes to print a figure, which usually may be quite high. Clogging problems in the filament head result in reprinting, increasing even more the average time. Besides the energy consumption might be an issue, especially in the industrial field, as well as the high contaminant levels, dependency on plastic materials, etc.

Nowadays, researchers are working on reducing the costs when building a 3D printer [4] in order to reach a wider audience, not just staying in the industrial or educational fields. Open Source projects as the initiated by the RepRap community [5] are achieving this. Also engineers are working in the space limitations when building a piece, reducing printing time and energy consumption to make them more portable [6], new types of materials [7], etc.

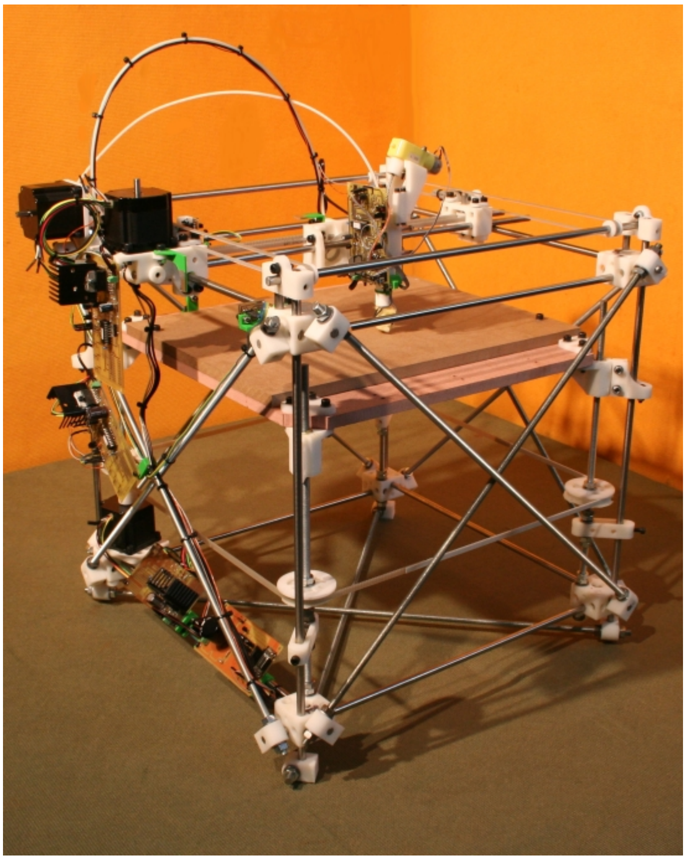

Figure 1.1: Project Darwin, the first RepRap prototype (Source: RepRap[5])

As already mentioned, one of the main problems is the elapsed time in printing. This project arises from the need to reduce this variable which in turn would result in a reduction of energy consumption and costs. The changes performed like the software to be implemented will be developed and distributed as Free Software.

Chapter 2

Objectives

The main objective of this Final Project is the modification and adaptation of the single-headed **X400 CE** 3D-printer, adding a second extruder which should be independent. On completion of the project, the 3D printer will use both heads in order to build up the same figure, allowing parallel printing.

This project will be achieved through the completion of the following objectives:

- Study of the structure and control of a 3D printer.
- Replacement of the current microcontroller by a more powerful and efficient one.
- Modification and adaptation of microcontroller's old software to the new microcontroller for single-headed printing.
- Change and design of new parts for the new structure of a 3D printer with two extruders.
- Incorporation of new hardware components to the old structure.
- Development of an adapter shield for connecting the new board with drivers, end-stops and sensors, etc.

Chapter 3

Project Background

A 3D printer is a device capable of generating a three-dimensional solid object by adding material [9]. These parts or models are obtained from a design by software or a 3D scanner and is only the digital representation of what is printed, as a result of a modelling software tool. This idea arises from the need to convert 2D designs into real prototypes or 3D figures.

3.1 Current projects

Companies such as *Autodesk* are working on a software project to make 3D design for parallel printers, which has been named *Project Escher - Parallel 3D Printing* [8]. This software distributes the printing between the different heads. This way, all heads are working in parallel and a part of the design will be assigned to each extruder, so they are able to work separately and together in order to build up the whole piece.

In the following image may be seen the subdivision performed by the software where different tasks are assigned to each head:

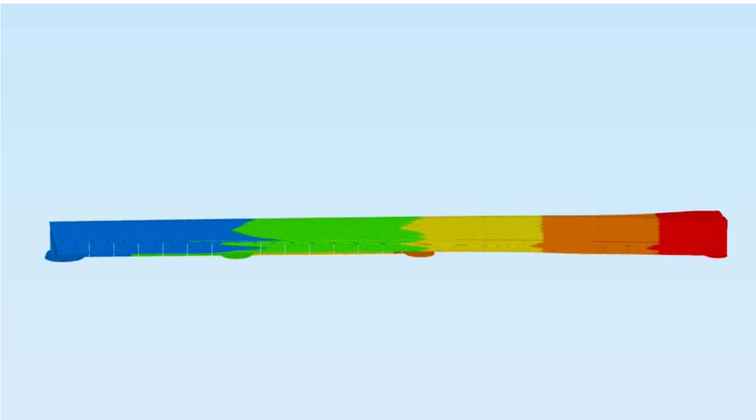

Figure 3.1: Subdivision of the printing (Source: Project Escher[8])

Here may be seen how all extruders work together on the same piece following the subdivision performed via software:

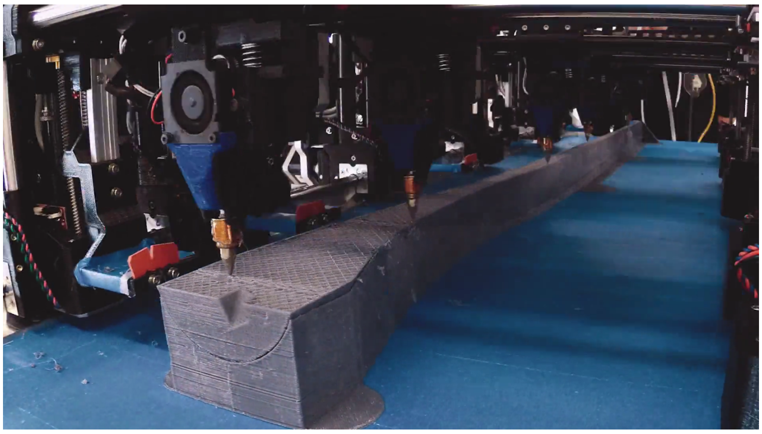

Figure 3.2: Parallel 3D Printing (Source: Project Escher[8])

This software is focused on printing large-sized pieces. If these parts are too small, both heads could collide.

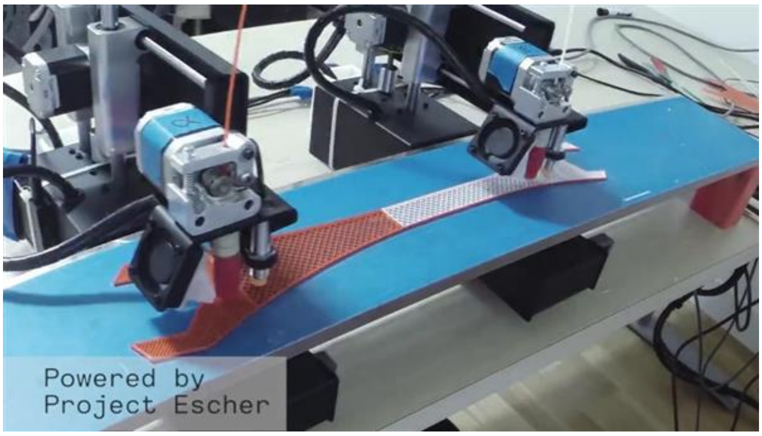

Figure 3.3: Two heads printing (Source: Project Escher[8])

3.2 3D printers features

In the field of 3D printing different models can be found, such as: stereolithography, compaction or addition. On one hand, in the group of compaction there are two main types: ink 3D printers and laser 3D printers. On the other hand, the addition printers are the most used. The present project is based on this technology. Then, the most important features to consider in an addition 3D printer are explained.

3.2.1 Types of materials

The addition 3D printers employ plastic materials to build pieces. This plastic is stored rolled around reels and is called filament. In the market can be found various types of filament, each one with different features and qualities. The most common are the ABS and PLA but there are many more, which are explained below [9] [10]:

- **ABS**: The ABS is one of the most widespread materials. It is a compound of acrylonitrile butadiene styrene. The extruder requires a temperature of about 240°Celsius and the hot bed, on which it is printed, requires a temperature of about 110°Celsius. This allows the printed piece to be retouched (sanding, painting, gluing, and so on.) and the final result will remain good. It is often used for industrial applications due to its extreme durability and has some flexibility. However, it must be kept in mind that this filament is not biodegradable and is affected by exposure to UV rays. It is soluble in acetone and its density is 1.05 g/cm3.

- **PLA**: The plastic PLA is also widely used. It is a compound of polylactic acid and is usually obtained from starch corn. The temperatures required are approximately 210º by the head and 60º for the hot bed. The main disadvantage is that it begins to decompose around 50°- 60°Celsius and post-processing (machining, painting and, especially, gluing) is much more complicated. It is used primarily in the domestic market. In this case, this material is biodegradable, and its density is among 1,2 y 1,4 g/cm3.

- **HIPS**: Material very similar to ABS, the HIPS is a high impact polystyrene. Often it is used in combination with the ABS to build parts with hollow spaces, employing the HIPS as a support which is then removed with D-Limonene. As the ABS, UV rays have a large impact on it and its density is 1.04 g/cm3. The required temperatures are the same as with the ABS.

- **PET**: The PET, polyethylene terephthalate, is one of most used materials for bottles and other containers. Its main advantage is its ability to crystallization so it can generate transparent parts. It is very strong and impact-resistant. Its crystalline density is 1.45 g/cm3. The required temperatures of the extruder and hot bed are the same as the PLA.

- **Laywoo-d3**: The required temperatures are the as with that the PLA but with the peculiarity that if we increase or decrease a few degrees, the colour obtained is darker or lighter. After cooling has wood-like texture.

- **Ninjaflex**: It is a revolutionary thermoplastic elastomer (TPE) for creating pieces with surprising flexibility. The temperature is very similar to the PLA, the extruder needs 215°Celsius and the hot bed needs 40°Celsius.

- **Nylon**: the nylon is perhaps one of the most complex materials in 3D printing. Its main problem is the lack of adhesion of the piece to the hot bed, which causes many failures and often easily catch moisture as well. In return, Nylon is a very durable material, slightly viscous, very resistant to temperature and there are different varieties that give it flexibility, transparency and other qualities.

Apart from plastic materials, printers capable of printing with metallic materials such as aluminium, steel or titanium may be found as well. Even with more innovative materials such as: ceramics, sand, crystal, wood or chocolate.

3.2.2 Number of extruders

An extruder is the fundamental part of any 3D printer. It is the part in which the plastic (filament) is introduced. The extruder heatd up the filament until it is melted and distributes it in layers. These layers are made slowly and once they have completed the 3D volume, the printed piece is finished.

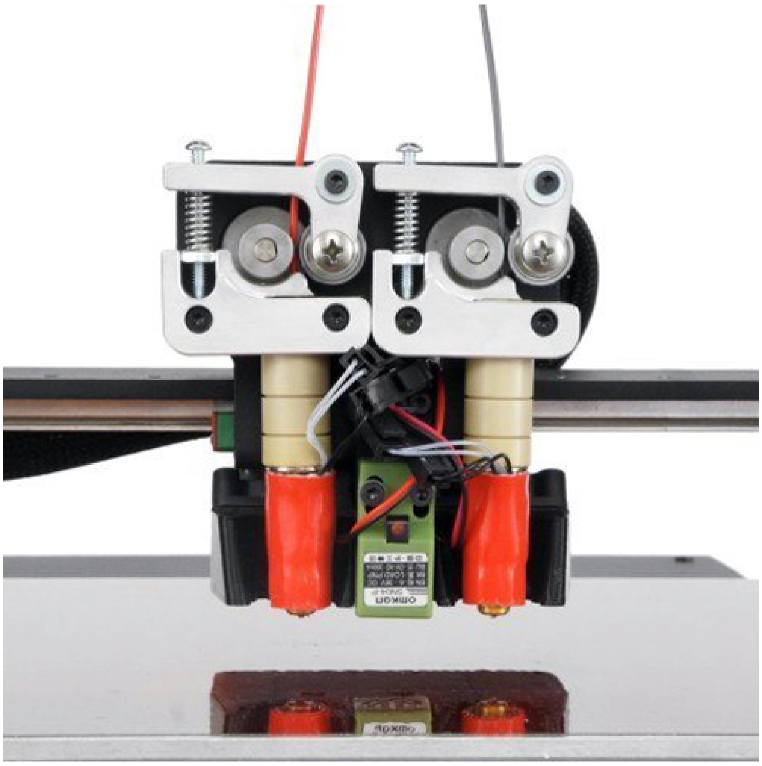

Figure 3.4: Two extruders with different filaments (Source: imprimalia3d[32])

Currently, the more extruders a printer has, the higher number of colours and materials can be used in one single piece. Usually each extruder has one colour and a 3D printer employs just one extruder. This project covers this limitation.

3.2.3 Open Source

Open Source is the expression which gives a name to those software freely that can be distributed and developed. It focuses more on practical benefits (access to source code) than on ethical issues. In the case of 3D printers, it is possible to access not only to the software but also the hardware in order to print our own pieces. That is known as Reprap project, where many parts can be downloaded to build your own printer.

This is something that should be considered, whether to buy open source or not. This approach has it advantages and disadvantages, as it is cheaper, easier to repair since it is personally built. However, it requires some knowledge on robotics and programming. This project will be open source focused, contributing to this initiative.

3.2.4 Printing tolerance

The concepts of print resolution and tolerance often appear mixed, overlapped and even exchanged. The printing tolerance depends on solidification process or finishing. Often the printing tolerance is more unfavourable than the resolution values. That is to say, one piece may be printed with a resolution of 0.1 but if it has low tolerance, it will not stay like its design being that the solidification is not adequate enough and the material will sink.

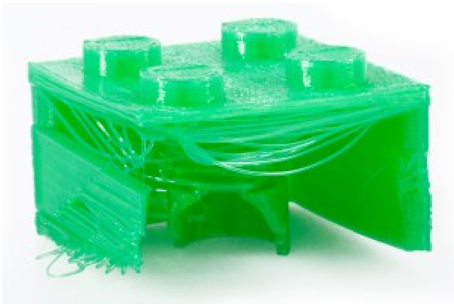

Figure 3.5: Low tolerance example (Source: makered[33])

3.3 Descriptive indices

- **Resolution**

  The resolution or precision in a low-cost 3D printer are unclear descriptives characteristics because these features can refer to different technical elements: layer thickness, inner diameter of the extrusion head or resolution of a stepper motor. Generally a printer which is able to deposit layers as thin as 0.05 to 0.2 mm could be considered as one with a good resolution [11].

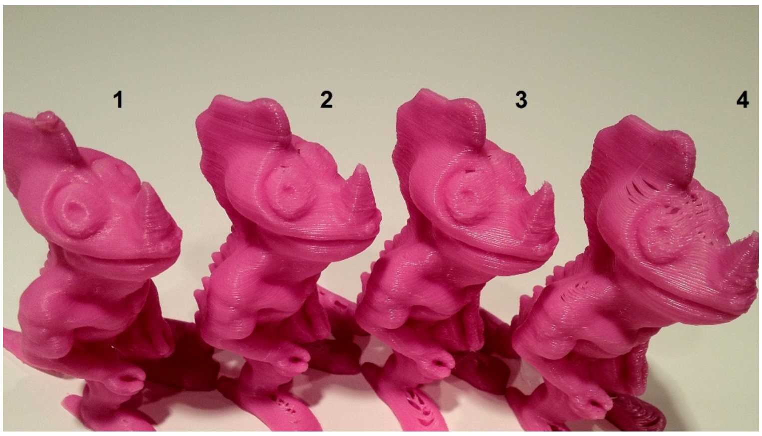

Figure 3.6: Example with 0.1mm, 0.2mm, 0.3mm, y 0.4mm (Source: makered[11])

- **Velocity**

  It is common to define the velocity of a 3D printer as the speed of movement of the heads in the XY plane measured in mm/s.

  One of the main parameters that directly affects the final result of the printing is velocity. Thus, a high printing velocity will worsen the finished part while a lower velocity would improve its final appearance. Therefore, the quality of the printing can be considered as directly proportional to the time invested on it.

But also the velocity affects the extrusion temperature because with a high velocity, the extruder will need more extrusion temperature[12].

- **Repeatability**

  To achieve identical pieces one after the other, the 3D printer requires a proper calibration. In the market, two different models of calibration may be seen: manual and automatic. While some machines offer self-calibration automatic function, the large majority has four manually calibrated screws that help to level the hot bed and to adjust the printing.

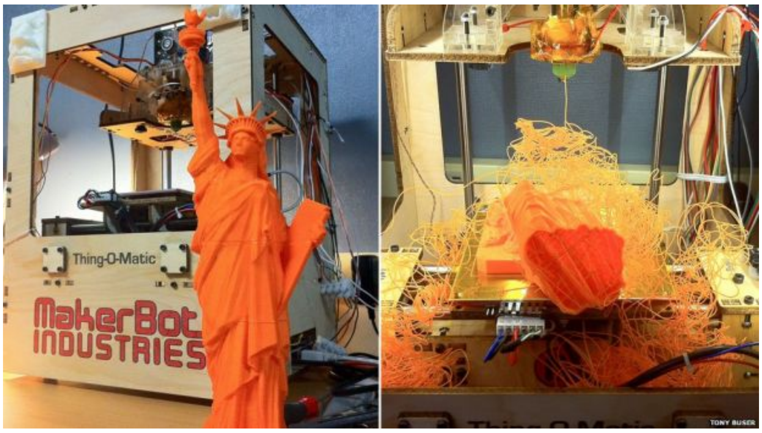

Figure 3.7: Example calibrate and non-calibrate (Source: elcomercio[34])

- **Noise**

  The 3D desktop printers are usually used at home or in the office, so it is important to consider the noise level when printing. Noise is sound that is not wanted by the perceiver, because it is unpleasant, loud, or interferes with hearing.[13] In the environment, it is defined as everything annoying to the ear. Given the hours it may take to print a piece, noise is a feature that should be taken into account. However, some printers are so quiet and clean as those printed on paper.

- **Consumption**

  Consumption of a 3D printer is a variable to be considered. It seems not being relevant for domestic purposes because its consumption is not very high but, in business, this is a factor to be aware of. As an example, Prusa I3 is taken as it is the most widespread domestic 3D printer [14]:

  - First test: printing for two hours at a speed a little faster than normal, hot bed working at 70°C and the extruder at 227°C. The consumption with these values is 0,02 €of power consumption at a rate of 0.13 cents per kwh.
  - Second test: printing for one hour at the same speed, hot bed working at 60°C and the extruder to 227°C. The consumption with these values is 0,0006 €of power consumption at a rate of 0.13 cents per kwh.

As can be seen, these consumption values are reduced at home environment. However, in the Industrial field they will be higher and of more importance.

- **Printing surface**

  Printing surface or heat bed is the maximum volume that can be printed, in other words, it is the size of the largest piece it is possible to obtain. This concept is very important for the present project, according to the use that is intended in a 3D printer.

- **Material (type and width)**

  As it shown previously, a great variety of materials can be found in the market, but not all printers accept every kind of material, the most common are ABS and PLA. Depending on the intended result at the end, it is necessary to choose the most appropiate material for it to be achieved. Some printers accept several but others are able to work just with one type.

3.4 Available materials

3.4.1 RepRap X400 CE

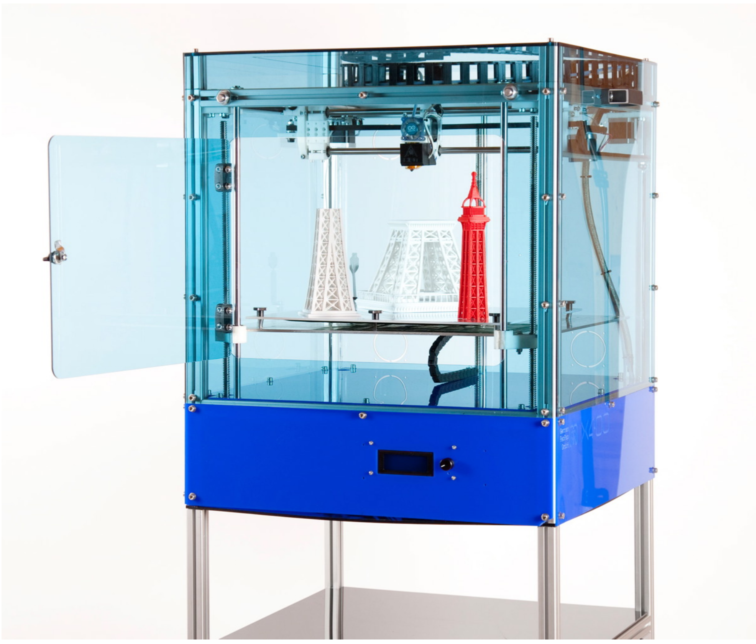

Figure 3.8: X400 3D-Printer (Source: germanreprap[15])

The X400 printer is a large-capacity rapid prototyper. Its main advantage is the considerably large printing volume of about 47,5 liter. On top of that, it is possible to extend and modify it. [15]

- Structure
  - Floor space (L/W/H) about 650 x 650 x 700 mm, without base cabinet.
  - Weight about 35kg, without base cabinet
  - Operating voltage 110/240V AC, 600 Watt (incl. hot bed)

- Power Transmission
  - Speed max. 15mm3 / second, depending on the printing and the material
- Extruder
  - DD-Extruder 1.75mm / 3mm Material.
  - Nozzle: optionally 0.3 0.4 0.5 0.75 1.0
  - Materials: ABS, PLA, PS, PP, PE, HDPE, LDPE, Wood, inter alia 1.75mm/3mm
- Stepper motors
  - Motors model: German RepRap FL42STH47-1304AC-01
  - Voltage: 0 - 12v
- Heat Bed
  - Max. operating temperature 280°C
  - Heating controller model: 230V switched, German RepRap Hot Bed Controller V1.0 (Crydom CX380D5)
  - Thermistor: 100k thermistor
- System requirements
  - MAC OS X
    - OS X 10.5 or higher
  - Windows
    - Windows XP or higher
    - .NET framework 4.0 or higher
    - OpenGL 1.5 or higher
  - LINUX
    - OpenGL 1.5 or higher
    - ideally Ubuntu/Debian
- Arduino and RAMPS
  - Arduino MEGA:

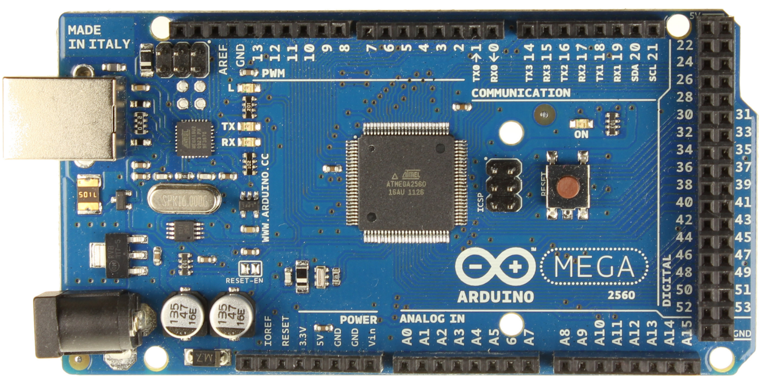

Figure 3.9: Arduino MEGA 2560 (Source: Arduino[17])

The Mega 2560 is a microcontroller board based on the ATmega2560 [17]. Its features are:

  * 54 digital input/output pins (of which 15 can be used as PWM outputs).
  * 16 analog inputs.
  * 4 UARTs (hardware serial ports).
  * 16 MHz crystal oscillator.
  * USB connection.
  * Power jack.
  * ICSP header.
  * Reset button.
  * Microcontroller ATmega2560.

- RAMPS v1.4.2.

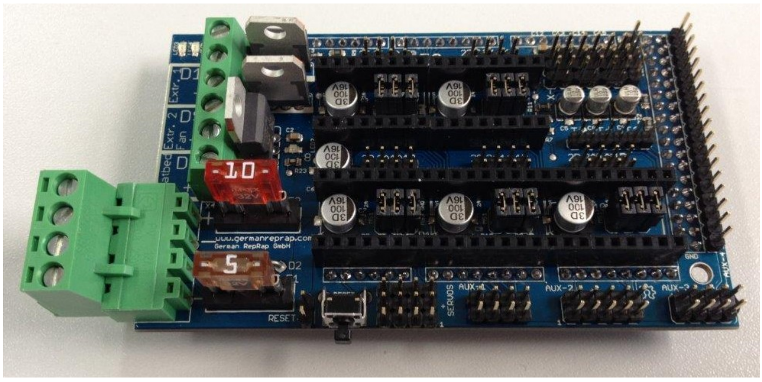

Figure 3.10: RAMPS v1.4.2 (Source: Arduino[35])

RepRap Arduino Mega Pololu Shield, or RAMPS for short. It is designed to fit the entire electronics needed for a RepRap, in one small package and at low cost. RAMPS interfaces an Arduino Mega with the powerful Arduino MEGA platform and has plenty room for expansion. The modular design includes plug in stepper drivers and extruder control electronics on an Arduino MEGA shield for easy service, part replacement, upgrade-ability and expansion. Additionally, a number of Arduino expansion boards can be added to the system as long as the main RAMPS board is kept on top of the stack.[5]

Version 1.4 uses surface mount capacitors and resistors to further cover edge-issue cases. As of version 1.3 in order to fit more functionalities, RAMPS is no longer designed for easy circuit home etching. Their features are:

  * It has provisions for the Cartesian robot and extruder.
  * Expandable to control other accessories.
  * 3 mosfets for heater / fan outputs and 3 thermistor circuits.
  * Fused at 5A for additional safety and component protection.
  * Hot bed control with additional 11A fuse.
  * Fits 5 Pololu stepper driver boards.
  * I2C and SPI pins left available for future expansion.
  * All the Mosfets are hooked into PWM pins for versatility.
  * Servo style connectors are used to connect endstops, motors and leds. These connectors are gold plated, rated for 3A, very compact, and globally available.

    * USB type B receptacle
    * SD Card add-on available – Available now by Kliment - Sdramps
    * LEDs indicating when heater outputs are on
    * Option to connect 2 motors to Z for Prusa Mendel

- Software
  - Marlin

Figure 3.11: Marlin logo (Source: Marlin[27])

Marlin[27] is the firmware for RepRap single-processor electronics, supporting RAMPS, RAMBo, Ultimaker, BQ, and several other Arduino-based 3D printers. It supports printing over USB or from SD cards with folders, and uses lookahead trajectory planning. Marlin is licensed under the GNU GPL v3 or later. It is based on Sprinter firmware, licensed under GPL v2 or later. The most active developers of Marlin are currently (January 2016) thinkyhead, AnHardt, ErikZalm, daid, boelle, Wackerbarth, bkubicek, and Wurstnase, with many others contributing on patches.[5] Their features are:

    * Interrupt based movement with real linear acceleration.
    * High step rate.
    * Look ahead (Keep the speed high when possible. High cornering speed).
    * Interrupt based temperature protection.
    * Preliminary support for Matthew Roberts' advance algorithm.
    * Full endstop support.
    * SD Card support, including folders and long filenames.
    * LCD support, both character-based and graphical (ideally 20x4 or 128x64).
    * LCD menu system for standalone SD card printing, controlled by a click-encoder.
    * EEPROM storage of several settings.
    * many small but handy things originating from bkubicek's fork.
    * Arc support.
    * Temperature oversampling.
    * Dynamic Temperature setpointing aka "AutoTemp."
    * Endstop trigger reporting to the host software.
    * Heater power reporting. Useful for PID monitoring.
    * CoreXY and CoreXZ kinematics.
    * Delta kinematics.
    * SCARA kinematics.
    * Automatic bed leveling and compensation.
    * Firmware binary size between around 50 kB and 100 kB, depending on options.
    * Filament Width Sensor support.
    * Filament Runout Sensor support.
    * Multiple Extruders (up to 4) supported.

The Marlin Project is hosted on GitHub (*https://github.com/MarlinFirmware/Marlin*).

Chapter 4

Restrictions

In this chapter, the design limitations of the proposed system are described. These limitations include:

- Data factors: those limitations that are inherent in our design, that is to say factors that are imposed by the definition of the problem.
- Strategic factors: those limitations chosen from different options available for the proper development of this project.

4.1 Data factors

As previously mentioned, the data factors are those data inherent in the nature of the problem and can not be modified, such as time constraints given by the delivery of the project, budgetary constraints, technology of existing hardware, etc.[18] Data factors are specified below:

- When modifying the structure of the 3D printer, the new parts must be printed using a 3D printer to facilitate their distribution among the RepRap community. The parts will be printed when it is possible, excluding critical parts like shafts and screws that cannot be printed in a safe manner.
- The parts must be appropiate on both heads, even though the two heads do not make the impression together. The parts must have the measures specified without distortion, leaving a margin to the adverse factors.
- The adapter shield must have the most optimal design possible. This should fit perfectly into the Arduino DUE.
- The shield which controls the drivers, must be adapted to the voltages of the new micro-controller and new elements which have are incorporated to control the new extruder.
- The 3D printer should obtain a high quality piece at the end of the process, without leaving aside the time to be printed.

- The correct connection of all elements on the shield, and from it to the Arduino DUE must be checked.

4.2 Strategic factors

The strategic factors are design variables which will be chosen between two or more possibilities, depending on the final solution adopted for the choice made.[18] The strategic factors are detailed below:

4.2.1 Electronic

In designing a 3D printer, one of the most important aspects is the main control unit which is to say, the part of the hardware responsible of all the system operates properly, both mechanics and software. This control unit is usually a microcontroller.

In this case, the x400CE has an Arduino MEGA along with a specific shield for controlling all drivers: the RAMPS v1.4.2.

4.2.1.1 Microcontroller

The Arduino MEGA, is an 8-bit microcontroller. In the requirements of the project, it has been indicated as an objective the "Substitution of the current microcontroller by a more powerful and efficient one". Thus, the microcontroller Arduino MEGA of 8-bit will be replaced for the Arduino DUE of 32-bit. With this change, the whole system will have more computing power and lower consumption. A comparison table of both microcontrollers is shown below, in order to identify the main points to be considered when choosing a shield.

Model	Processor	Voltage Opering/Input	CPU Speed	Analog In/Out	Digital IO/PWM	EEPROM	SRAM	Flash	UART
DUE	ATSAM3X8E (32-Bits)	3,3v/7-12v	84 MHz	12/2	54/12	-	96	512	4
MEGA 2560	ATmega 2560 (8-Bits)	5v/7-12v	16 MHz	16/0	54/15	4	8	256	4

Table 4.1: Comparative Arduino DUE vs Arduino MEGA

After this comparison, the following question [5] may be asked: *Why Arduino Due should be selected instead of Arduino Mega?*

- DUE has lower power consumption, computes faster, and has much more storage than the ATmega2560.
- Its CPU operates at 3.3V.
- High-current IO pins are capable of 15 mA source, 9 mA sink.

- Low-current IO pins capable of 3 mA source, 6 mA sink.
- CPU package has an absolute max of 130mA.
- The DUE has 1 dedicated SPI port, and 4 multipurpose USART/SPI ports. The SPI port is only routed to the 6 pin header used for ICSP on Mega, but this is not used for ICSP on Due.
- The DUE does not have any EEPROM.

4.2.1.2 Drivers control Shield

After completion of this modification, a new shield must be provided to Arduino DUE for controlling the drivers, end-stops, hot bed, etc. To do this, there are some available options:

- **Modify RAMPS v1.4**

  To modify the RAMPS, it is necessary to make bridge power pins and change the logic levels from 5V to 3.3V. This option is quite unstable and not recommended.[19]

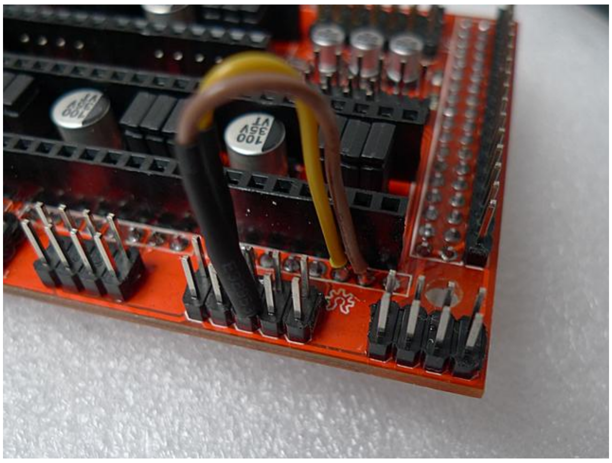

Figure 4.1: Hacked RAMPS 1.4 (Source: Forums Reprap[19])

- **RAMPS-FD**

  The project, RAMPS-FD [5], was born because the Atmel SAM3X8E chip used on the DUE operates at 3.3V and is not compatible with 5V. Therefore the RAMPS shield will not work with DUE, and applying 5V to the DUE's inputs will likely damage the chip. The characteristics are similar to RAMPS but RAMPS-FD includes some variations.

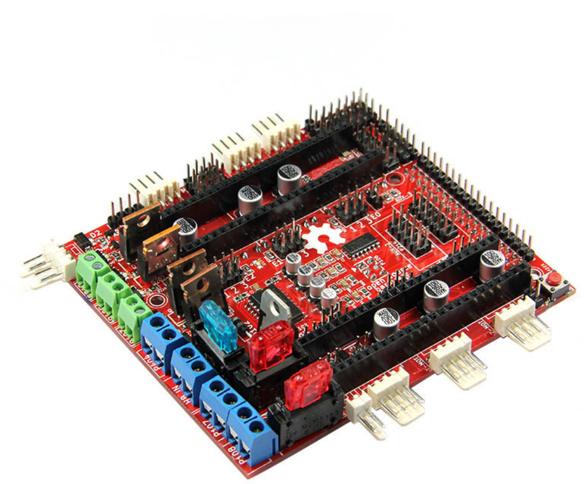

Figure 4.2: RAMPS-FD (Source: Reprap.org[5])

The advantages of RAMPS-FD versus RAMPS are:

- The RAMPS-FD has a different hardware protection, through the jumper cap control motor drive IC.
- The RAMPS-FD includes more 2-way PWM signals than Ramps1.4 2.
- The RAMPS-FD has a larger driving power than Ramps1.4.
- The RAMPS-FD "Power" has two choices: 12v and 24v.

- **RADDS**

  The greatest difference between RADDS[5] and other shields is that it is not open source. Its main characteristics, in terms of connectivity, are:

  - 6 Steppers: e.g. 3 axis and 3 extruders (2 of the driver sockets are fitted with 2pin strips)
  - 6 High-current loads: e.g. 1 hot bed, 3 hotends and 2 fans
  - SD-Card(micro-sd-slot onboard, optional external SD-slot)
  - Standard LCD(5V) with 4x20 characters (HD44780 compatible)
  - Rotating encoder
  - 6 endstops
  - 5 thermistors and an ADC
  - 3 servo motors
  - I2C, SPI, CAN, DAC, RS232 and 8 digital-pins available via pin strips
  - 1 Bluetooth to Serial (RF-transceiver bluetooth-module hc-06 rs232)
  - 1 Thermocoupler(AD8495)
  - EEPROM
  - Control-LEDs for loads and operation voltage
  - Catch-diodes at the FETs

- Car-fuses instead of thermofuses
- Operation with 12/24V possible
- Hot-bed current can be up to 15A without a heat sink
- Premium screw terminals

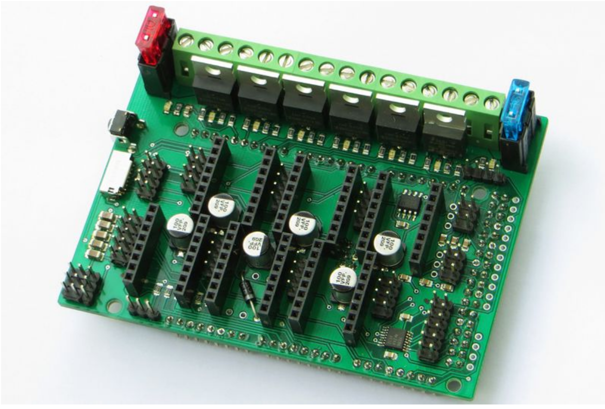

Figure 4.3: RADDS (Source: Reprap.org[5])

- **Designing a shield from scratch**

  In this case, it may be selected between two options. On one hand, the schematic of RAMPS-FD can be modified, because it is open source, in order to add some parts that will be needed in the new 3D printer. On the other hand, as we know all the elements that we will control, we could design a shield from scratch without basing on any schematic. The second option would be the most complete but at the same time it is the most difficult and requires more time than the other one.

Before selecting a shield, it is necessary to know what the printer requires. Those elements are presented and then added with modifications, in order to properly control each of them. To achieve that, there must be enough inputs as well as analog and digital outputs.

- Currently the RAMPS v1.4.1 of X400CE must control:
  - Motor X, Head 1
  - Motor Y1, Head 1
  - Motor Y2, Head 1
  - Motor Z
  - Motor Extruder, Head 1
  - Opto-endstop X, Head 1
  - Opto-endstop Y, Head 1
  - Opto-endstop Z
  - Hotend heating-element, Head 1
  - Hotend thermistor, Head 1
  - Hotend fan, Head 1

- Printbed, heating controller
- Printbed, thermistor
- Housing fan
- Supply 12V
- Supply 12V2
- Supply 5V

- The new shield must control, in addition to the above mentioned, the following:
  - Motor X, Head 2
  - Motor Y1, Head 2
  - Motor Y2, Head 2
  - Motor Extruder, Head 2
  - Opto-endstop X, Head 2
  - Opto-endstop Y, Head 2
  - Opto-endstop Collision Detection
  - Hotend heating-element, Head 2
  - Hotend thermistor, Head 2
  - Hotend fan, Head 2
  - Printbed, heating controller
  - Printbed, thermistor
  - Supply 3.3V

In order to see it more clearly, a comparison of the previous shields with an ideal shield will be shown. In this comparative, the RAMPS is put aside because the other two shields are specific for Arduino DUE. This is because Arduino DUE works at 3.3V and Arduino MEGA works at 5V. To use the RAMPS, it is necessary to make a modification of the shield for allowing it to work at 3.3V.

						End			Motor			
	Heat Bed	num. Cooling	Heater HotEnd	num. Termistor	LCD	Z	Y	X	Z	Y	X	extruder
IDEAL	1	2	2	2 HotEnd 1 HotBed	yes	1	2	2	1	4	2	2
RADDS	1	2	3	3 HotEnd 1 HotBed	yes	1	1	1	2	1	1	3
RAMPS-FD	1	3	3	4	No (need Addons)	1	1	1	1	1	1	3

Table 4.2: Comparative of shields

As shown at the table, any of these shields are perfectly adapted to the project needs, so it was decided that the best choice is to design a specific shield from scratch.

4.2.1.3 Type of Stepper Motor Driver

This is an important factor when making the printing, being that this device is responsible for controlling the step-motor, Nema 17, delivering the rotational power and precision that should have.

In the characteristics of Nema 17 [5] it can be seen that the step-motor has a step angle of 1.8°. This means that its resolution is 200 steps per revolution (360°). But these steps are not controlled by the step-motor, it needs an external circuit. This circuit, called driver, is the Pololu.

For controlling the motor, the driver has a potentiometer located on top of the device. The voltage flowing to the engine will be controlled by turning this potentiometer. This shows a problem, the higher the voltage is delivered, the more power is consumed, so the step-motor can heat up and skip some steps. The middle ground must be found, obtaining the optimal power without skipping steps or suffering overheating.

Due to the importance of this device, different options will be studied.

- **Pololu A4988**

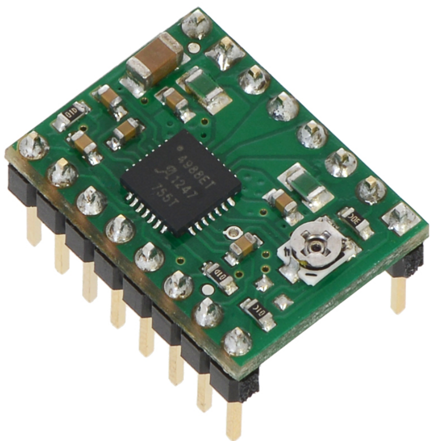

Figure 4.4: Pololu A4988 (Source: Pololu[25])

The driver, *Pololu Allegro A4988*, is mounted by the x400CE and its features are [25]:

- Max. theoretical current: 2A
- Max. microsteps : 1/16
- Adjustable current control by means of a potentiometer.
- Over-temperature thermal shutdown, over-current shutdown, and under-voltage lock-out: yes
- Logic supply voltage: 3 - 5.5 V.
- Step-motor supply voltage: 8 - 35 V.
- Vref formula: I-TripMax = Vref/(8*Rs) [1]
- Small heatsink necessary: yes

– Active cooling required?: Recommended

- **Pololu DVR8825**

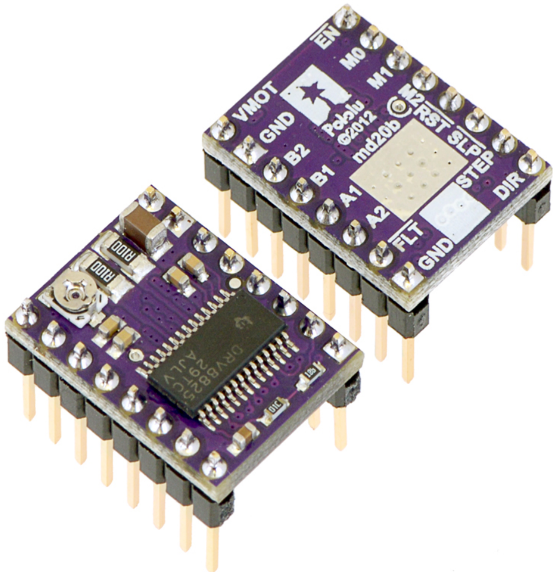

Figure 4.5: Pololu DVR8825 (Source: Pololu[25])

The Pololu DVR8825, by Texas Instruments, whose features are [25]:

– Max. theoretical current: 2.5A

– Max. microsteps : 1/32

– Adjustable current control by means of a potentiometer.

– Over-temperature thermal shutdown, over-current shutdown, and under-voltage lock-out: yes

– Logic supply voltage: 2.5 - 5.25 V.

– Step-motor supply voltage: 8.2 - 45 V.

– Vref formula: I-TripMax= Vref/(5*Rs) [1]

– Small heatsink necessary: Recommended but not necessary

– Active cooling required?: Recommended

Based on the characteristics shown above, there is a point to consider. The over-temperature shutdown system typically acts when it reaches a temperature of around 150 - 160 °). This affects both drivers but the heat dissipation in the DVR8825 is better than the A4988. According to a test by RepRap[5] community, its recommendations are:

Both stepper driver ICs have an exposed metal pad under the chip that contacts the which is the "path of least resistance" for heat dissipation. The secondary path is through the package and, in this aspect, the DRV8825 provides a slightly better power dissipation compared to the A4988.

[1] For adjusting the stepper driver current, see these instructions: here.

Comparing different features, it is decided to choose the **DRV8825** drivers for the parallel 3D printer. The most important reasons [25] are:

- The maximum number of microsteps : 1/32, provides twice the resolution of the A4988.
- Support more step-motor supply voltage, 45 V vs 35 V, which means the DRV8825 can be used more safely at higher voltages and is less susceptible to damage from LC voltage spikes.
- The DRV8825 can deliver more current than the A4988 without any additional cooling: 1.5 A per coil for the DRV8825 vs 1 A per coil for the A4988.
- Better heat dissipation.

4.2.2 Design Software

- **CAD modeling tools**

  Computer-aided drafting (CAD) [13] is the use of computer systems to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improves the quality of designs, improves communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for printing, machining or other manufacturing operations.

  CAD software for mechanical design uses either vector-based graphics to depict the objects of traditional drafting, or may also produce raster graphics showing the overall appearance of designed objects. However, it involves more than just shapes. As in the manual drafting of technical and engineering drawings, the output of CAD must convey information, such as materials, processes, dimensions and tolerances, according to application-specific conventions.

  In order to design the printer parts, a free software tool like *FreeCAD* [20] is chosen.

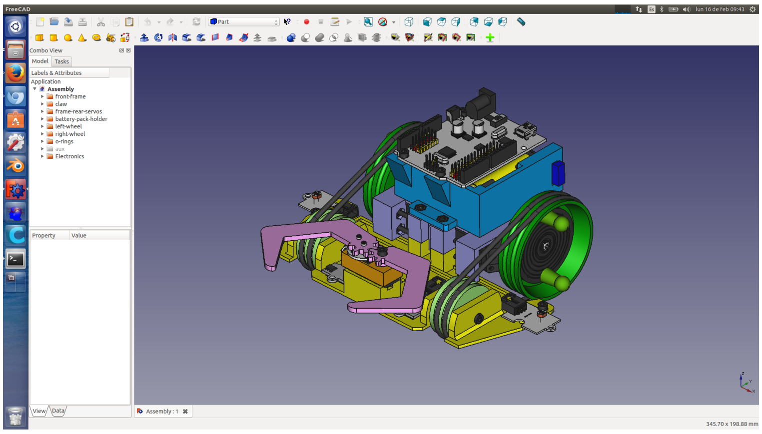

Figure 4.6: FreeCAD example (Source: FreeCAD[20])

  FreeCAD is a parametric 3D modeller primarily made to design real-life objects of any size. Parametric modelling allows to easily modify the design by going back into your model history and changing its parameters. *FreeCAD* is open-source and highly customizable, scriptable and extensible.

This tool has been chosen because of its great potential for 3D designing, to the great existing community for advising us in case of any doubt and because it is an open source tool.

- **CAM tools laminate**

  Computer-aided manufacturing (CAM)[13] is the use of software to control machine tools and related ones in the manufacturing of workpieces. CAM is a subsequent computer-aided process after computer-aided design (CAD) and sometimes computer-aided engineering (CAE), as the model generated in CAD and verified in CAE can be input into CAM software, which then controls the machine tool. CAM is used in many schools alongside Computer Aided Design (CAD) to create objects.

  The *gcode* files for 3D printer contain the print settings. In the *gcode* file is indicated to the 3D printer the type of material to use, if the piece have a support, the fill density, etc. To this work, the free software tool *Slic3r* have been chosen because it is the most complete when a *gcode* file needs to be configured.

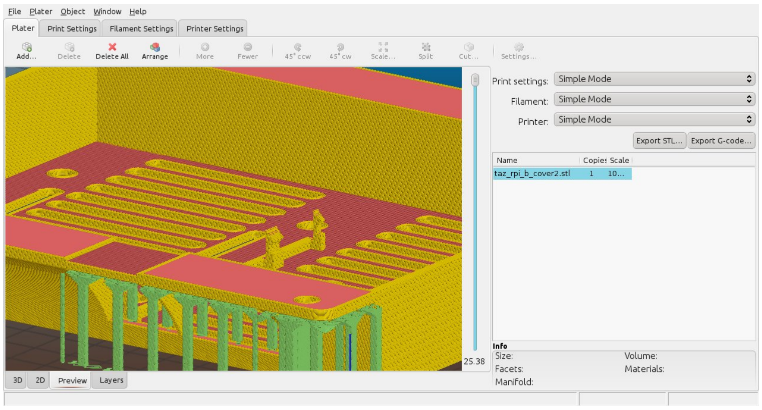

Figure 4.7: Slic3r example (Source: Slic3r[21])

Slic3r[21] is a tool for converting a 3D model into printing instructions for your 3D printer. It cuts the model into horizontal slices (layers), generates toolpaths to fill them and calculates the amount of material to be extruded.

4.2.3 3D Printer Control Software

- **Marlin4Due 3D Printer Firmware**

  As shown above, *Marlin* is the software responsible for managing all elements of the 3D printer. This software will download the *gcode* from a SD card and configure the 3D printer according to the type of material by changing parameters such as the temperature of the hot bed, extruder, etc. Marlin makes these changes based on what it indicated on this file.

  Because of the Arduino employed for this 3D printer is not Arduino MEGA, it is necessary to use a modified software adapted for Arduino DUE. This software is *Marlin4Due* [26].

4.2.4 Type of material for printed parts

Once designed and modified all the parts, they will be printed by means of another 3D printer. One of two types of materials will be chosen, ABS or PLA. Previously both were defined, their composition, melting temperature, etc. Now, one type of material [22] will be chosen in order to print the new parts.

- Precision Both ABS and PLA are capable of creating dimensionally accurate parts, but there are some aspects that differentiate them.
  - **ABS**: For most, the greatest hurdle for accurate parts in ABS will be a curling on the surface in direct contact with the 3D Printer's bed. A combination of heating the print surface and ensuring it is smooth, flat and clean involves a long way in eliminating this issue.

    For fine features on parts involving sharp corners, such as gears, there will be often a slight rounding of the corner. One solution may be to install a fan able to provide a small amount of active cooling around the nozzle, what can improves corners.
  - **PLA**: Compared to ABS, PLA demonstrates much less warping on parts. For this reason, it is possible to successfully print without a hot bed. Ironically, removing the hot bed can still allow the plastic to slightly curl up on large parts, though not always.

    PLA undergoes more of a phase-change when is heated-up and becomes much more liquid. If actively cooled, more sharper details can be obtained on printed corners without risk of cracking or warping. An increased flow can also lead to stronger bindings between layers, improving the strength of the printed part.
- General Material Properties
  - **ABS**: ABS as a polymer, in general, is a strong plastic with slight flexibility (compared to PLA). The flexibility of ABS makes creating interlocking pieces or pin connected pieces easier to be built, sanded and machined. Notably, ABS is soluble in Acetone which allows to weld parts together with one drop or two, making them smoother or creating high gloss by brushing or dipping full pieces into Acetone.

    Its strength, flexibility, machinability and higher temperature resistance make ABS often the preferred plastic by engineers and those with mechanical purposes in mind.
  - **PLA**: Created from processing specific plants, PLA is considered a more 'earth friendly' plastic compared to petroleum-based ABS. It is used primarily in food packaging and containers. Also, the PLA is stronger and stiffer than ABS, which occasionally makes it more difficult to work with in complicated interlocking assemblies and pin-joints. With a little more work, PLA can also be sanded and machined. The lower melting temperature of PLA makes it unsuitable for many applications. Even finished pieces spending the day in a hot car can be distorted.

Once this comparison have been done, ABS is chosen in order to print the new pieces. The reasons are:

- Improved heat resistance. Because of the temperature reached on the extruder and the hot bed, the risk of deforming the parts is lower.

- Greater flexibility and strength. The parts need to be embed, such as bearings and motors, in the printed piece. Because of this material is more flexible and easier to be sanded, it will be simpler to work with.

4.2.5 Other factors

- **Git**

  Git will be employed to perform an accuracy test to the modified code, designing of the parts and even the technical manual. To store the Git project repository online, GitHub is used.

  Git [13] is a version control system for software development and other version control tasks. As a distributed revision control system, it is aimed at speed, data integrity and support for distributed, non-linear workflows.

  GitHub [13] is a web-based Git repository hosting service. It offers all of the distributed revision control and source code management (SCM) functionality of Git as well as adding its own features. Unlike Git, which is strictly a command-line tool, GitHub provides a Web-based graphical interface and desktop as well as mobile integration. It also provides access control and several collaboration features such as bug tracking, feature requests, task management and wikis for every project.

- **IDE Arduino**

  Once the firmware Marlin4Due [26] is finished, the microcontroller Arduino DUE must be programmed. The software Arduino IDE provided by Arduino will be used. This will allow us to program the Arduino board as well as changing the firmware and compile it.

  The Arduino integrated development environment (IDE) [13], is a cross-platform application written in Java. It includes a code editor with features such as syntax highlighting, brace matching and automatic indentation, and provides simple one-click mechanism to compile and load programs to an Arduino board. A program written with the IDE for Arduino is called a "sketch". The Arduino IDE supports the languages C and C++ using special rules to organize code.

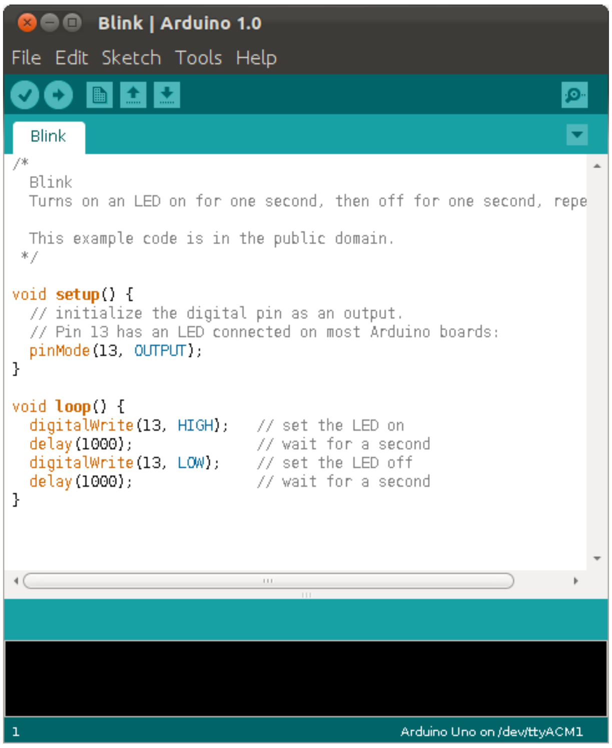

Figure 4.8: Arduino IDE example (Source: Arduino[17])

- **LaTeX**

  The document preparation system LaTeX[16] is employed to carry out the technical documentation. This was chosen due to its high typographical quality and the professional finish obtained. The software editor used for creating and compiling the LaTeX to PDF is *LaTeXila* [23]. It runs on Linux systems with the GTK+ library installed.

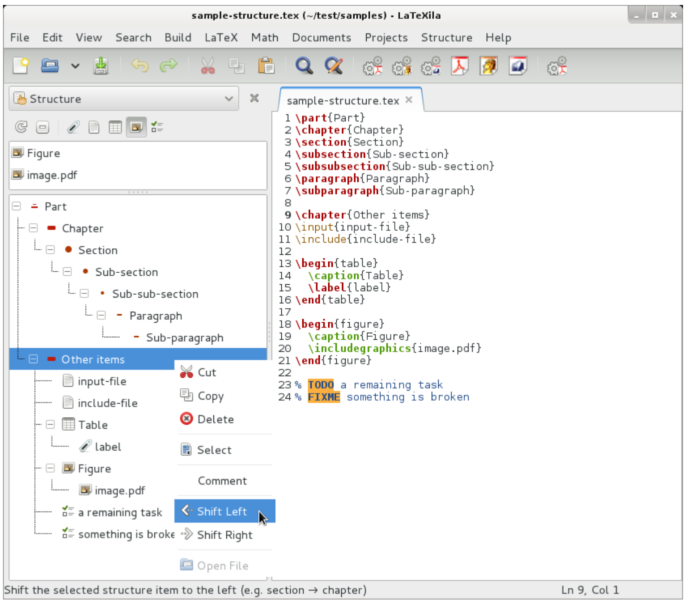

Figure 4.9: LaTeXila example (Source: Gnome[23])

- **Repetier-Host**

  Repetier host [29] is a software tool selected to calibrate the 3D printer once the mounting of the new structure is finished. This software will communicate the PC with the 3D printer by means of a USB connection.

  It is decided to use this software being that it is strongly recommended by the RepRap community[5] because it is free software and the community has obtained very good results with it. Also, apart from print *.gcode* files, *Repetier Host* will allow a perfect control of the temperatures both from the extruder and the hot bed. This will give us the chance to detect the errors during the mounting phase.

  Repetier Host permits to give orders that help the user in the calibration of the printer. Orders as: Moving Y-Axis forward 50 cm, extruding filament 10 cm, heat up extruder to "x" degrees, etc.

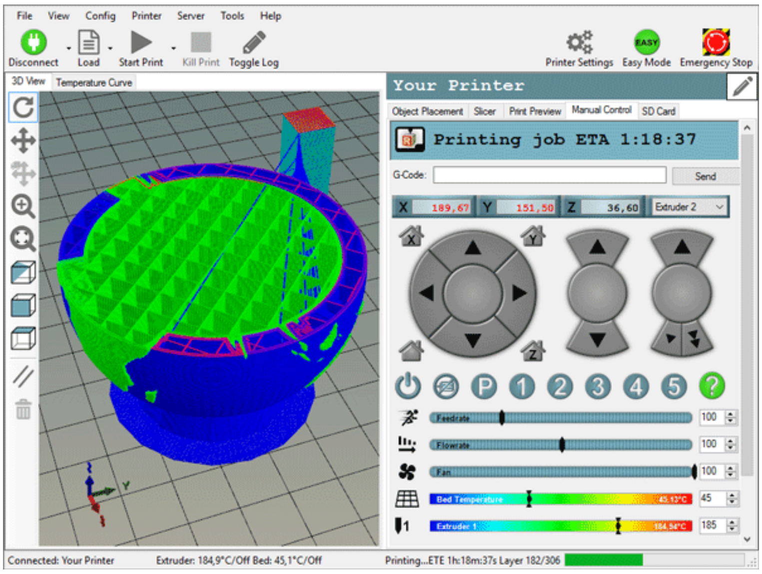

Figure 4.10: Repetier Host example (Source: Repetier[29])

Chapter 5

Resources

Consequently, the resources needed to carry out this project under optimal conditions are described below.

5.1 Human Resources

Directors:

- **Prof. Dr.-Ing. Peter Glösekötter**, full professor of the Department of Electronics and Computer Engineering at the University of Applied Sciences of Münster.
- **Prof. Dr.-Ing. José Manuel Muñoz Palomares**, associate professor in the Department of Computer Architecture, Electronics and Electronic Technology at the University of Cordoba.

As author of the Final Degree Project:

- **Antonio Jurado Caballero**, student of Degree in Computer Engineering at the University of Cordoba.

5.2 Software Resources

In this section are described all software elements employed in this project for the implementation of the 3D printer. This includes all programs, operating system and development environments used in developing. These software are:

- **Ubuntu 14.04 LTS operating system**, the operating system will be the basis on which the programs and development environments will work.

- **Arduino IDE**[17], development environment in charge of programming the firmware for our Arduino DUE.
- **FreeCAD**[20], CAD software for designing the parts of our 3D printer.
- **Slic3r**[21], CAM software which converts the *STL* file to *gcode* in order to print the parts with the 3D printer.
- **Marlin4Due**[26], firmware for controlling our 3D printer. This will be uploaded to the Arduino DUE.
- **LateXila**[23], software employed to write the project documentation.
- **Repetier-Host**[29], software in charge of the calibration of the 3D printer.

5.3 Hardware Resources

In this section, all hardware components that must be employed for this project are defined below. This hardware is divided into two blocks:

- Hardware resources development: Here, we include those hardware resources which are necessary for the design and development phases of the project.
- Production hardware resources: Here, we include those hardware resources which we will included in our 3D printer.

5.3.1 Hardware resources for development

For the development of this project, the following resources are employed:

- **Personal notebook** with i7 processor, 8GB of RAM, 640GB hard drive, 250GB SSD, graphic card ATI HD5730 1GB and operating system Ubuntu 14.04 LTS 64-bit.
- **3D printer** of German RepRap model X400 EC[15].

5.3.2 Production hardware resources

For a proper development of the double-headed 3D printer, several components are required:

- **Arduino DUE**:

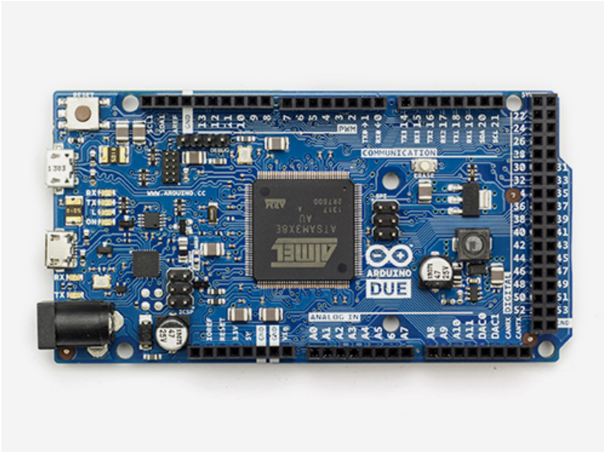

Figure 5.1: Arduino DUE (Source: Arduino[17])

The Arduino DUE[17] is a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. It is the first Arduino board based on a 32-bit ARM core microcontroller. Their features are:

  – 54 digital input/output pins of which 12 can be used as PWM outputs.
  – 12 analog inputs.
  – 4 UARTs.
  – 84 MHz clock.
  – USB OTG capable connection.
  – 2 DAC (digital to analog).
  – 2 TWI.
  – Power jack.
  – SPI header.
  – JTAG header.
  – Reset button and an erase button.
  – Operating Voltage is 3.3V.
  – Flash Memory, 512 KB all available for the user applications.
  – SRAM 96 KB (two banks: 64KB and 32KB)

- **Drivers shield**:

This component will be implemented in future phases of this project. This shield must have the following electronic connections:

  – Power connections: 11A and 5A.
  – Engines connections: 9 connections, 4 connectors in parallel, in pairs.
  – Drivers connections: this component depends on the design of the shield, because they could be integrated on the shield. If the modification of RAMPS's schematic is chosen, 7 sockets for Pololu controller must be included.
  – Sensors connections: 3 inputs connections for thermistors.

  - Hot-end/Hot bed connections: 3 outputs connections for 2 hot-ends and a Heat bed.
  - EndStop connections: 6 inputs connections.

- **Other components**:

  - 9 Stepper motors: 1 axis Z, 2 axis X, 4 axis Y and 2 extruders.
  - 6 EndStops: 1 axis Z, 2 axis X, 2 axis Y and 1 in case of heads collision.
  - 7 Pololus, step-motor drivers.
  - 2 Hot-Ends
  - 1 Hot bed
  - 3 Thermistors: 2 hot-end and 1 hot Bed.
  - 3 Air cooling: 2 extruders and 1 components box.
  - Different parts of the extruder: 2 drive gear, 2 reduction gear, 2 pulley pressure, 2 nozzle, 2 heat sinks and 2 filament guides.

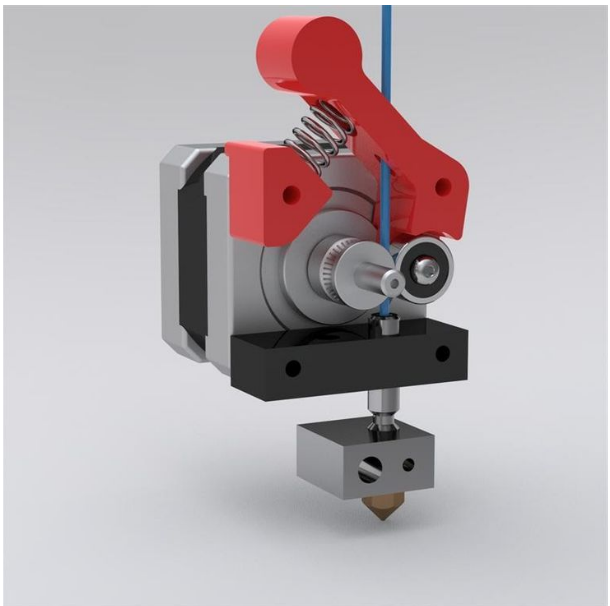

Figure 5.2: Extruder (Source: Pinterest[36])

Part II

Analysis

Chapter 6

System Analysis

As it has been discussed throughout this document, the main objective of this project is the modification and adaptation of a single-headed 3D printer by adding a second extruder, which must be independent.

In this section, the requirements to perform the stated objectives are described, in terms of hardware and software. This procedure is carried out in a clear and concise manner. In this project two main parts can be identified, hardware and software.

6.1 Hardware System Analysis

In chapter *Resources*, it was determined to utilize the following components, which are an Arduino DUE board together with a control shield from scratch.

6.1.1 Arduino DUE

The DUE Arduino has a microprocessor AT91SAM3X8E, ARM Cortex-M3 CPU. The Atmel SMART SAM3X/A[24] series is a member of a family of Flash microcontrollers based on the high performance 32-bit ARM Cortex-M3 RISC processor. It operates at a maximum speed of 84 MHz and features up to 512 Kbytes of flash and up to 100 Kbytes of SRAM.

The peripheral set includes a High Speed USB Host and Device port with embedded transceiver, an Ethernet MAC, 2 CANs, a High Speed MCI for SDIO/SD/MMC, an External Bus Interface with NAND Flash Controller (NFC), 5 UARTs, 2 TWIs, 4 SPIs, as well as a PWM timer, three 3-channel general-purpose 32-bit timers, a low-power RTC, a low-power RTT, 256-bit General Purpose Backup Registers, a 12-bit ADC and a 12-bit DAC. The SAM3X/A devices have three software-selectable low-power modes: Sleep, Wait and Backup.

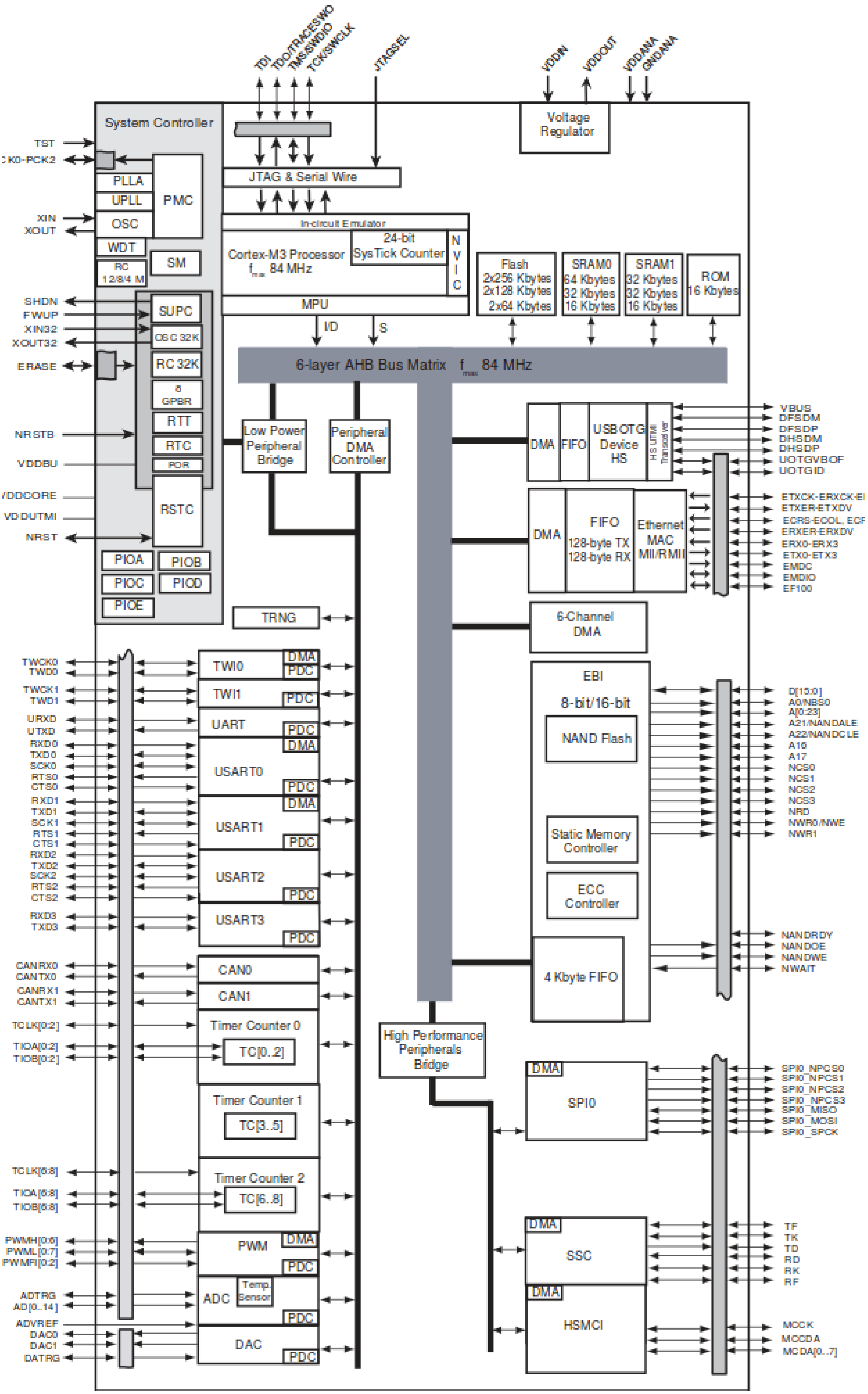

Figure 6.1: SAM3X48E (144 pins) Block Diagram (Source: Arduino[17])

In order to make the connections with the shield, it is important to identify each pin:

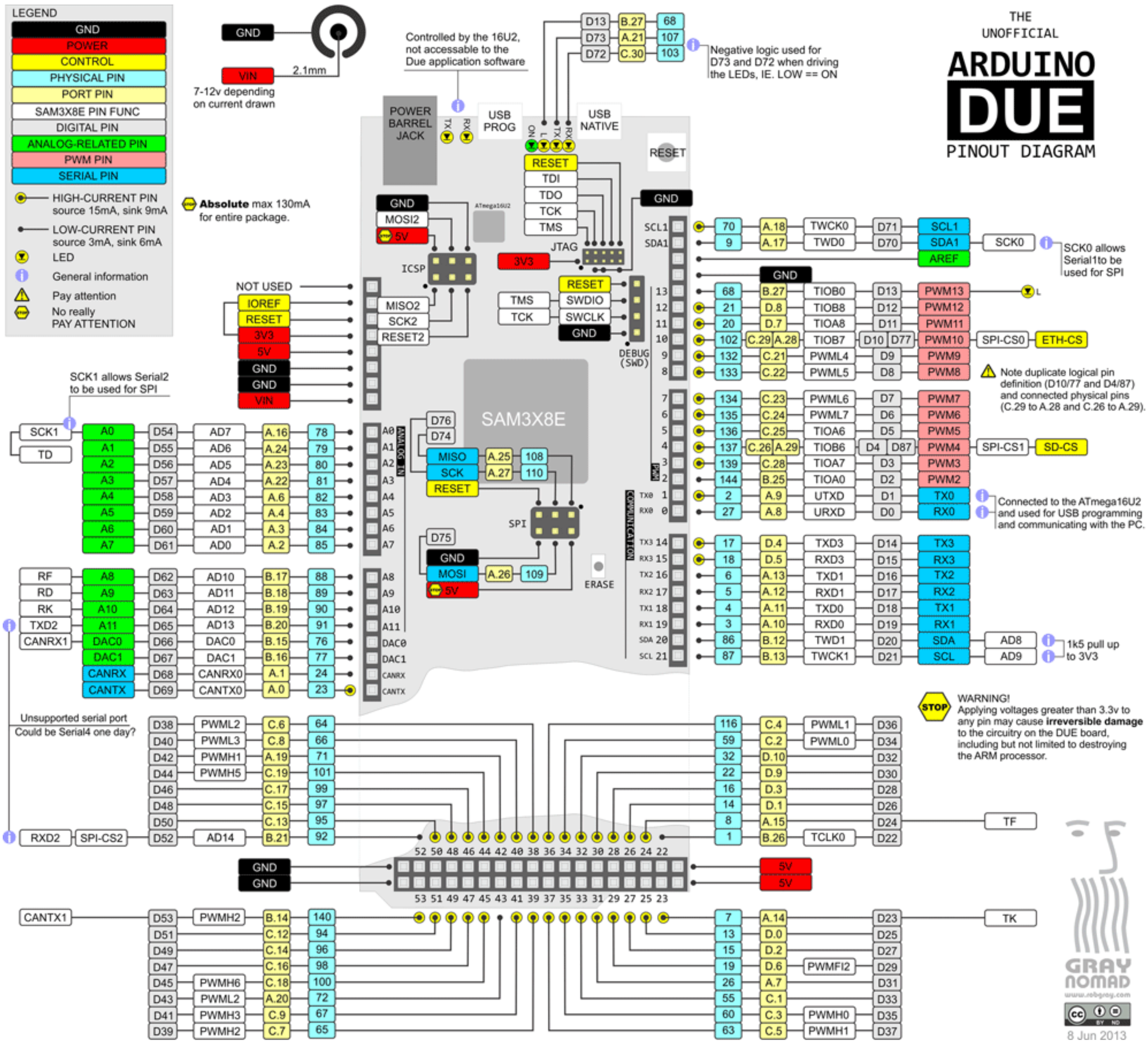

Figure 6.2: Pin out diagram for the DUE (Source: Arduino[17])

6.1.2 Control Shield

This device is not developed yet but here the different connections are indicated which it should incorporate[1].

[1]This list is not definitive, so it is indicated as a reference for the developer.

Component	Mechanical connector (cable side)	Electrical	comment
Motor X, Head 1	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor X, Head 2	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Y1, Head 1	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Y2, Head 1	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Y1, Head 2	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Y1, Head 2	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Z, Head 2	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Extruder, Head 1	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Motor Extruder, Head 2	Pin headers 2.54 mm, 1X04, female	0V 12V	Driver: Pololu DRV8825, Motor: German RepRap FL42STH47-1304AC
Opto-endstop X, Head 1	Pin headers 2.54 mm, 1X03, female	5V supply, signal: 0 5V	German RepRap Opto-endstop V1.2
Opto-endstop X, Head 2	Pin headers 2.54 mm, 1X03, female	5V supply, signal: 0 5V	German RepRap Opto-endstop V1.2
Opto-endstop Y, Head 1	Pin headers 2.54 mm, 1X03, female	5V supply, signal: 0 5V	German RepRap Opto-endstop V1.2
Opto-endstop Y, Head 2	Pin headers 2.54 mm, 1X03, female	5V supply, signal: 0 5V	German RepRap Opto-endstop V1.2
Opto-endstop Z	Pin headers 2.54 mm, 1X03, female	5V supply, signal: 0 5V	German RepRap Opto-endstop V1.2
Opto-endstop Collision Detection	Pin headers 2.54 mm, 1X03, female	5V supply, signal: 0 5V	German RepRap Opto-endstop V1.2
Hotend heating-element, Head 1	2x 2.5 mm^2 conductor with wire end ferrule plus plastic collar	12V	-
Hotend heating-element, Head 2	2x 2.5 mm^2 conductor with wire end ferrule plus plastic collar	12V	-
Hotend thermistor, Head 1	Pin headers 2.54 mm, 1X02, female	100k thermistor, ntc	model no. or characteristics to be found ot
Hotend thermistor, Head 2	Pin headers 2.54 mm, 1X02, female	100k thermistor, ntc	model no. or characteristics to be found ot
Hotend fan, Head 1	Pin headers 2.54 mm, 1X02, female	12V	-
Hotend fan, Head 2	Pin headers 2.54 mm, 1X02, female	12V	-
Printbed, heating controller	2x 0.5 mm^2 conductor with wire end ferrule plus plastic collar	5V signal	230V switched! German RepRap Heated Bed Controller V1.0 (Crydom CX380D5)
Printbed, thermistor	Pin headers 2.54 mm, 1X02, female	100k thermistor ?	model no. or characteristics to be found ot
Housing fan	2x 0.5 mm^2 conductor with wire end ferrule plus plastic collar	12V	-
Supply 12V	2x 2.5 mm^2 conductor with wire end ferrule plus plastic collar	12V	from PSU
Supply 12V2	2x 2.5 mm^2 conductor with wire end ferrule plus plastic collar	12V	from PSU, second 12V rail
Supply 5V	2x 2.5 mm^2 conductor with wire end ferrule plus plastic collar	5V	from PSU
Supply 3.3V	2x 2.5 mm^2 conductor with wire end ferrule plus plastic collar	3.3V	from PSU

Table 6.1: Shield Interface, Peripheral to Driver Board

6.1.3 Pololu DRV8825

The DRV8825 [25] is a stepper motor driver which allows to control one bipolar stepper motor at up to 2.2 A output current per coil. Here are some of the driver's key features:

- Simple step and direction control interface.
- Six different step resolutions: full-step, half-step, 1/4-step, 1/8-step, 1/16-step, and 1/32-step.

- Adjustable current control for the maximum current output by a potentiometer.
- Intelligent chopping control that automatically selects the correct current decay mode (fast decay or slow decay).
- 45 V maximum supply voltage.
- Built-in regulator (no external logic voltage supply needed).
- Can interface directly with 3.3 V and 5 V systems.
- Over-temperature thermal shutdown, over-current shutdown and under-voltage lockout.
- Short-to-ground and shorted-load protection.
- 4-layer, 2 oz copper PCB for improved heat dissipation.
- Exposed solderable ground pad below the driver IC on the bottom of the PCB.
- Can deliver up to 0.75 A per coil without a heat sink (1.2 A max with proper cooling).
- Requires a motor supply voltage of 8.2 – 45 V to be connected across VMOT and GND.
- The step resolution selector inputs (MODE0, MODE1, and MODE2) enable selection from the six step resolutions according to the table below.

MODE0	MODE1	MODE2	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	1/4 step
High	High	Low	1/8 step
Low	Low	High	1/16 step
High	Low	High	1/32 step
Low	High	High	1/32 step
High	High	High	1/32 step

Table 6.2: DRV8825 Interface, Periphery to Driver Board (Source: Pololu[25])

The basic wiring diagram for connecting a microcontroller to a DRV8825 stepper motor driver carrier (full-step mode) is shown below:

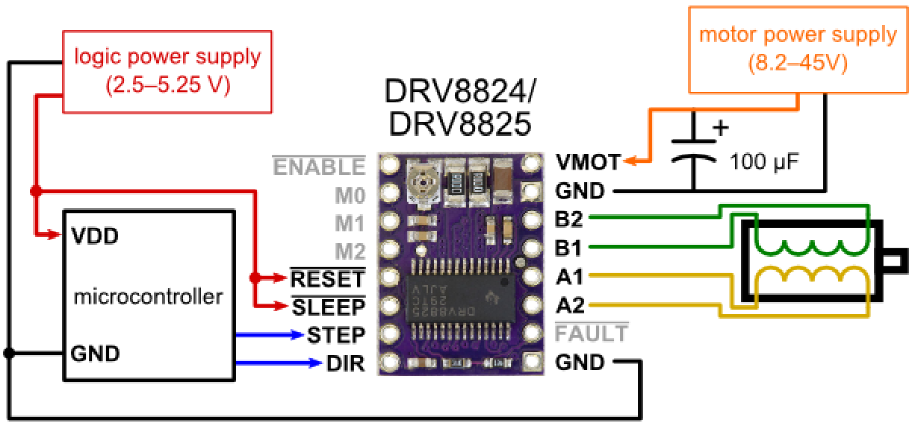

Figure 6.3: Using the driver DRV8825 (Source: Pololu[25])

To design the *Drivers Control Shield*, it is important to identify each pin:

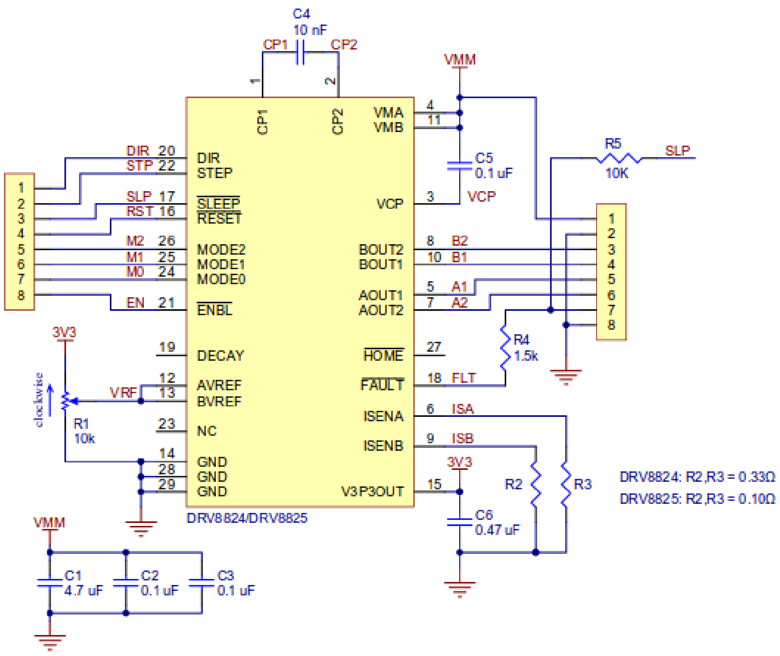

Figure 6.4: Schematic diagram for the DRV8825 (Source: Pololu[25])

6.2 Description of Components

In this section, the functionality of the above mentioned devices is specified.

- **Arduino DUE**:

  The main use of this microprocessor will be controlling all the operation of the 3D printer. This requires maintaining its control over the device, so that it will communicate with the Control Shield. This will configure the printer according to the type of material, temperature control to switch off the 3D printer if overheating ocurrs, auto-calibration the 3D printer before it starts to print and the sending of the coordinates of the new figure to different devices.

- **Control Shield**:

  On one hand, the main purpose of this shield will be to control different devices, motors, hot bed and extruder. These orders are received from the Arduino. On the other hand it provides information to Arduino about temperature thermistors and endstops. With this information the Arduino takes a decision.

- **Pololu DRV8825**

  The Pololu driver keeps the power that drives the motors separate from the power that is on the Arduino. The arduino cannot provide enough energy to power the stepper motors directly. This is why it is necessary to use separate chips to sort of devices like valves that control how the motor spins. On the other hand they provide fractional steps. This helps smooth out the motion of the stepper motor.

6.3 Software System Analysis

In this project, there is a software that directly controls the printer, *Direct Control Software*. On the other hand there is a software that will the calibration, and changing the file's format, *stl* files to another language that the 3D printer software can interpret correctly, *gcode* files.

6.3.1 Direct Control Software

The software that controls the Parallel 3D printer, in the first stages of a process of development [2], will be Marlin4Due [26] designed by *Wurstnase*. This software adapts the architecture of Arduino DUE to different control shields, as it is shown in previous parts of this document, in order to control the 3D printer.

Marlin4Due must check the status of the 3D printer before printing. To that end, it will check the different components once started: end-stops, thermistors, step-motors, etc. Then it will remain until an order by a software or SDcard is delivered, in order to read a *.gcode* file. Once it is received, it prepares the function settings of the printer. When the printer is ready, it starts the printing.

Its flow scheme, in a generic way, is as follows:

[2] About to be done in future stages and discussed in the chapter about future improvements.

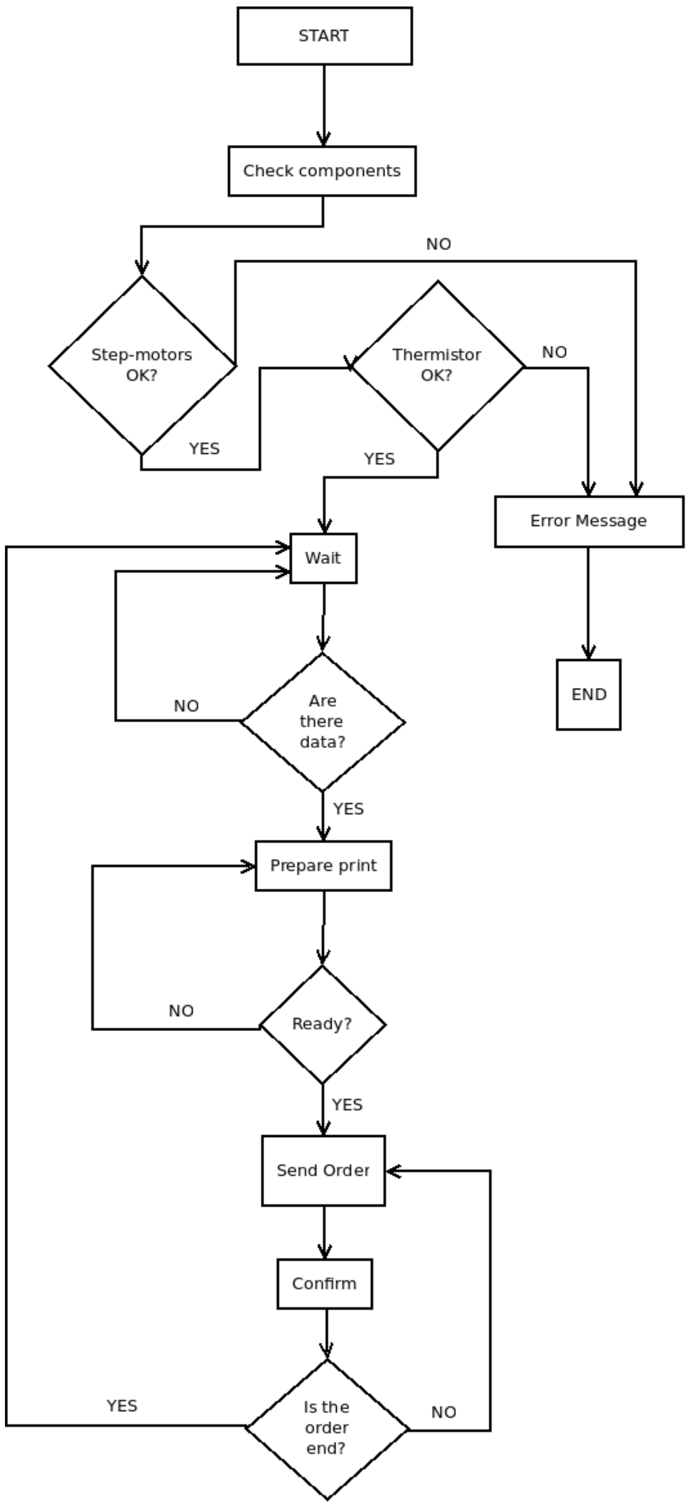

Figure 6.5: Marlin4Due generic flow scheme

In this software should only be configured the file *configuration.h*. The software of drivers to control the step-motors, thermistor, and so on, is already implemented and is of free distribution[5].

6.3.2 Indirect control software

As it has already been discussed, here the software involved indirectly is referred. It is indicated the flow that is followed until the printing starts.

First, the piece is designed using a CAD tool, exporting this file into *.stl* format. At this stage there are two options: to use two separate tools or just a sofware that integrates them. It is needed a CAM tool that generates the *.gcode* file from the *.stl* file. Finally, it is required a software to communicate with the 3D printer. Once the file is sent to the printer, Marlin4Due configures the 3D printer basing on the features of *.gcode* and starts the printing.

The flow scheme is as follows:

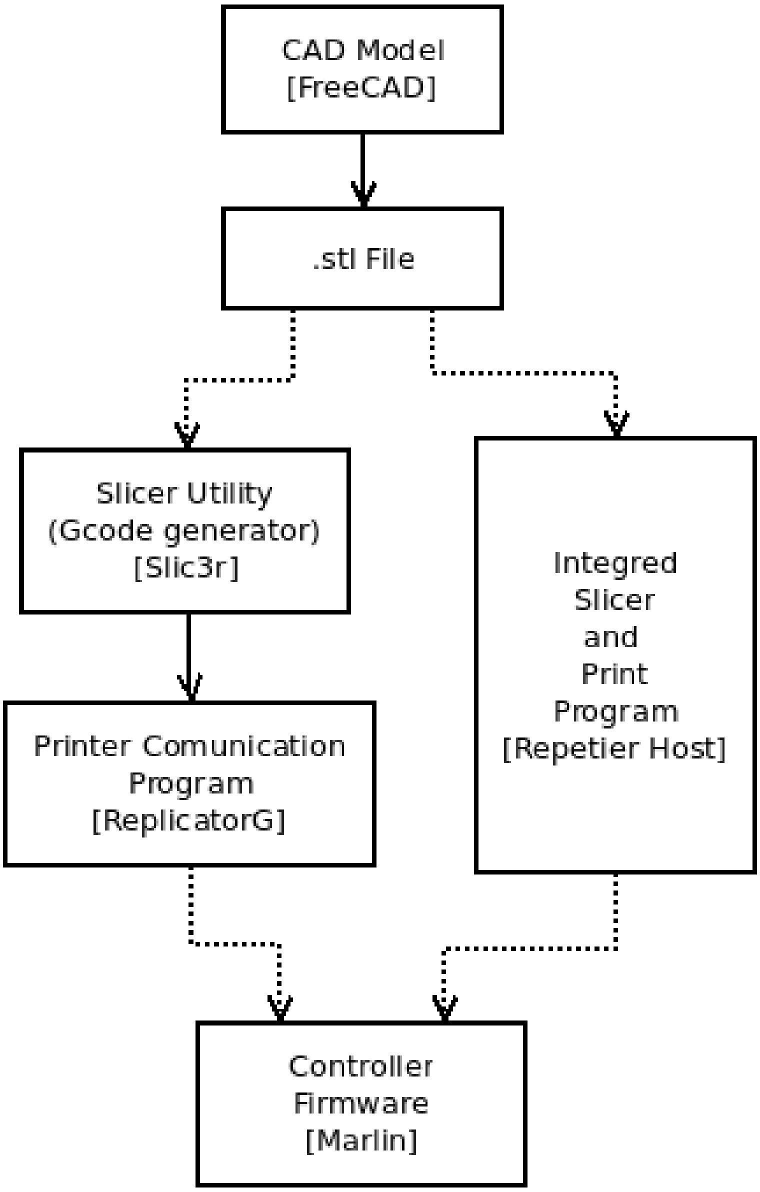

Figure 6.6: Design a part to print flow scheme

Part III

Design

Chapter 7

System Specification and Requirements

This Chapter discusses the stages of design and modification of the *X400 CE* 3D printer in a concise manner, until the final result.

7.1 Design and Creation of Hardware system

In order to design the hardware system there are two main stages: the design of the different printed parts and the design of the electronic system. The design of the parts is also divided into two parts: the first stage in which the original part are replicated and the second, where these parts are modificated in order to obtain the functionality of the double extruder.

7.1.1 Original Structure

To achieve the 3D design of the original parts, some measurements are performed to design a sketch with the accurate representation of the original model. With these measurements and *FreeCAD* software[20], is created the 3D design. The original parts later modified are:

- **Original X-glider**

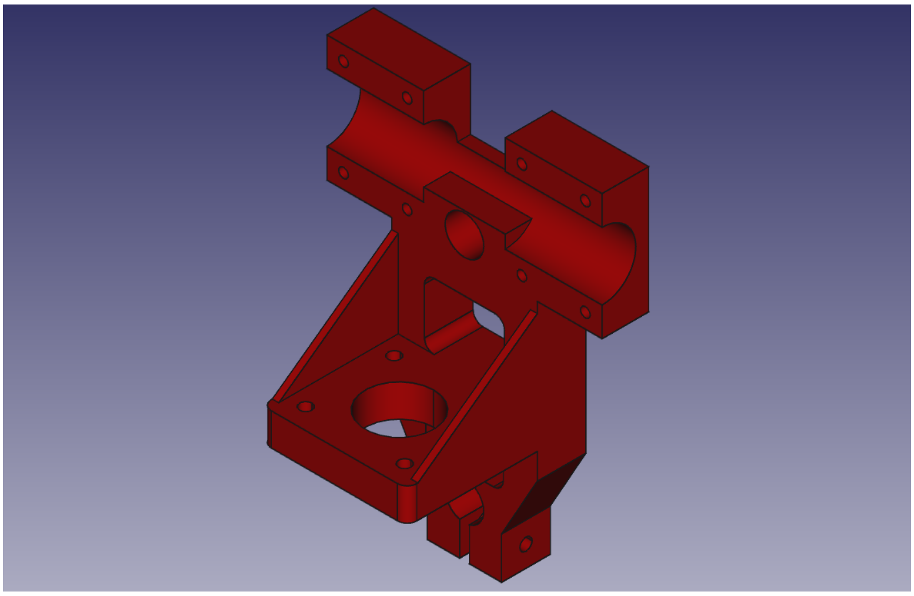

Figure 7.1: Original X-glider

- **Original X-glider clamp LM12UU**

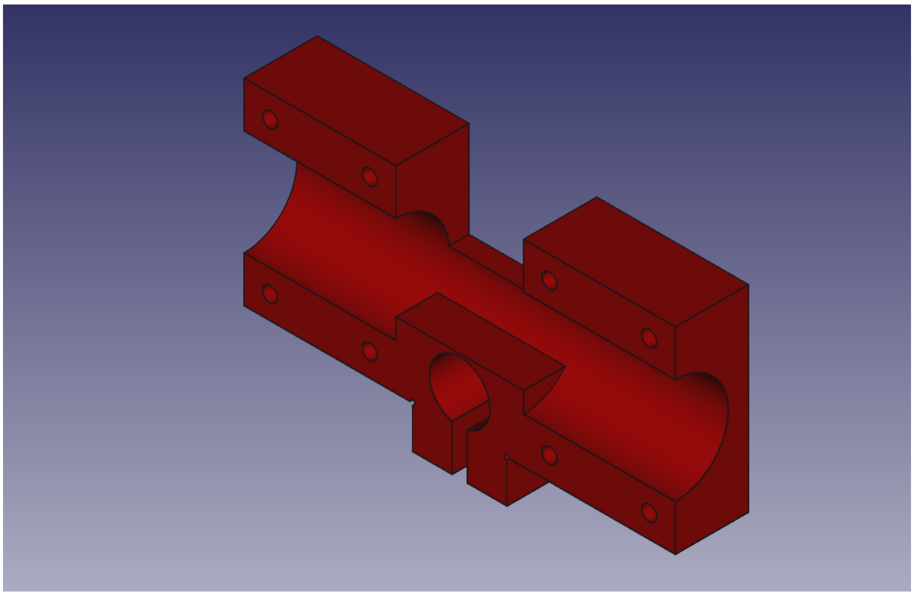

Figure 7.2: Original X-glider clamp LM12UU

- **Original X-glider clamp belt**

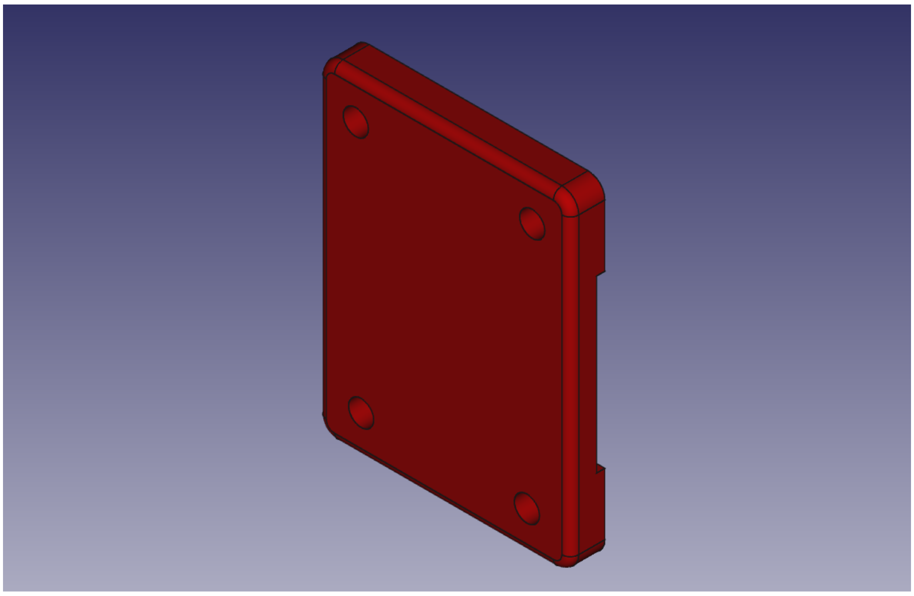

Figure 7.3: Original X-glider clamp belt

- **Original POM NEMA 17 Mount**

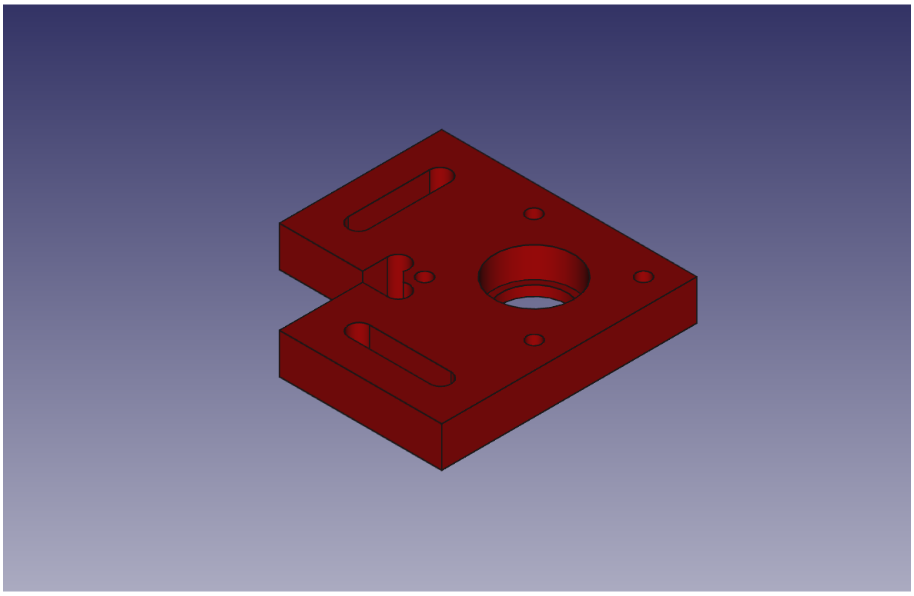

Figure 7.4: Original POM NEMA 17 Mount

The original design of the 3D printer was as follows:

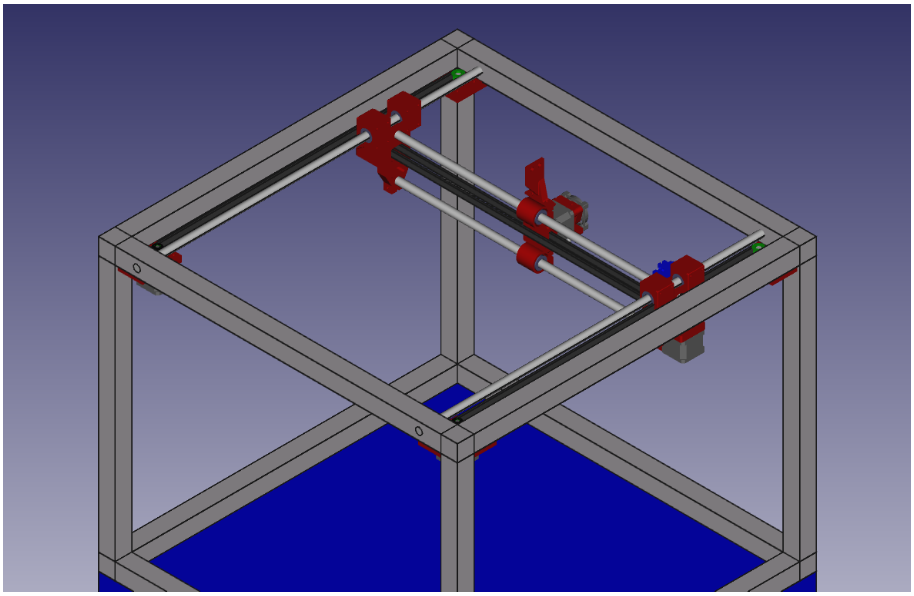

Figure 7.5: Original design of the 3D printer

7.1.2 Modified Structure

Based on the original parts, their designs are modified in order to be assembled to the 3D printer. Once designed, the models were printed in ABS by means of a X400 model CE 3D printer. Finally, these new components were mounted on the 3D printer along with the originals parts.

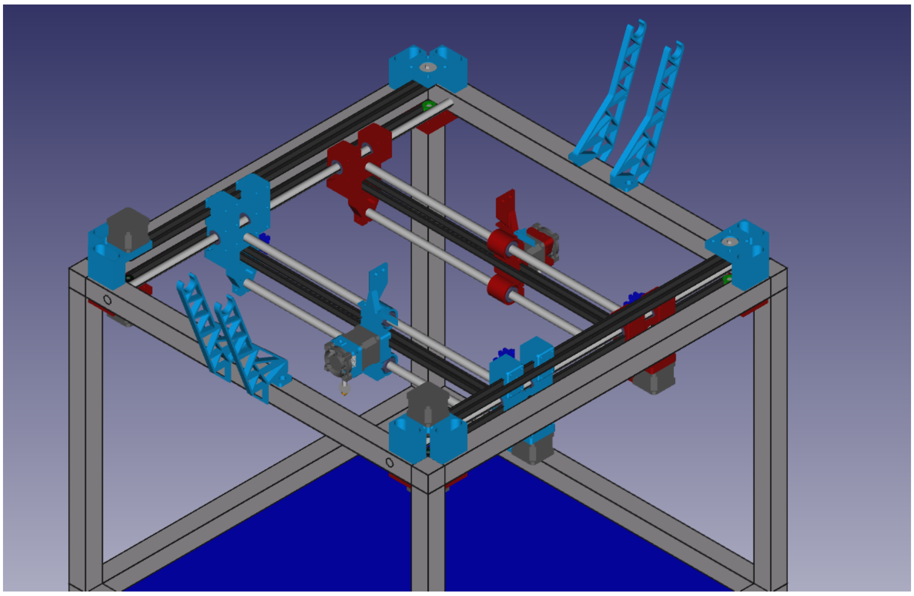

Figure 7.6: X400 CE Modified v1.0

To see the design of each part, the employed materials and the assembly process, an Annex 1 with all the data is attached. The name of this Annex 1 is *User Manual*.

7.1.3 Electronics

Since the control shield is not designed yet, it has not been possible to connect components with arduino DUE. Arduino Mega and 1.4.1 Ramps shield has been chosen for controling the different components so that the testing of the structure can be carried out. Due to this limitation, the use of the two heads working simultaneously in a parallel manner is not possible, but both of them have been tested individually.

The wiring diagram that has been done is as follows[1]:

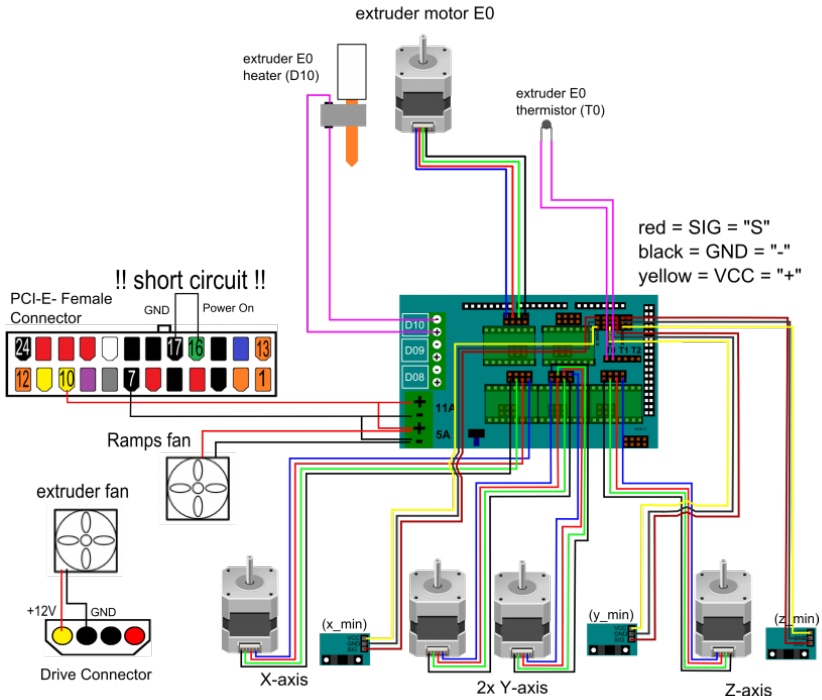

Figure 7.7: X400 CE Connection Diagram (Source: germanreprap[15])

It is important to point out that the modified extruder is inversely adjusted to the original one. In other words, the point 0.0.0 of the Axis is in inverse order. The reason is to avoid collisions and so to save one end-stop [2]. To reverse the modified Y-Axis of the 3D printer, it can be done via software or hardware. In this case, hardware will be used being that it is only needed to connect the motors in reverse.

7.2 Design and Creation of Software system

This section describes the control software the 3D printer will use and the one employed for the design tests.

[1]"In case of any doubt, the manual X400 CE is available on the internet [15]."
[2]This design is not definitive but it is used to carried out the tests.

7.2.1 Control Software

As it has been mentioned several times along this document, Marlin4Due will be the software responsible for controlling the components of the 3D printer. Due to the problem above mentioned with the control shield, just the compilation of Marlin4DUE[26] into the Arduino board has been verified.

Marlin4Due is based on Marlin[27], whose software structure is similar just changing the architecture for which it is developed. Marlin was designed for Arduino Mega[17] and Marlin4Due was redesigned for Arduino DUE[17]. Therefore, Marlin will be loaded to the Arduino Mega.

To configure the 3D printer, it is neccessary just to modify in Marlin the *configuration.h* file [3]. In Annex 1, some interesting links can be found to perform the correct configuration of this file. The better this calibration is done, the better results in printing are obtained.

[3]The file is the same for Marlin4Due and Marlin, so the configuration is the same as well.

Chapter 8

Testing

In this chapter, the different tests made throughout this project are explained, expecting the results are optimal and thus, accomplishing the stated objectives. The tests have been divided into two main groups: the test involving the hardware and those involving the software. Besides, hardware testing have been divided into three parts as well: X-Axis, Y-Axis and both together. Software testing have been split into two parts: the control of components and the printing of figures.

8.1 Tests on the modified structure

In this section, hardware tests are performed, being divided into X-Axis, Y-Axis and both Axis together.

8.1.1 X-Axis testing

- **Test 1**: Positioning the X-Axis in its position.
  - *Problem found*: The original Y-Axis' belt grazed and blocked the *modified X-glider* .
  - *Proposed solution*: the piece is modified, *Modified X-glider clamp belt* , before covering the complete back part of the *modified X-Glider* . Now it covers just the top part and performs its tasks perfectly, holding the belt of Y-Axis.
  - *Verification*: The result has been satisfactory.
- **Test 2**: Positioning the Extruder in the (0,0,0) position.
  - *Problem found*: When the extruder is looking for the position 0 on the X-Axis, a collision with the x-Glinder is caused because it does not set the end-stop.
  - *Proposed solution*: a longer and more robust end-stop activator is designed.
  - *Verification*: The result has been satisfactory.

8.1.2 Y-Axis testing

- **Test 3**: Positioning the Y-Axis in its position.
  - *Problem found*: When putting the piece at the back of the structure, a problem is observed. Pulley's nut of the *POM NEMA 17 Mount* clashed with the polley's nut of new part, *POM NEMA 17 Mount Modified.*
  - *Proposed solution*: The bottom of the piece attached to the structure has been increased to a certain distance, avoiding the collision.
  - *Verification*: The result has not been satisfactory.
- **Test 4**: Positioning the Y-Axis in its position.
  - *Problem found*: To design a *POM NEMA 17 Mount Modified* with an increased distance at the bottom part, the screws are too short.
  - *Proposed solution*: the piece is redesigned with some holes in the part attached to the structure. A simpler solution would be to change the type of screw but this solution would increase the cost and would not use the same parts [1].
  - *Verification*: The result has been satisfactory.

8.1.3 Both Axes testing

- **Test 5**: Extruder movement to a coordinate (x,y) without filament.
  - *Problem found*: With the movement of the extruders, it is observed that the *extruder energy chain* collided with the other *extruder energy chain*, preventing the extruder's movement. The *extruder energy chain* keeps the wiring away from the hot bed. With this support, the extruder cable is always horizontal and protected.

Figure 8.1: Extruder energy chain (Source: germanreprap[15])

  - *Proposed solution*: The best way for extruder to move without obstacles is by removing this element, so this is made. To avoid problems,on one hand, this should

[1] In every moment throughout the project we have tried to use components that have already been used in the model X400 CE.

be as sufficiently tense not to touch the hot bed. On the other hand, it should not be as too tense that it obstructs the extruder.

  - *Verification*: The result has been satisfactory.

- **Test 6**: Extruder movement to one coordinate (x,y) with filament.
  - *Problem found*: When the belt of the modified Y-Axis is above structure and the head extrudes the filament, a little friction ocurrs. This could be a problem over time.
  - *Proposed solution*: A filament support for being held at the top of the structure is designed.
  - *Verification*: The result has been satisfactory.

8.2 Tests on the operation of firmware

In this section the software tests performed to Marlin [27] are included, divided into: Marlin running the test of components and acting to inappropriate values and then the printing test.

8.2.1 Control testing components

- **Test 1**: Turn on the 3D printer with the thermistors disconnected.
  - *Problem found*: The printer shows an error message on the LCD screen. This indicates that the value of the thermistor is below the minimum. This does not permit any impression because it remains locked.
  - *Proposed solution*: The solution is to connect the two thermistors, both, the extruder and the hot bed.
  - *Verification*: The result has been satisfactory.
- **Test 2**: Heating the extruder to 240°.
  - *Problem found*: When the temperature exceed 200°,it is not increasing as fast as the first 200°. The software detects the lack of heat and shows an error, stopping the heating of the extruder.
  - *Proposed solution*: We reconfigured the PID of the extruder [2].
  - *Verification*: The result has been satisfactory.
- **Test 3**: Extruding with a temperature below of a filament fusion temperature.
  - *Problem found*: When sending the order to the 3D printer, filament is not extruded until it reaches the proper temperature.
  - *Proposed solution*: Not to extrude the material until the proper warm temperature is reached.
  - *Verification*: The result has been satisfactory.

[2] How to do it can be found in the following link [28].

8.2.2 Printing test

- **Test 5**: Printing cube with size 3x3x3cm.
  - *Problem found*: The extruder holds the material and is filled with filament, shaving the hot bed.
  - *Proposed solution*: The solution is to drop tension in the extruder controller *Pololu* [25]. Changing the number of steps per unit in the archive *configuration.h* (#define DEFAULT_AXIS_STEPS_PER_UNITx,y,z,extruder). Finally the pulley bracket pressure support is changed because it does not apply enough pressure.
  - *Verification*: The result has been satisfactory.
- **Test 6**: Printing cube with size 3x3x3cm.
  - *Problem found*: The piece measures were not correct and the filling presents ribbon form.
  - *Proposed solution*: The solution is drop tension in the controllers *Pololu*[25] [3] Then the number of steps per unit in the archive *configuration.h* (#define DEFAUL_AXIS_STEPS_PER_UNITx,y,z,extruder) is changed.
  - *Verification*: The result has been satisfactory.
- **Test 7**: Printing frame with size 7x15x1cm.
  - *Problem found*:When performing the printing, the layers are not joined together because they are not well fused.
  - *Proposed solution*: The proposed solution was to lift the hot bed 1mm more.
  - *Verification*: The result has been satisfactory.
- **Test 8**: Printing cube with size 1x1x1cm with two extruders, first original then modified.
  - *Problem found*: Because of the modified extruder is nearer to the hot bed, 0.6 cm, the calibration of this bed cannot be the same for both extruders. To print with an extruder and then with the other is necessary to calibrate the bed.
  - *Proposed solution*: the solution is made the modified extruder equal to the original extruder.
  - *Verification*: In the absence of two identical extruders, it can not be verified.[4].

[3] It is noticed that some Pololu's potentiometer, that adjust the tension, are damaged. Replacement is recommended because it does not allow precision.

[4] This problem is included in the chapter future improvements

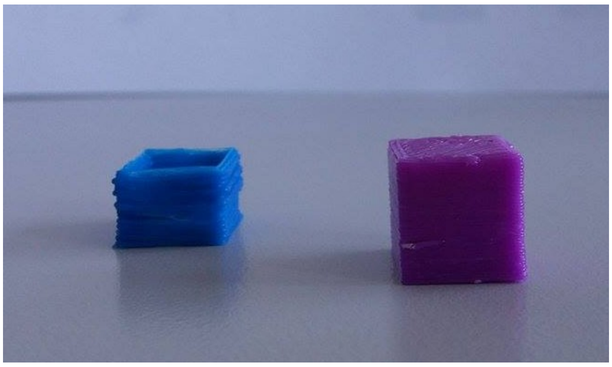

Figure 8.2: Calibration of hot bed for both extruders

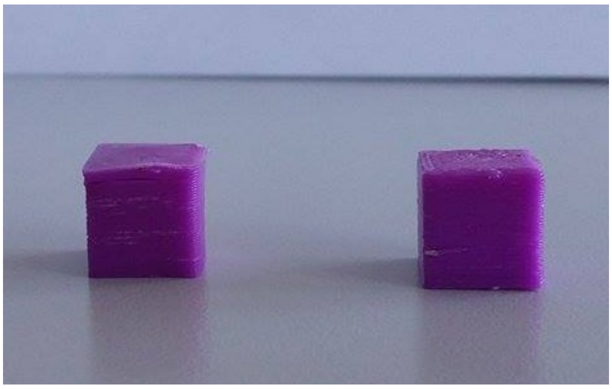

Figure 8.3: Calibration of hot bed for different extruders

Chapter 9

Conclusions and future improvements

In this chapter, the conclusions obtained after completion of all stages of the project are described and therefore, an analysis of the work is made. It is possible to see whether all of the objectives have been accomplished. After this, there will be expounded some improvements in order to obtain an upgraded version of the proposed solution.

9.1 Conclusions

In this section, the objectives of this project, defined in Chapter 2 are evaluated.

- It has been acquired great knowledge of 3D printers. Not only about internal function and use, but also the development in all its phases. From the 3D design of a piece with *FreeCAD* [20],their subsequent preparation with *Slic3r*[21], to generate the *.gcode* and finally to build the figure.

- The old microcontroller, *Arduino Mega* [17], has been successfully replaced by one that remains compatible with all hardware and give us a better energy efficiency, providing more processing power, *Arduino DUE* [17].

- A new software compatible with this new microcontroller, *Arduino DUE* has been provided. After the verification that the old microcontroller, *Arduino Mega*, was not compatible with *Marlin*[27], the current works with *Marlin4Due* [26].

- New parts for the structure of the 3D printer have been designed and modified, allowing us to add a second extruder to the mentioned structure.

- Finally, all these designed parts have been mounted on the structure, verifying the proper behaviour during the working progress.

- The objective of *Develop a connections adapter shield to interconnect the new board*, has not been completed.

This problem is due to the fact that the responsible of the project to design the *Drivers Control Shield* has not finished before the deadline [1]. Therefore, the absence of the *Drivers Control Shield* has not allowed to design the adapter shield. This point will be added to future improvement.

Regarding the above mentioned, it is considered that the objectives have been achieved.

Apart from these objectives, there are some personal goals which have been involved during this project and they are pointed out as follows:

- Great knowledge about 3D printing, assembly, calibration, configuration and error-solving has been obtained.
- Some familiarity regarding LaTeX [16] text editor has been earned. This software has been used to document all this project.
- The electronics knowledge has been consolidated, due to the components employed in this project.
- Finishing a project, accomplishing the deadline in a different country and in a foreign language. This has supposed a great personal experience as well.
- English skills have been improved.

9.2 Future improvements

Finally, a number of possible improvements in the design are described. These will help to increase the system's functionality.

- Improved extruders.

  Because of their large size, this would make difficult the printing in parallel because both extruder were separated. Two possible solutions can be proposed [28]:

[1]This project is made in parallel with the design of the structure of the 3D printer. Once this process is completed, both projects are finished at once.

– Setting the extruders in an inverse manner on their support.

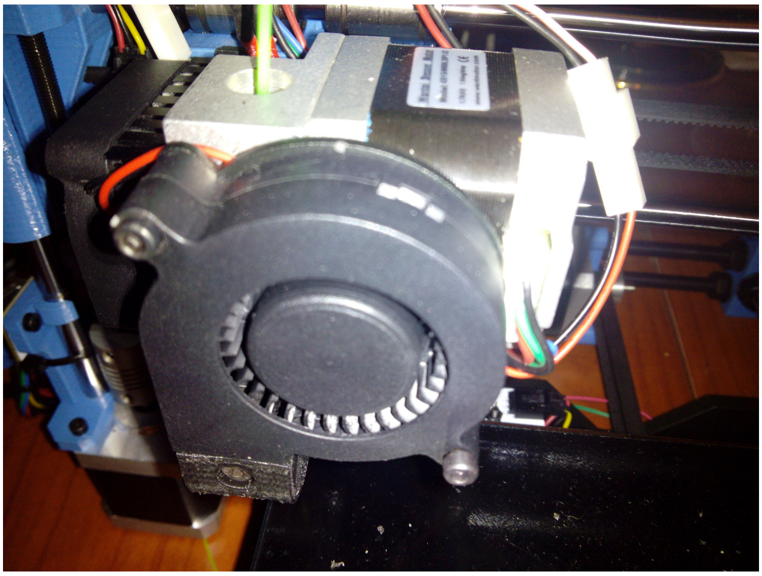

Figure 9.1: Inverted extruder (Source: mybqyyo [28])

– Put the motor out of the extruder support (Bowden Extruder).

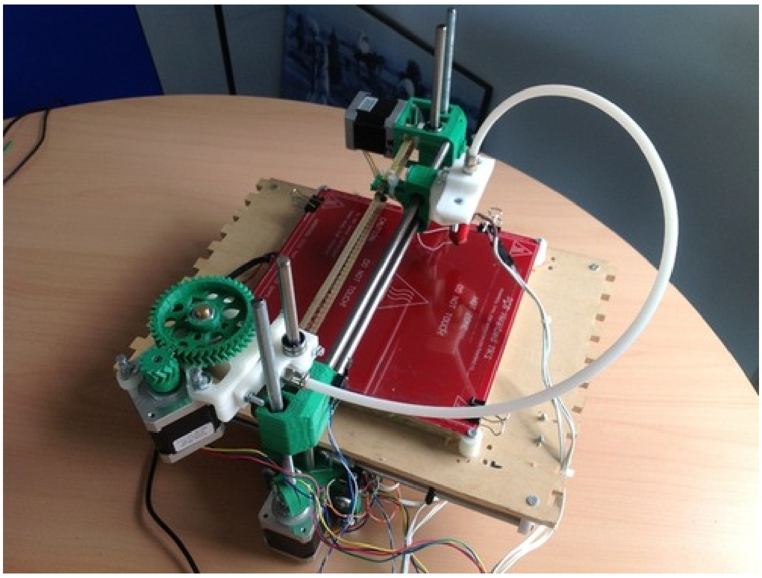

Figure 9.2: Bowden extruder (Source: mybqyyo [28])

- Extension of the hot bed.

  Because of the new extruder has more positioning surface, this extension will allow us to print larger parts.

- Modifying the software to print with single or double extruder.

  Also, it should be studied the accomplishment of both extruder positioning in a coordinate 0,0,0. Once they are in this position, the software would use one or two.

- Automatic levelling system of the hot bed.

  Creating a system that allows automatically levelling of the hot bed, being that the firmware Marlin [27] already has the support.

- Designing the control shield.

  This is the most important improvement in the future so that the project is able to progress.

- Bridge to hold the *cable loom* [2]. Because of the problem explained above in the Test Chapter, the *extruder energy chain* had to be removed, so that the cable of extruders is not supported by any element. The function of this bridge would be to hold the wiring by a structure upon the 3D printer.

- Providing the 3D printer with wireless connection

  This will facilitate its use, being able to print from home or from another department. One possible suggestion to this would be to use the hardware Raspberry pi[30] with the software OctoPrint[31]. Besides, the user can remotely monitor the 3D printer, being that Octoprint allows us to set a webcam for watching the printing process.

- Both extruders should be equal.

  With different extruders, you can find the problem[3] of have the hot head at different heights. To avoid that, the best option would be to include two similar extruders. In this way, both hot heads would have the same heights.

[2] Wiring of the extruder
[3] Chapter 8.2.2, test 8

Bibliography

[1] IMPRESORAS 3D Short history of 3D printing [online]. [Date consulted: 6 June 2016]. Available in: https://impresoras3d.com/

[2] WIKIPEDIA Stereolithography - Definition [online]. [Date consulted: 6 June 2016]. Available in: https://en.wikipedia.org/

[3] Jurado Caballero, A.; Rubias Montes, I. *Final work of subject Interfaces and Peripherals - 3D Printers*. Universidad de Córdoba

[4] Farhan Javed; Salman Javed. 2016. *Design Methodology and Development of an Economical 3D Printer*. Conference: SAE 2016 World Congress and Exhibition.

[5] REPRAP Open Source Community of 3D Printers [online]. [Date consulted: 18 April 2016]. Available in: http://www.reprap.org/

[6] Julielynn Y. Wong. 2015. *Ultra-Portable Solar-Powered 3D Printers for Onsite Manufacturing of Medical Resources*. Aerosp Med Hum Perform. 86(9):830-834.

[7] Hiroaki Kumagai; Masanori Arai; Jin Gong; Hidemitsu Furukawa. 2016. *Modeling the transparent shape memory gels by 3D printer Acculas*. Conference: SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring.

[8] AUTODESK Projecto Escher - Software for Parallel 3D printer [online]. [Date consulted: 19 April 2016]. Available in: http://projectescher.com/

[9] 3D IMPRESORAS 3D Definition of 3D printer [online]. [Date consulted: 18 April 2016]. Available in: http://www.3dimpresoras3d.com

[10] SILICON Types of filaments [online]. [Date consulted: 9 June 2016]. Available in: http://www.silicon.es/

[11] AIRWOLF3D Printing tolerance [online]. [Date consulted: 15 June 2016]. Available in: http://airwolf3d.com

[12] FILAMENT2PRINT Temperature and printing speed [online]. [Date consulted: 20 June 2016] Available in: http://filament2print.com

[13] WIKIPEDIA Definition of noise [online]. [Date consulted: 20 June 2016] Available in: https://en.wikipedia.org

[14] PRINTED PARTS Energy / electricity consumed by a Prusa i3 3D Printer [online]. [Date consulted: 20 June 2016] Available in: http://printedparts.blogspot.de

[15] GERMAN REPRAP X400CE 3D Printer Manual [online]. [Date consulted: 22 June 2016] Available in: http://wiki.germanreprap.com

[16] LATEX Official web page [online].[Date consulted: 14 April 2016] Available in: https://www.latex-project.org/

[17] ARDUINO Specification of Arduino [online].[Date consulted: 5 July 2016] Available in: https://www.arduino.cc

[18] Salas-Morera, L. *Apuntes de Proyectos*. Universidad de Córdoba

[19] FORUMS.REPRAP Hacked RAMPS 1.4 [online]. [Date consulted: 1 July 2016] Available in: http://forums.reprap.org/read.php?219,479626,page=1

[20] FREECAD Definition of FreeCAD [online].[Date consulted: 3 July 2016] Available in: http://www.freecadweb.org/

[21] SLIC3R Definition of Slic3r [online].[Date consulted: 4 July 2016] Available in: http://slic3r.org

[22] PROTOPARADIGM The Difference Between ABS and PLA for 3D Printing [online].[Date consulted: 4 July 2016] Available in: http://www.protoparadigm.com

[23] GNOME Definition of LaTeXila [online].[Date consulted: 4 July 2016] Available in: https://wiki.gnome.org

[24] ATMEL Atmel SAM3X8E ARM Cortex-M3 CPU Datasheet [online].[Date consulted: 12 July 2016] Available in: http://www.atmel.com

[25] POLOLU Description of components [online].[Date consulted: 4 August 2016] Available in: https://www.pololu.com/

[26] GITHUB Marlin4Due 3D Printer Firmware [online].[Date consulted: 5 August 2016] Available in: https://github.com/Wurstnase/Marlin4Due

[27] GITHUB Marlin 3D Printer Firmware [online].[Date consulted: 5 August 2016] Available in: https://github.com/MarlinFirmware/Marlin

[28] MIBQYYO Adjusting the PID of your 3D printer [online].[Date consulted: 6 August 2016] Available in: http://www.mibqyyo.com/

[29] REPETIER Repetier-Host official website [online].[Date consulted: 4 August 2016] Available in: https://www.repetier.com/

[30] RASPBERRY PI Raspberry Pi official website [online].[Date consulted: 7 August 2016] Available in: https://www.raspberrypi.org/

[31] OCTOPRINT OctoPrint official website [online].[Date consulted: 7 August 2016] Available in: http://octoprint.org/

[32] IMPRIMALIA3D Double extruder in the Metal 3D printer Printrbot [online].[Date consulted: 7 August 2016] Available in: http://www.imprimalia3d.com

[33] MAKERED Elementary: do not buy a 3D printer [online].[Date consulted: 7 August 2016] Available in: http://makered.nl

[34] ELCOMERCIO The failures of 3D printers [online].[Date consulted: 9 August 2016] Available in: http://elcomercio.pe

[35] DIY3DPRINTING RAMPS v1.4.2 open source control board [online].[Date consulted: 9 August 2016] Available in: http://diy3dprinting.blogspot.de

[36] PINTEREST Extruder image [online].[Date consulted: 9 August 2016] Available in: http://pinterest.com