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MEJORAS EN EL PROCESO DE IMPRESIÓN BASADO EN UNA IMPRESORA DE MODELADO POR DEPOSICIÓN FUNDIDA

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TÍTULO: IMPROVEMENTS FOR THE 3D PRINTING PROCESS BASED ON AN FDM PRINTER

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Resumen

El TFG esta realizado sobre una impresora 3D de la marca Ultimaker. Consta de 3 partes diferentes. La primera es la búsqueda y creación de un sistema de auto calibrado de la base sobre la que se imprime. La segunda analiza los diferentes parámetros que influyen en el proceso de impresión. Por ultimo se analizan los fallos que aparecen al imprimir paredes delgadas en diferentes materiales plásticos, buscando posibles soluciones.

Palabras claves

Impresora 3D, modelado deposición fundida

HOCHSCHULE OSNABRÜCK
UNIVERSITY OF APPLIED SCIENCES

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Bachelor Thesis

IMPROVEMENTS FOR THE 3D PRINTING PROCESS BASED ON AN FDM PRINTER

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Me da vértigo el punto muerto
y la marcha atrás,
vivir en los atascos,
los frenos automáticos y el olor a gasoil.

Me angustia el cruce de miradas
la doble dirección de las palabras
y el obsceno guiñar de los semáforos.

Me da pena la vida, los cambios de sentido,
las señales de stop y los pasos perdidos.

Me agobian las medianas,
las frases que están hechas,
los que nunca saludan y los malos profetas.

Me fatigan los dioses bajados del Olimpo
a conquistar la Tierra
y los necios de espíritu.

Me entristecen quienes me venden clines
en los pasos de cebra,
los que enferman de cáncer
y los que sólo son simples marionetas.

Me aplasta la hermosura
de los cuerpos perfectos,
las sirenas que ululan en las noches de fiesta,
los códigos de barras,
el baile de etiquetas.

Me arruinan las prisas y las faltas de estilo,
el paso obligatorio, las tardes de domingo
y hasta la línea recta.

Me enervan los que no tienen dudas
y aquellos que se aferran
a sus ideales sobre los de cualquiera.

Me cansa tanto tráfico
y tanto sinsentido,
parado frente al mar mientras que el mundo gira.

Ideario (Francisco M. Ortega Palomares)

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I would like to thank to Mrs. Birgit Tepe from the metrological department for providing me the suitable instruments to carry out this thesis.

II Abstract

One main challenge in the usage of FDM printers is the printing process reliability. A lot of parameters influence the success of printing approaches and the quality of the results. In this thesis the process of adjustment of the build plate and the speed of the printing process related to the final result of the pieces printed are analyzed. Always looking for the best final result of the pieces printed in the less time possible.

In addition, a research about FDM-printing of thin shell structures is carried out. Analyzing in an objective way the problems and their causes. Finally, several solution are found to solve these problems.

III Declaration

I hereby confirm that I have used my Bachelor Thesis independently and no other than the specified sources and aids have been used.

Date

Signature

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VII Nomenclature

A	Ampere
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
3D	Three Dimensional
CAD/CAM	Computer Aided Design and Manufacturing
CPE	Chlorinated Polyethylene
CT	Computer Tomography
FDM	Fused Deposition Modeling
GB	Gigabyte
GPIO	General Purpose Input/Output
HDMI	High-Definition Multimedia Interface
PCB	Printed Circuit Board
PLA	Polylactic Acid
SD	Secure Digital
TV	Television
USB	Universal Serial Bus
V	Voltage
WLAN	Wireless Local Area Network
g	Gram
kg	Kilogram
R_a	Arithmetic-mean-surface roughness
R_{max}	Maximum roughness depth
min	Minute

mm	Millimetre
mm/s	MI limiters per second
µm	Micrometer
nm	Nanometer
ºC	Grade Celsius
dl	Change in object length
L_0	Initial length of object
α	Linear expansion coefficient
t_0	Initial temperature
t_1	Final temperature

1-Introduction

3D printing is a term that refers to the technology known as additive manufacturing (AM). AM is a process to create three-dimensional objects under automated control. ISO/ASTM52900-15 defines seven categories of AM processes within its meaning: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination and Vat Photopolymerization. They all share the common theme of sequential-layer material addition. This thesis is based on Material Extrusion Technology, better known as Fused Deposition Modeling (FDM). This process consists of depositing successive layers of material to achieve the final shape.

This bachelor thesis analyzes the process for the adjustment of the build plate of a FDM 3D printer, creates and evaluates concepts for the improvement of the adjustment process, and builds a prototype solution for an auto levelling system.

Secondly, this thesis examines and explains how different parameters influence the final result of a piece printed by FDM. The main parameters discussed are layer thickness, printing head speed and extruder temperature.

Finally, this thesis investigates printing on thin-walled shapes while observing the problems that appear and looking for possible solutions.

1.1-Antecedents

It cannot be denied that 3D printing is a technological revolution. 3D printing is transforming not only engineering but also many other fields like architecture, medicine, education and archaeology.

For example, this technology allows architects to create complex and durable models. In fact, developments in this technology could transform the way buildings are made.

Medical applications for 3D printing have also increased very fast. This technology is applied in different fields like tissue and organ fabrication; creation of customized prosthetics, implants, and anatomical models; and pharmaceutical research regarding drug dosage forms, delivery, and discovery.

Educational institutions are beginning to understand the potential benefits that this technology can provide. 3D printers make it easy for teachers to raise the interest of their students compared to just showing 2D representations in books. Also, they improve hands-on learning and learning by doing.

In archaeology, this technology allows researchers to scan and replicate historical objects in order to preserve original collections.

2- Project management

2.1- Project subject

3D printing with FDM (Fused Deposition Modeling) printers is nowadays a standard process for the creation of physical items from virtual models. Semi-professional printers like the Ultimaker 2 are able to produce reasonable results which can be used for a broad variety of products.

One main challenge in the usage of FDM printers is the printing process reliability. A lot of parameters influence the success of printing approaches and the quality of the results.

The topic of the bachelor thesis is to analyze such parameters with the focus on certain classes of products.

The 3D printer model used for this purpose is the Ultimaker 2 Extended + whose features have already been explained in the thesis of Sergio, C. A. (2016). *Characterization of 3D Printing Parameters.* Thus, this thesis can be considered a continuation of the previous one.

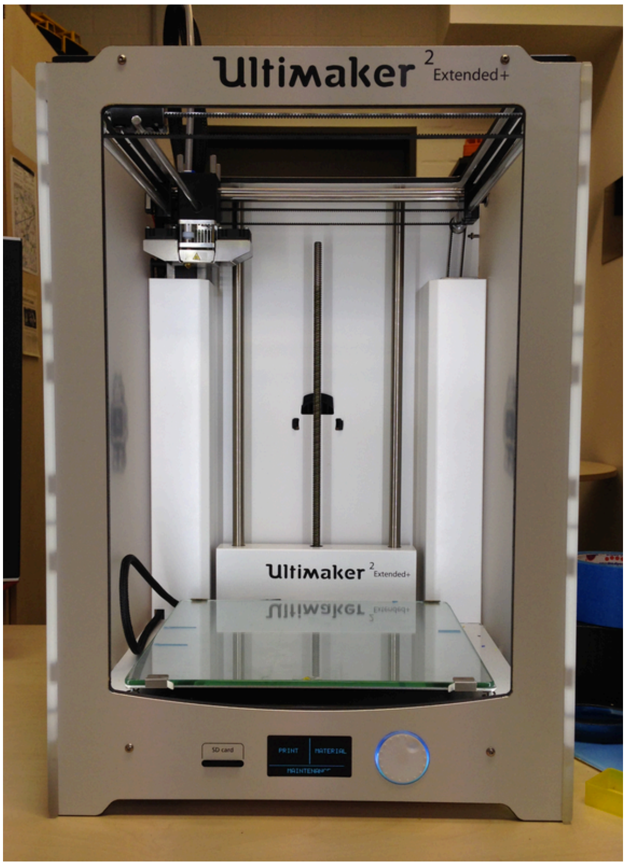


Figure 1: Ultimaker 2 Extended + 3D printer

2.2- Requirement specification

2.2.1- Task number 1

The first task is to analyze the process for the adjustment of the build plate of an FDM 3D printer. Create and evaluate concepts for the improvement of the adjustment process. Build a prototype solution for an improved adjustment process.

Work breakdown structure:

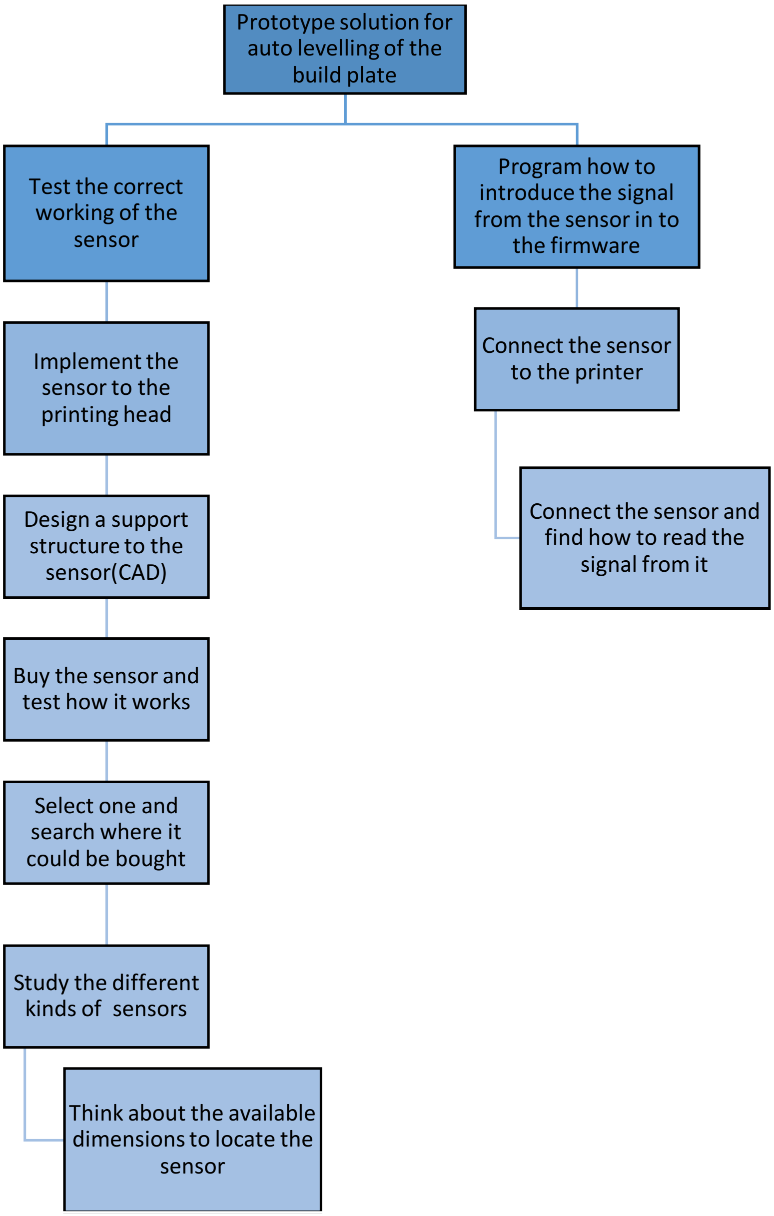


Figure 2: Work breakdown structure of the prototype solution for auto levelling

Gantt chart:

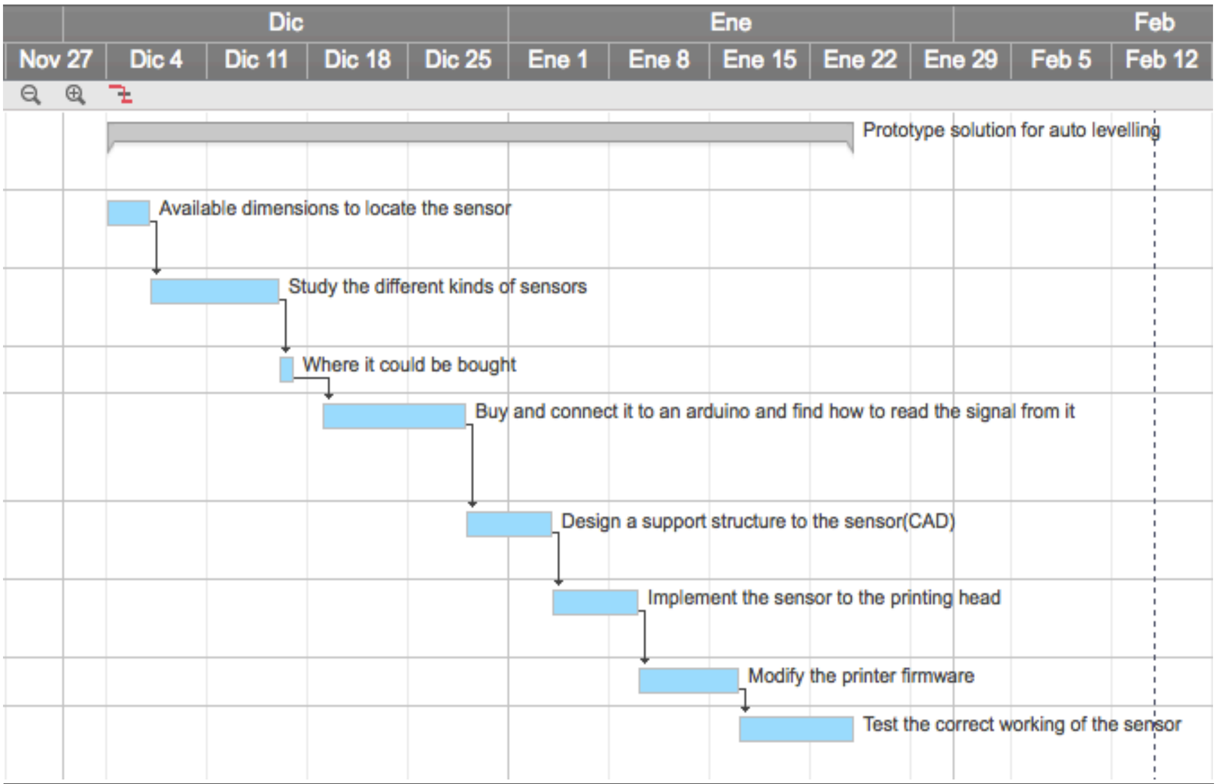


Figure 3: Gantt chart of the prototype solution for auto levelling

2.2.2- Task number 2

The second task is to analyze the speed of the printing process. The parameters layer thickness, nozzle diameter and printing head speed influence – amongst others – the speed of the printing process. These parameters have to be varied for certain test bodies. The resulting quality of the test bodies and possible problems have to be documented.

Work breakdown structure:

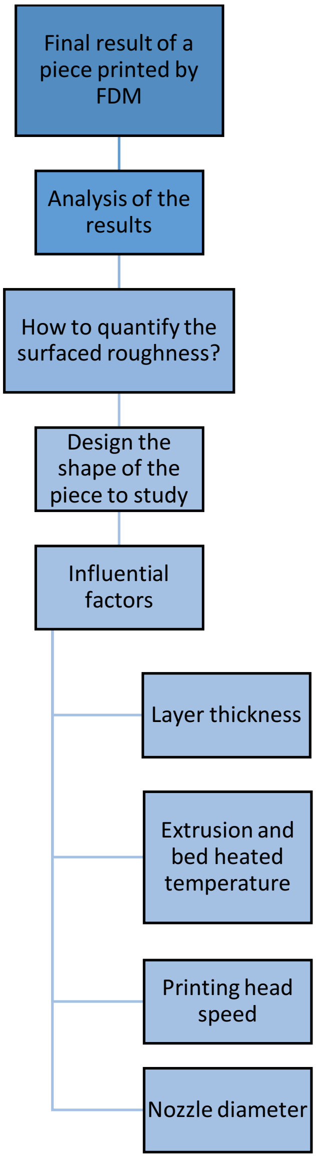


Figure 4: Work breakdown structure of the study of final result of a piece printed by FDM

Gantt chart:

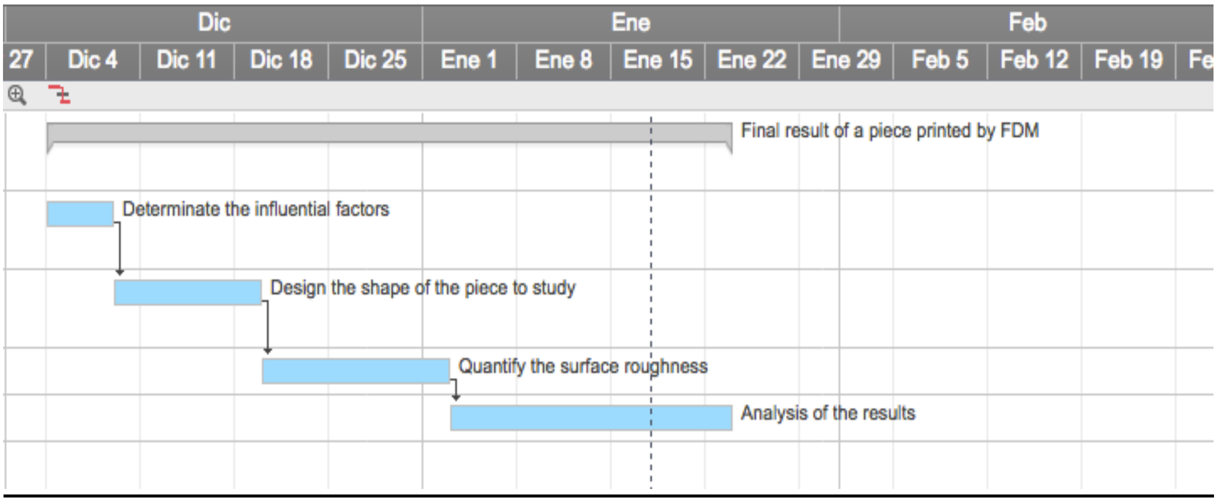


Figure 5: Gantt chart of the study of final result of a piece printed by FDM

2.2.3- Task number 3

The third task is to research about FDM-printing of thin-shell structures. Objects with thin walls can be printed with FDM-printers, but often they are not as stable as expected. Solutions for this problems have to be investigated and example objects have to be printed and examined.

Work breakdown structure:

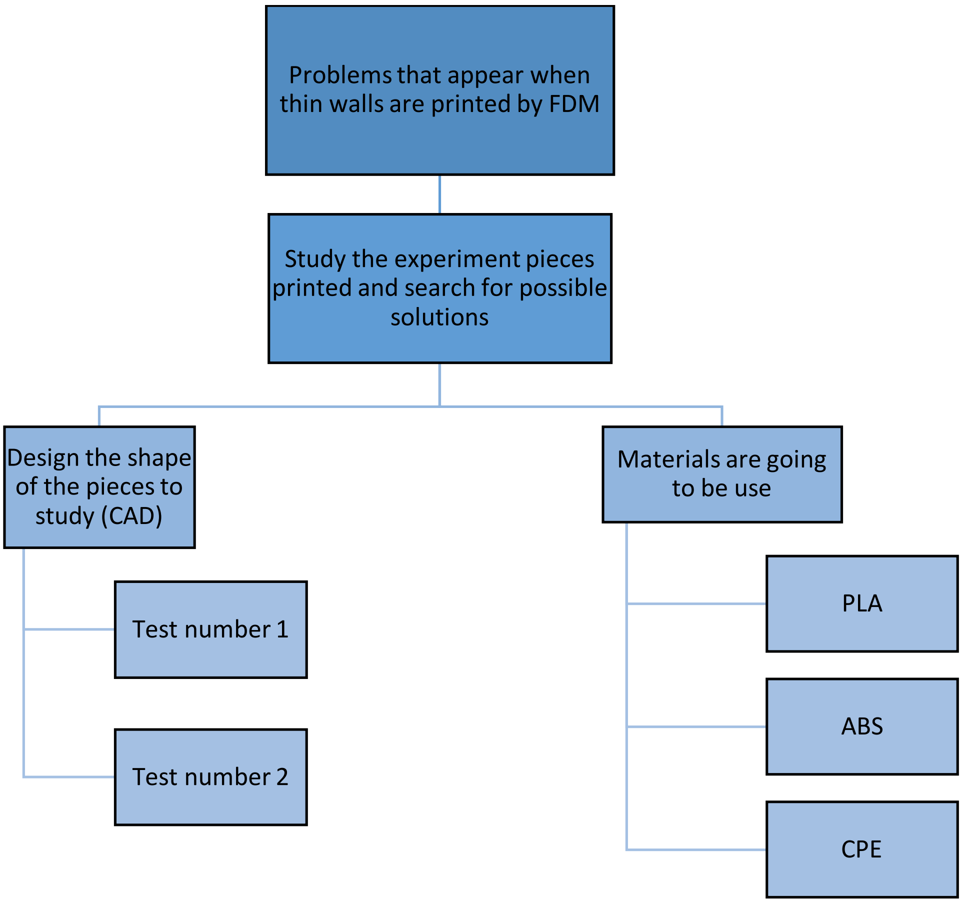


Figure 6: Work breakdown structure of the study of thin wall problems

Gantt chart:

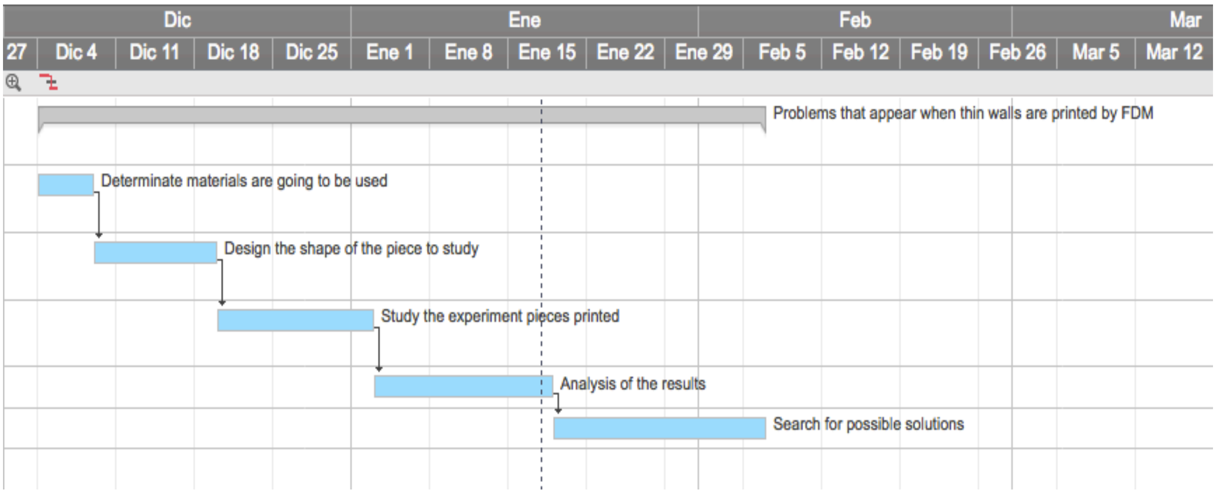


Figure 7: Gantt chart of the study of the problems when thin walls are printed by FDM

3- Auto levelling system for Ultimaker 2 Extended+

Before starting to print with the 3D printer, it must be ensured that the build plate is properly calibrated. This means there has to be a predetermined distance between the build plate and the nozzle.

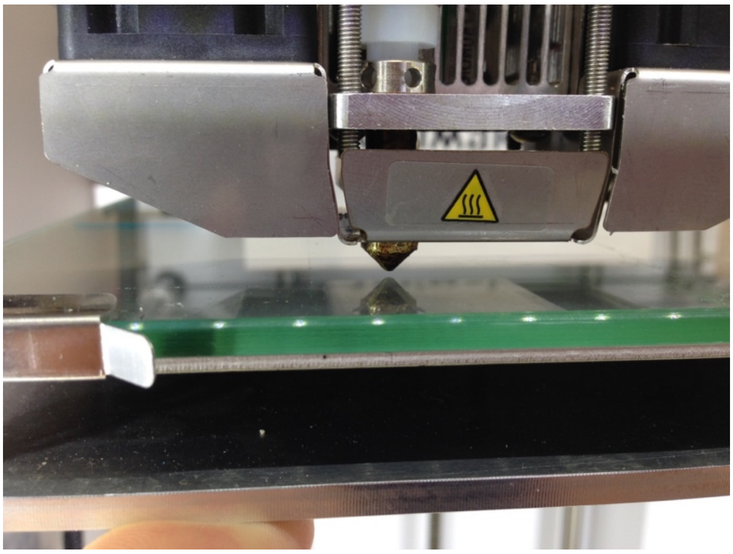


Figure 8: Distance between the build plate and the nozzle

But what is the best distance? Usually the thickness of a piece of paper is good enough, as it should be approximately 0,1 millimeter with the cold nozzle. The nozzle and the heater column are made of brass which has a thermal linear expansion coefficient of $18,7{*}10^{-6}$ °C. The nozzle and the heater column have a vertical effective length of 30 millimetres.

$$dl = L_0 * \alpha * (t_1 - t_0) \quad (1)$$

Where:

dl = change in object length (m)
L_0 = initial length of object (m)
α = linear expansion coefficient (°C)
t_0 = initial temperature (°C)
t_1 = final temperature (°C)

Following equation 1, as the nozzle heats up from room temperature (20°C) to the printing temperature (170°C-240°C), it expands approximately by 0,1 millimetres. So the 0,1 millimetre distance is saved as the z=0 position for the 3D printer. Therefore, when the 3D printer starts to print, it puts the extruder to the first layer height that you previously set in Cura, the slicer software used for the Ultimaker printers. This particular starting position of the nozzle over the build plate is crucial for successful printing.

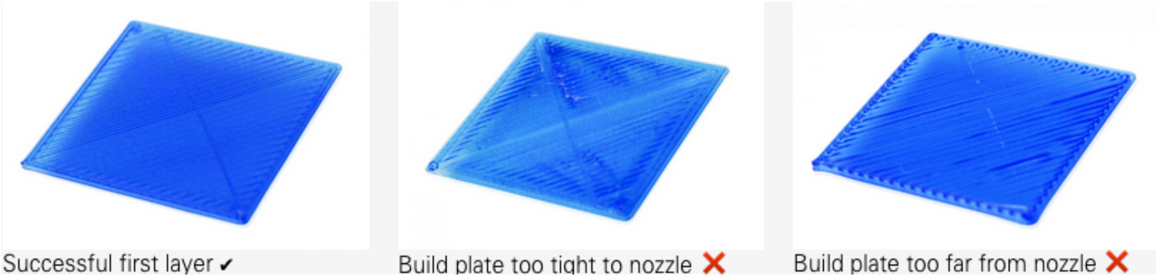


Figure 9: Correct build plate calibration (Ultimaker. *https://ultimaker.com*)

A feeler gauge can also be used to measure the gap between the build plate and the nozzle with great precision. Feeler gauges are mostly used in engineering to measure the gap between two parts. A successful first layer is vital to a successful print.

3.1- Current adjustment system

The current system for adjusting the distance between the build plate and the nozzle is semi-manual. This semi-manual system consists of the adjustment of said distance in three points. One is in the middle of the back edge of the build plate and the other two are in the two front corners. In these corners there is a screw in a spring which can be turned to raise this corner up and down. With these three points, a plane is defined which serves to balance the build plate.

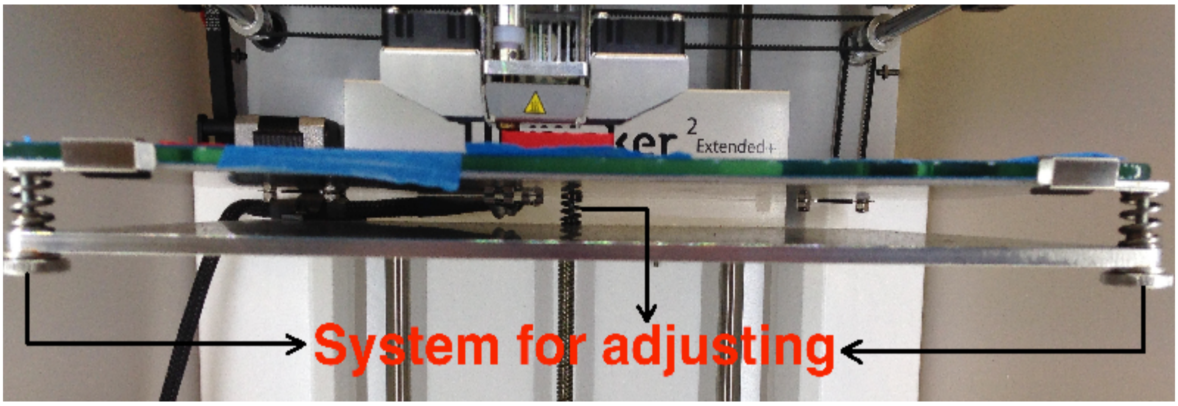


Figure 10: Current system for adjusting the build plate

3.2- Why should the current adjustment system be improved?

Doing this calibration process each time the printer wants to be used is very time-consuming, and a bad adjustment can cause warping, moving and shifting. Therefore, this process has to be done very carefully and errors often occur. That is why the idea of developing an auto levelling system has arisen. In order to carry out the adjustment process it is necessary to control the build plate up and down. And to control the build plate without using the traditional display of the 3D printer, which is limited in determining the position of it, a computer is needed.

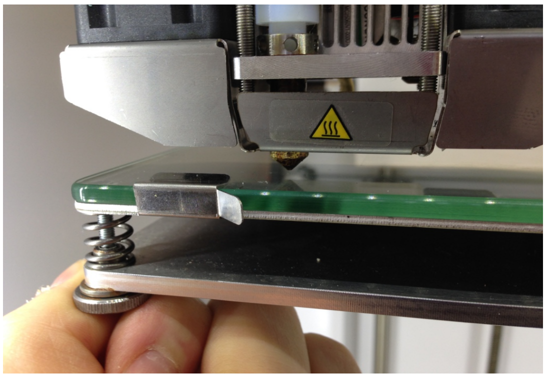


Figure 11: Screw of the build plate corner

3.3- Operating the printer using a computer

To control the 3D printer with a computer the first thing that is necessary is a program to connect it with the 3D printer. This program is called a host. A host is a software program on your computer that allows you to communicate with your 3D printer. It makes it possible for your computer to send G-code to the 3D printer through a USB connection. G-code files contain instructions for the 3D printer on when, where, and how fast to make movements. A host and a G-code sender are the same thing.

There are two free and open source hosts suitable for this purpose: Repetier Host and Printrun/Pronterface. The interfaces of the two hosts are as follows.

Repetier Host:

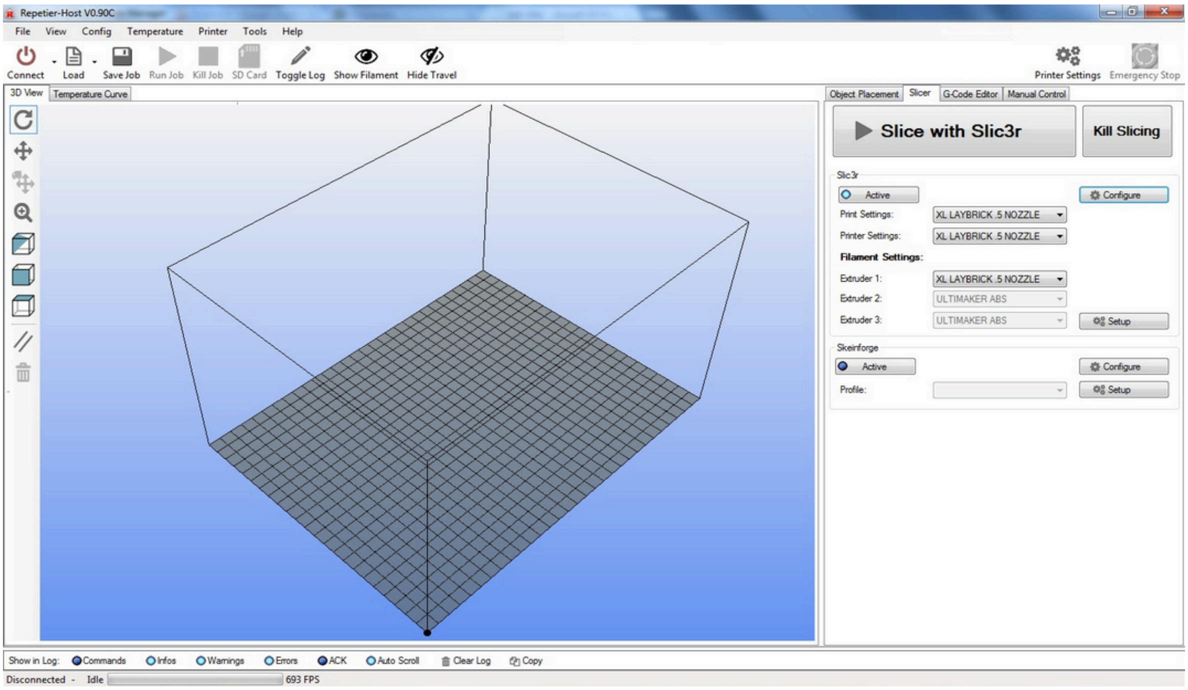


Figure 12: Interface of the Repetier Host

Printrun/Pronterface:

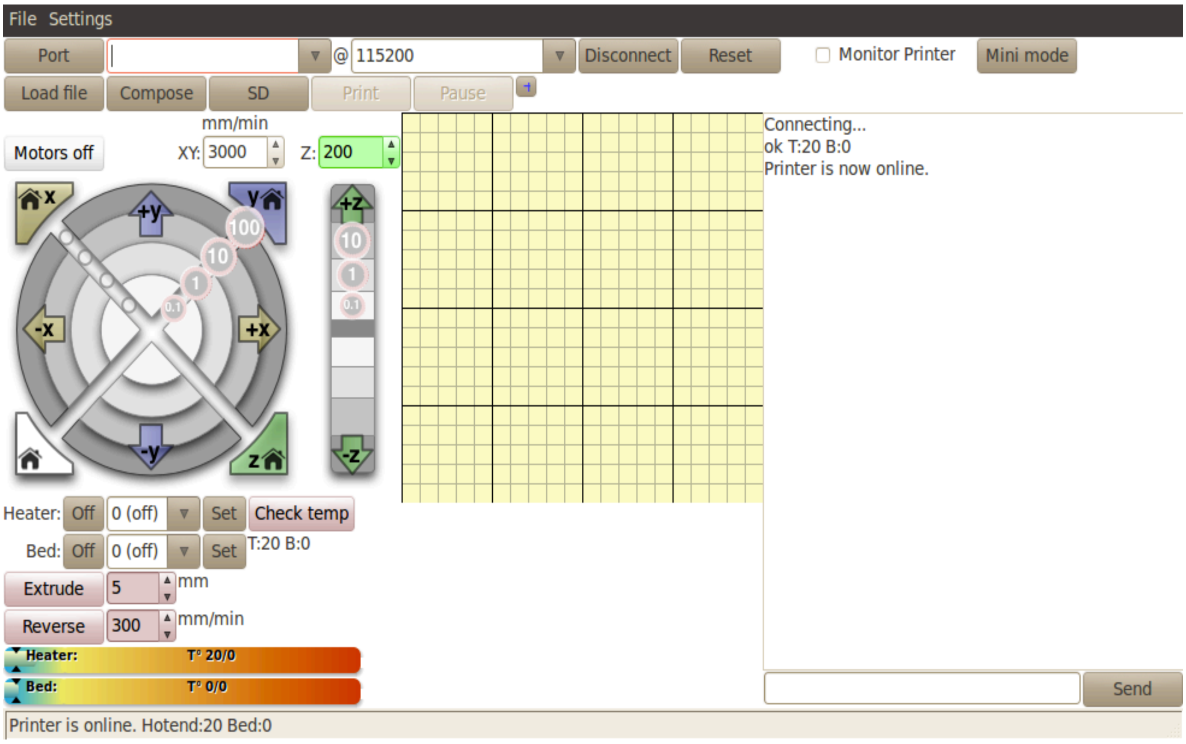


Figure 13: Printrun/Pronterface host Interface

After trying to connect with the two hosts, the Ultimaker printer could only be managed with the host Printrun/Pronterface. When you have selected the correct port and speed (25000), you can start controlling the printer. As you can see, you now have a display with the printing controls, and on the right side it is possible to send G-code to move the printing head. Each section´s functions of the Printrun/Pronterface programme are explained in Figure 14.

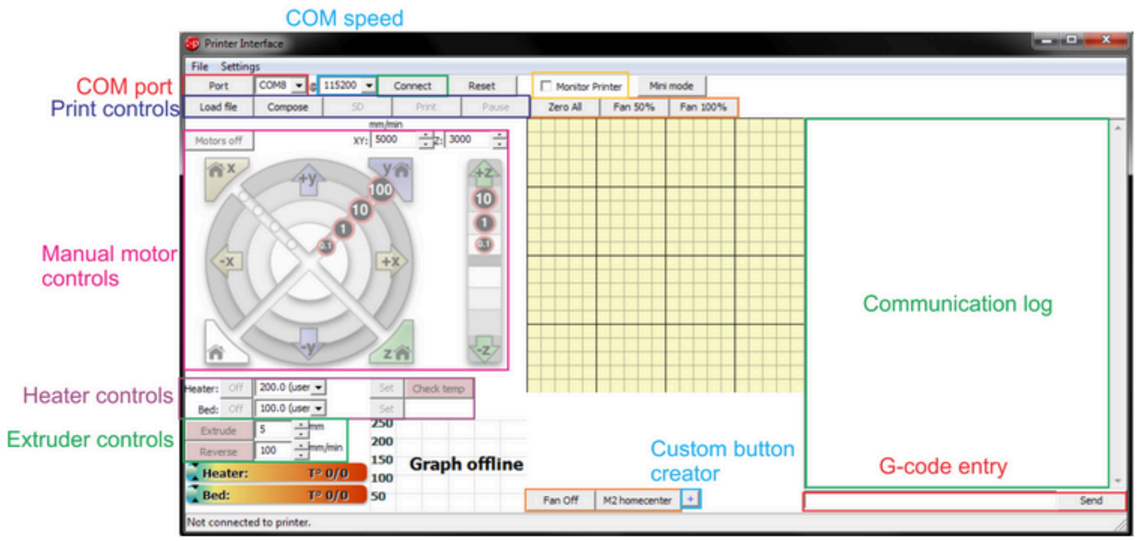


Figure 14: Explanation of the Printrun/Pronterface host interface

3.4- Sending G-code to the printer

You can communicate with the printer using G-code. G-code is the most widely used numerical control programming language. A slicer uses .STL files to create .G-code files. Thus, knowing the basic control of G-code is the next step. Here are the main G-code commands with their functions:

- G0: Rapid linear Move
- G1: Linear Move
- G2: Arc move
- G4: Dwell
- G10: Tool Offset
- G20: Set Units to Inches
- G21: Set Units to Millimeters
- G28: Move to origin (Home)
- G29: Detailed Z-Probe
- G30: Single Z Probe
- G31: Report Current Probe status
- G32: Probe Z and calculate Z plane
- G90: Set to Absolute Positioning
- G91: Set to Relative Positioning
- G92: Set Position

The commands G0 and G1 are used to control the stepper motors which move the printing head in the horizontal plane (axes X and Y) and the build plate in the vertical one (axis Z). The way it has to be written is as follow:

G0 Xnnn Ynnn Znnn Fnnn
G1 Xnnn Ynnn Znnn Fnnn

Xnnn: position to move to on the X axis.
Ynnn: position to move to on the Y axis.
Znnn: position to move to on the Z axis.
Fnnn: the feed rate per minute of the move between the starting point and ending point.

Among all the rest of the commands, those important for our purpose of designing an auto levelling system are the G29 and G32 command. Both commands probe the build plate at a number of selected points. The G32 command is implemented as a more sophisticated form of bed levelling which uses a transformation matrix or motorized correction. That means that the z axis is correcting his position every single moment. For our purpose it is sufficient with the command G29.

3.5- How could the adjustment system be improved?

The goal of this project is to implement automatic calibration and levelling in a way that would be simple to implement and require no special ongoing interaction with the machine itself. After controlling the stepper motors of the printer by sending G-code, the next step can be analyzed. For the creation of an auto build plate levelling, a device able to measure distances with great precision is needed. Thus, a study of the different devices available has to be done.

3.6- Types of proximity sensors

A proximity sensor can detect objects without physical contact. It does this by using electromagnetic fields or radiation. It also detects changes in the field or in the return signal. There are different types of proximity sensors depending on the material which needs to be detected.

- Capacitive sensors

Capacitive sensors can detect and measure materials that are conductive or materials with a high polarizability. The sensor is formed by an oscillator whose capacity is formed by an internal electrode (part of the sensor itself) and an external electrode (constituted by a piece connected to the ground). The external electrode can be realized in two different ways. In some applications, the electrode is the object to be sensed, previously connected to the ground; Then the capacity will vary depending on the distance between the sensor and the object. In contrast, in other applications a fixed mass is placed and then the body that has to be detected is used as dielectric, it is introduced between the mass and the active plate, and thus it modifies the characteristics of the equivalent capacitor.

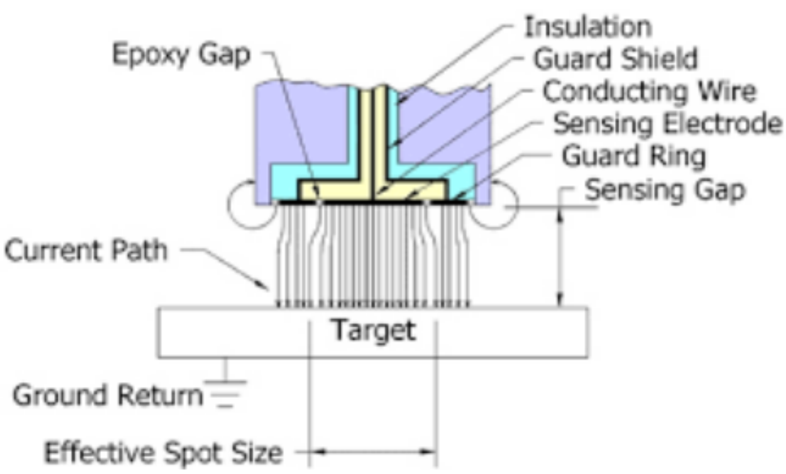


Figure 15: Capacitive sensor components (https://es.wikipedia.org/)

- Inductive sensors

Inductive sensors can only detect metal objects. The sensing distance range of an inductive switch depends on the type of metal being detected. The working principle is a current flowing through a conducting loop generating a magnetic field which is associated with it. When a metal approaches the magnetic field generated by the proximity sensor, it is detected.

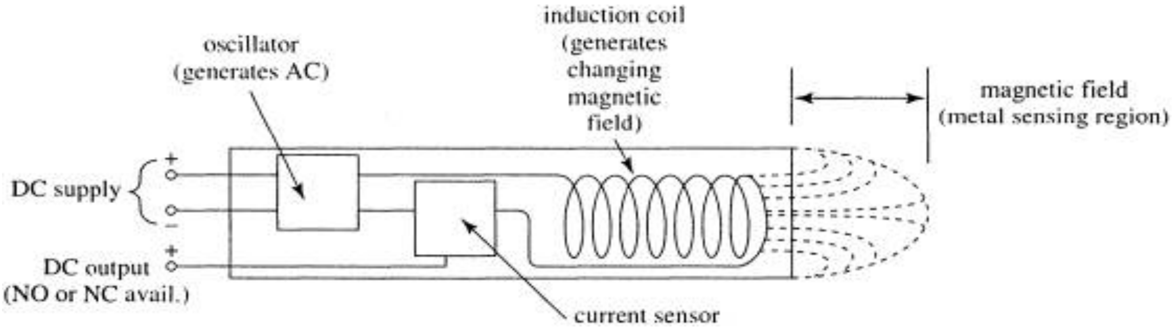


Figure 16: Inductive sensor components (https://es.wikipedia.org/)

- Laser distance sensors

Laser distance sensors work according to the procedure of the time of light reflection. A beam of light is emitted and reflected through an object. It measures the time that the light beam needs to make the path of the unit to the object and the object to the unit. Since the speed of light is constant, the runtime allows you to calculate the distance. There are many types of laser sensors, but the problem is that this technique is not appropriate for high precision sub-millimetre measurements.

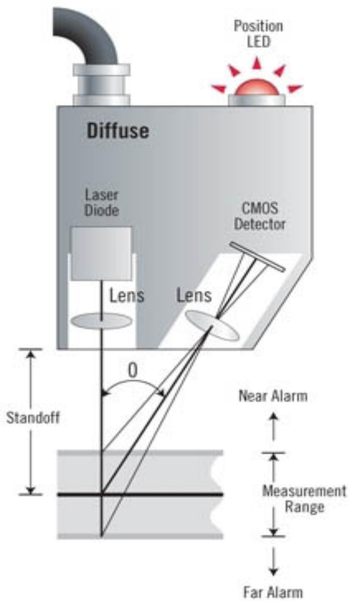


Figure 17: Laser sensor components (https://es.wikipedia.org/)

- Photosensors or photodetectors

A photodetector is a sensor that generates an electrical signal dependent on light or another electromagnetic radiation. These sensors require an emitter component that generates light, and a receiver component. The efficiency of a photodiode is related to its responsiveness, that is, the amount of electrons it is able to generate in relation to the received photons. In other words, it is the electric current delivered to the output in relation to the optical input power.

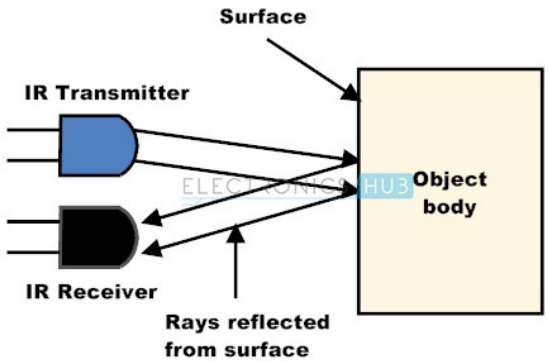


Figure 18: Photodetector sensor components (https://es.wikipedia.org/)

3.8- Decision of the sensor

The first idea was to use an inductive sensor because it is cheap, small in size and accurate enough. However, this type of sensor needs a metal surface to detect it and the current base is made of glass. After consultation, it was decided not to remove the glass build plate. So, another alternative was found. This alternative is to use a micro switch.

Mechanical switches are preferred because they are cheaper, easier to install, work just as well as proximity sensors and have high durability. Switching happens reliably at specific and repeatable positions of the actuator.

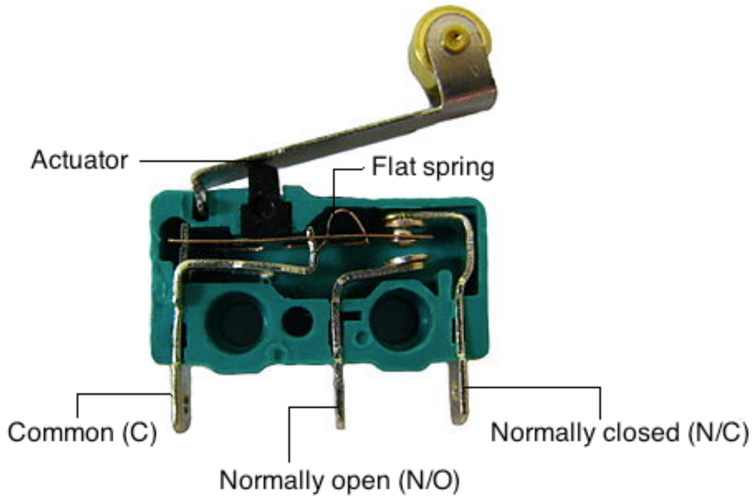


Figure 19: Micro switch components (https://es.wikipedia.org/)

The working principle of a micro switch is easy to understand. A micro switch changes the direction of the power when the actuator is pressed. It uses a spring-loaded lever to open and close connections inside it. The spring makes it possible to change the direction of power quickly. The micro switch has three connections points. The first one is called ¨C¨ for common, the second one ¨N/O¨ for normally open and the third one ¨N/C¨ for normally closed.

In the first moment the micro switch 250 Vac 10 A was chosen which is available in the Conrad online shop: *http://www.conrad.com/ce/en/product/704558/Microswitch*.

Figure 20: Micro switch 250 Vac 10 A ((www.conrad.de)

3.9- Designing the micro switch support

The idea is to put the micro switch on the bottom of the support and the protruding part in the gap between the two metal plates of the printing head. The printing head of the Ultimaker 2 extended + printer is shown in the next picture:

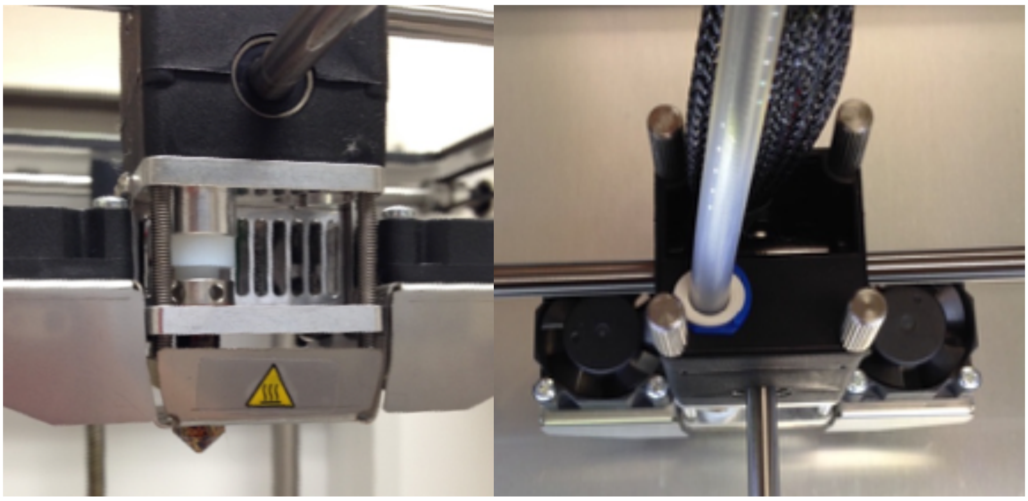


Figure 21: Ultimaker 2 Extended + printing head

Figure 22 shows the mounting of the support in the printing head:

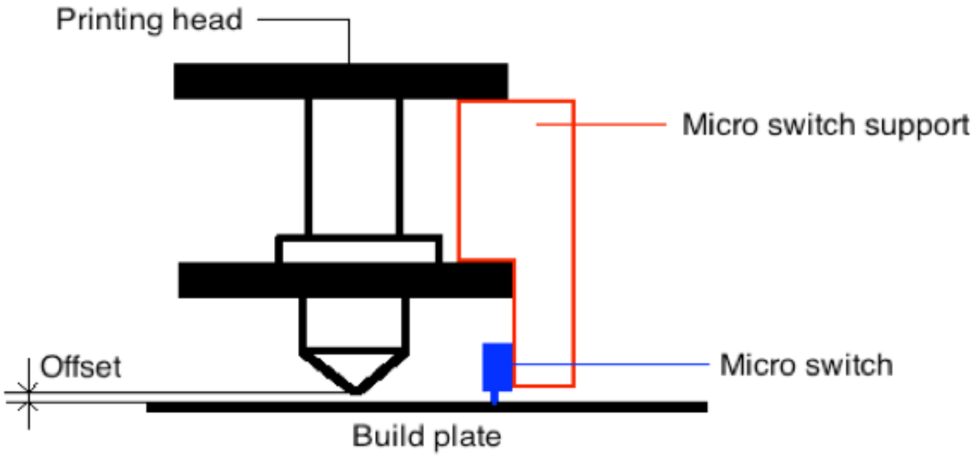


Figure 22: Diagram of the mounting support in the printing head

The two metal plates of the printing head, which can be moved up and down using four screws located on the top of the printing head, press the support and prevent it from moving. In this way the support is perfectly secured. The micro switch is located at the bottom of the support. This is secured by placing two screws through the two holes in the micro switch.

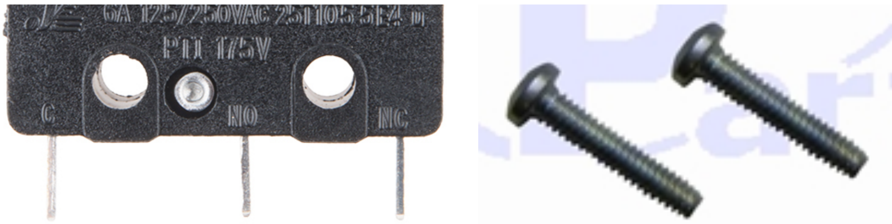


Figure 23: Micro switch 250 Vac 10 A and its head screws M3.2x15 *(*www.conrad.de)

An Arduino starter kit was ordered; this Arduino starter kit contained the Arduino Mega 2560 Rev3 which is a microcontroller board based on the ATmega2560, the same one that the Ultimaker 2 uses.

After ordering an Arduino starter kit to do the right tests, a new kind of tiny six millimeter micro switch was contained in this kit so finally that one was used to do the auto levelling system. Thus, the only thing that needed to be changed is the way to secure the micro switch to the support. These new micro switch specifications are as follows on the next page.

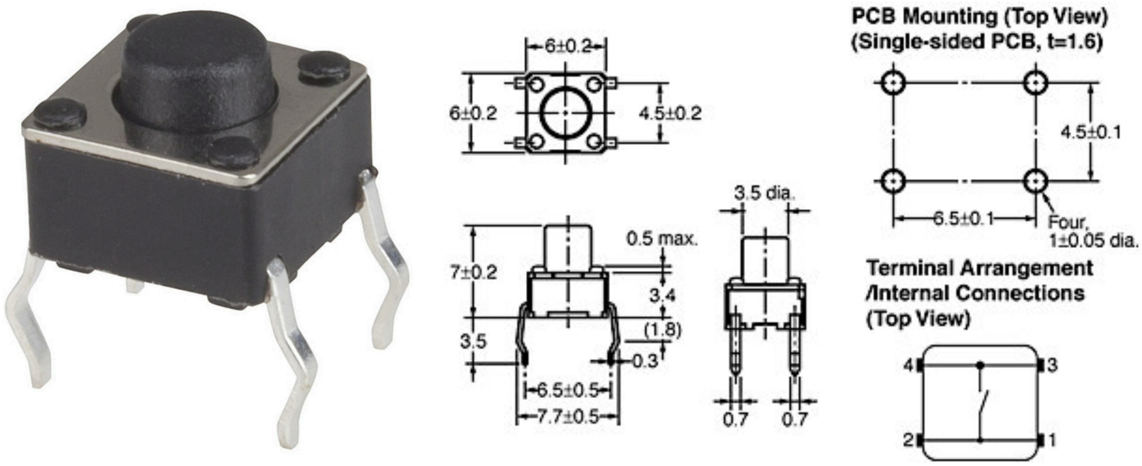


Figure 24: Micro switch dimensions (http://www.kr4.us)

Therefore this micro switch is secured by four small holes in the support where the pins of the micro switch are located. The diameter of the holes of the support is a few microns smaller, this way the pins of the micro switch enter under pressure preventing them from moving.

After carefully measuring the vertical length that is needed for the correct offset of 0,1 millimetres between the build plate and the end of nozzle, the final design for the new micro switch was the next step. Printing the support in PLA plastic material with the 3D printer was considered, taking into account the difference in the support dimensions between the design by Computer Aided Design (CAD) and the final result due to the contraction of the PLA plastic material once cooled. In addition, trying several support designs looking for the best properties such as small size, ease of coupling the micro switch and its connections as well as ease of grip to place it between the two metal plates, the final design has the following shape:

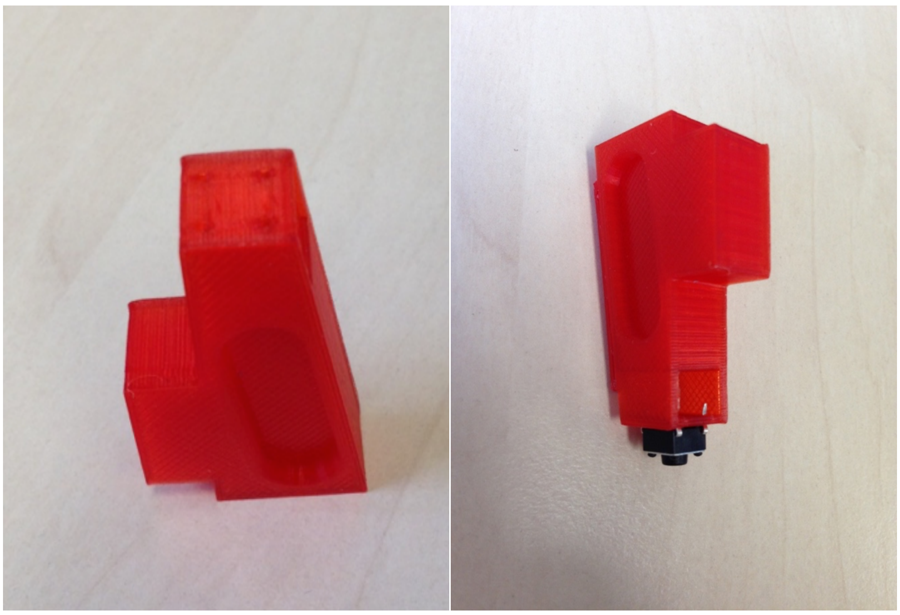


Figure 25: PLA printed support and the PLA printed support with the micro switch attached

In Figures 26 and 27 the PLA printed support attached in to the printing head of the 3D printer can be seen:

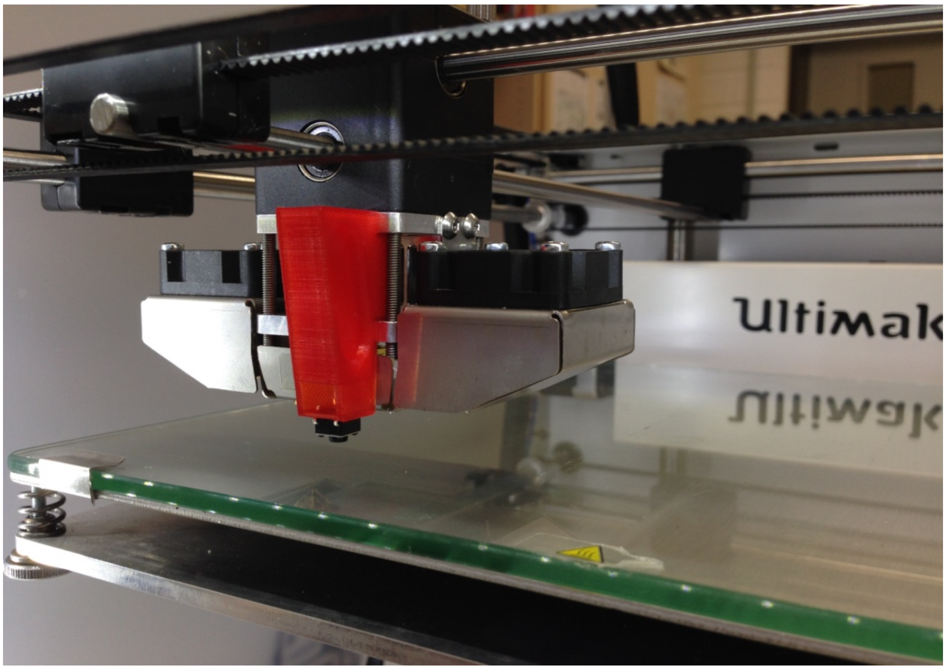


Figure 26: PLA printed support attached in the printing head view I

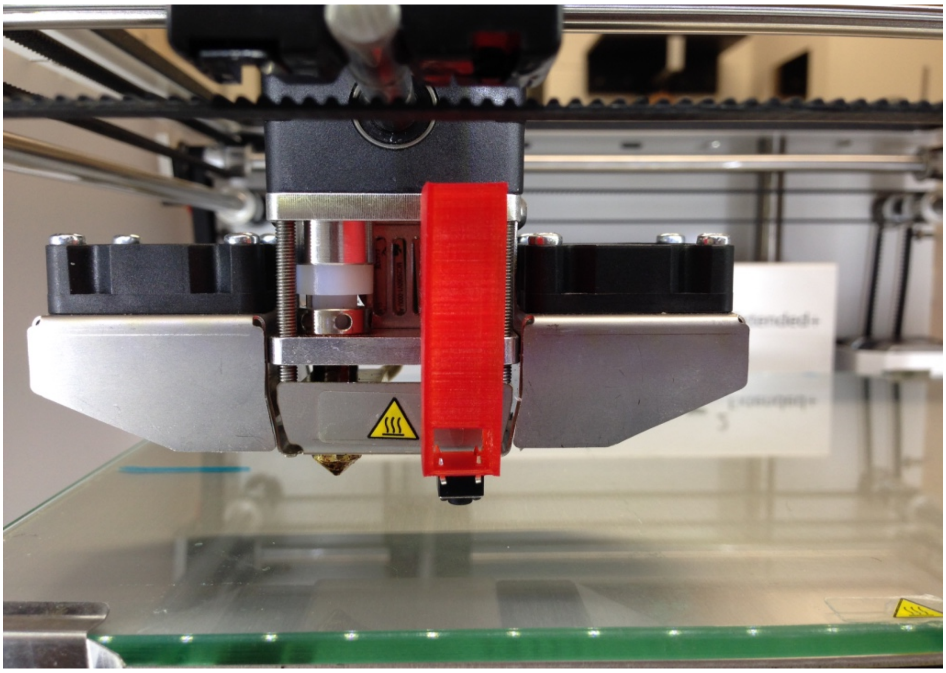


Figure 27: PLA printed support attached in the printing head view II

3.10- Actions that must be carried out when auto levelling is activated

By pressing one button the printer should start to raise the build plate quickly until it is about twenty millimeters from the end of the nozzle, the same that happens when the previous semi-manual levelling is run. After this, the build plate should go up as slowly as possible and with each step of the servomotor it should check if the switch has been pressed. If it has not been pressed the built plate raises another minimum unit of distance, until the switch is pressed at a distance of 0.1 millimeters. This distance is saved as z=0 position to start the printing. It is important to point out that the build plate is checked just in one point, so the others screws should stay fixed.

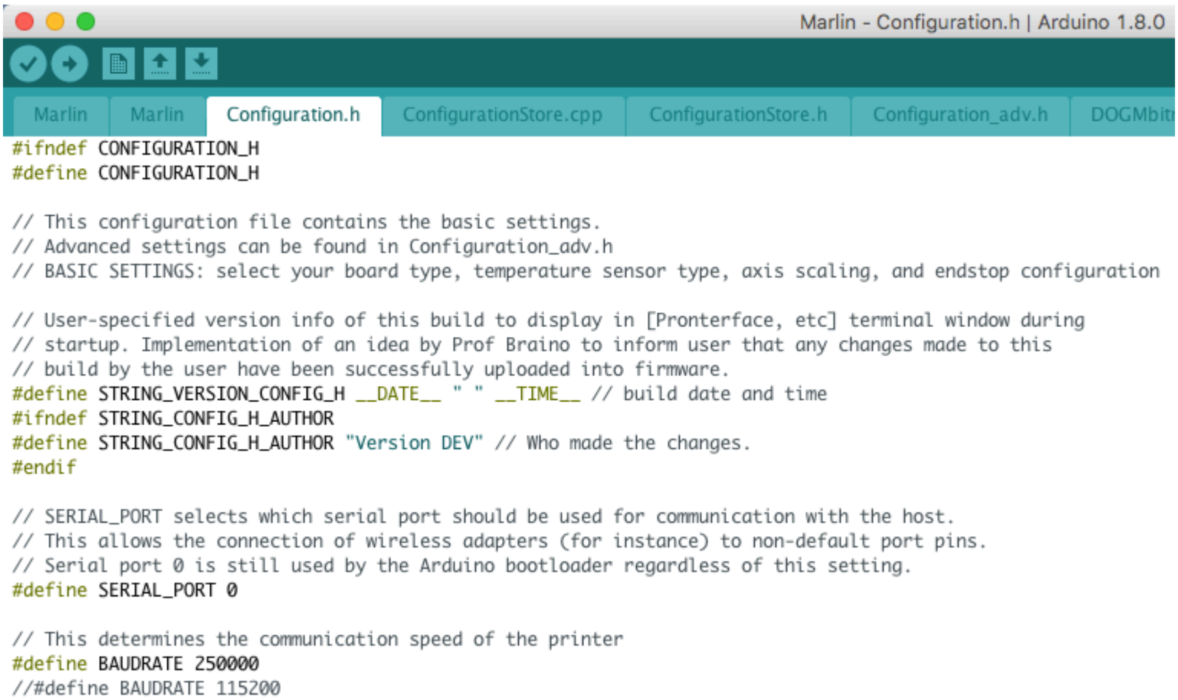
Two different options exist to achieve this task. The first one consists of directly implementing the auto levelling system in the motherboard of the Ultimaker 2, so that the motherboard receives the signal from the micro switch. The second option consists of connecting the Ultimaker 2 to a Raspberry Pi via serial USB cable, and the Raspberry Pi to the micro switch. This way the Raspberry Pi is the one which receives the signal from the micro switch and processes it. Then the Raspberry Pi instructs the motherboard of the Ultimaker 2 how to work.

3.11- Implementing the auto levelling system in the motherboard

This is the most reasonable and simple option because no external device, such as a Raspberry Pi, is needed. The micro switch signal is sent directly to the controller or motherboard, eliminating communications between the Ultimaker 3D printer and the Raspberry Pi.

3.11.1- Firmware (Marlin) of the Ultimaker motherboard

The next step is to get the open source firmware which works in the motherboard. It is possible to find it on the next website: *https://github.com/Ultimaker/Ultimaker2Marlin*. Thus, it can be downloaded. The archive finished in '.ino' must be opened with the Arduino program that it is easy to find on the Internet.




```
#ifndef CONFIGURATION_H
#define CONFIGURATION_H

// This configuration file contains the basic settings.
// Advanced settings can be found in Configuration_adv.h
// BASIC SETTINGS: select your board type, temperature sensor type, axis scaling, and endstop configuration

// User-specified version info of this build to display in [Pronterface, etc] terminal window during
// startup. Implementation of an idea by Prof Braino to inform user that any changes made to this
// build by the user have been successfully uploaded into firmware.
#define STRING_VERSION_CONFIG_H __DATE__ " " __TIME__ // build date and time
#ifndef STRING_CONFIG_H_AUTHOR
#define STRING_CONFIG_H_AUTHOR "Version DEV" // Who made the changes.
#endif

// SERIAL_PORT selects which serial port should be used for communication with the host.
// This allows the connection of wireless adapters (for instance) to non-default port pins.
// Serial port 0 is still used by the Arduino bootloader regardless of this setting.
#define SERIAL_PORT 0

// This determines the communication speed of the printer
#define BAUDRATE 250000
//#define BAUDRATE 115200
```

Figure 28: Marlin firmware of the Ultimaker 2 Extended + motherboard

It is necessary to modify the ¨Configuration.h¨ section in the firmware of the Ultimaker 2 extended +. The firmware modification needed is the end stop in Z axis with the G-code command G29. The auto levelling system will be replacing the 3D printer z end stop on the control board. The old z stop is not needed because the micro switch will be probing the bed for its z position.

This code needs to be copied in the G29 command section:

// coarse Endstop Settings
#define ENDSTOPPULLUPS // Comment this out (using // at the start of the line) to disable the endstop pullup resistors

#ifndef ENDSTOPPULLUPS
// fine Enstop settings: Individual Pullups. will be ignored if ENDSTOPPULLUPS is defined
#define ENDSTOPPULLUP_XMAX
#define ENDSTOPPULLUP_YMAX
#define ENDSTOPPULLUP_ZMAX
#define ENDSTOPPULLUP_XMIN
#define ENDSTOPPULLUP_YMIN
//#define ENDSTOPPULLUP_ZMIN
#endif

```
#ifdef ENDSTOPPULLUPS
  #define ENDSTOPPULLUP_XMAX
  #define ENDSTOPPULLUP_YMAX
  #define ENDSTOPPULLUP_ZMAX
  #define ENDSTOPPULLUP_XMIN
  #define ENDSTOPPULLUP_YMIN
  #define ENDSTOPPULLUP_ZMIN
#endif

const bool X_ENDSTOPS_INVERTING = true; // set to true to invert the logic of the endstops.
const bool Y_ENDSTOPS_INVERTING = true; // set to true to invert the logic of the endstops.
const bool Z_ENDSTOPS_INVERTING = true; // set to true to invert the logic of the endstops.
//#define DISABLE_MAX_ENDSTOPS
//#define DISABLE_MIN_ENDSTOPS
```

3.11.2- Electrical connections required

The microcontroller that the Ultimaker 2 Extended + uses is Atmel Mega2560-based, using the same family of Allegro drivers as most other controllers for small 3D printers.

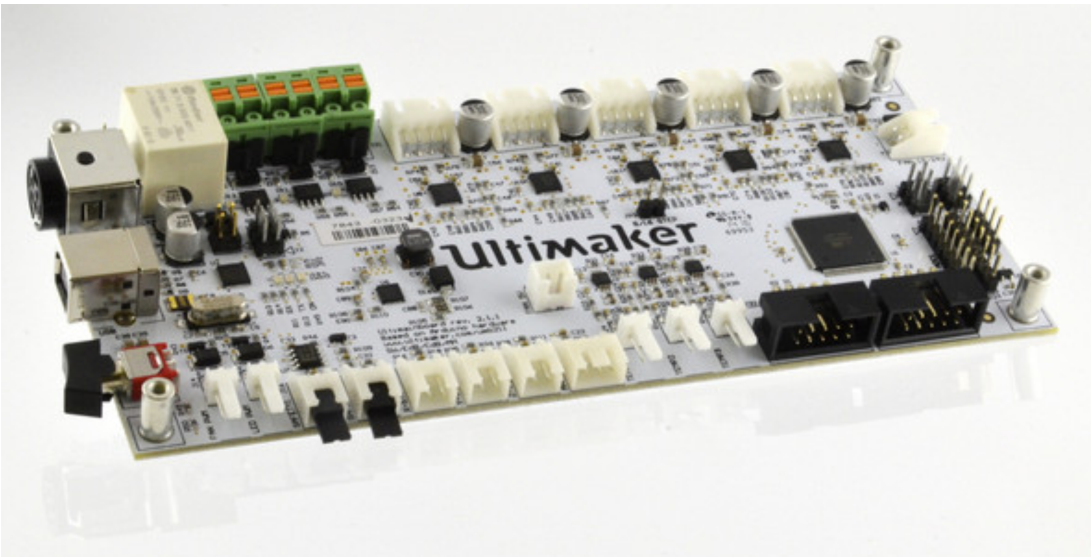


Figure 29: Ultimaker 2 Extended + motherboard (https://ultimaker.com)

The micro switch has to be connected to the motherboard of the Ultimaker 2 extended +. Thus, the 5V power pin from the board has to be connected to the common (C) point of the micro switch. This energizes the spring inside the micro switch. The normally open port (N/O) has to be connected to a pull up and then to the end stop pin of the motherboard of the Ultimaker 2 printer. In this way the motherboard receives the signal from the micro switch when the actuator is pressed, and if the actuator is not pressed, the spring inside the micro switch is touching the normally closed pin so no signal is sent.

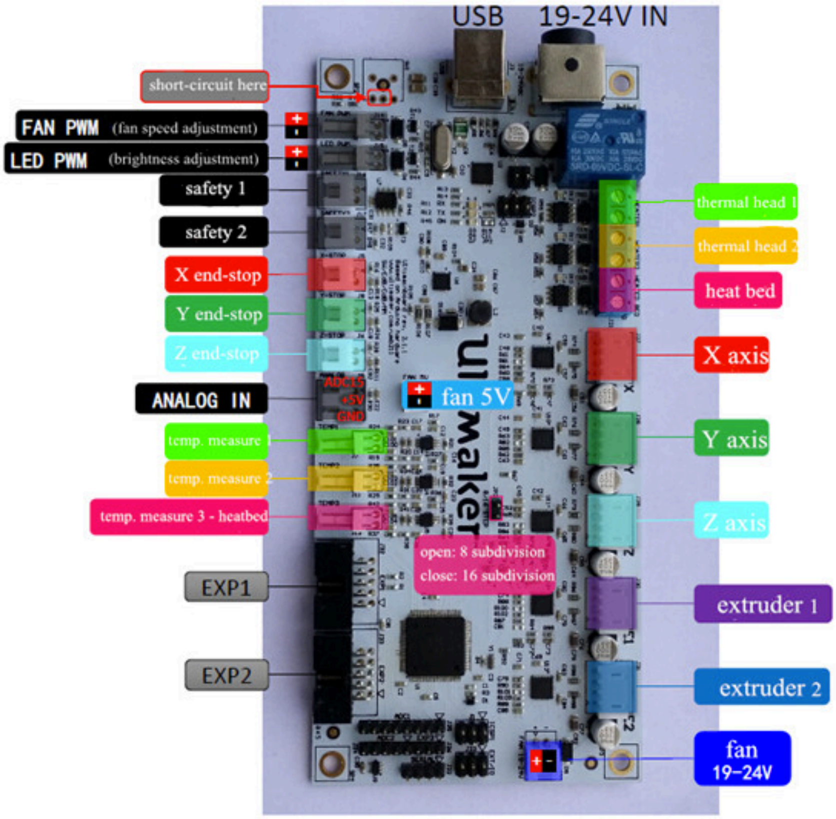


Figure 30: components of the Ultimaker 2 Extended + motherboard (https://ultimaker.com)

The pull ups are needed when a micro switch is connected directly between the signal and ground pins. Using pull ups the floating effect is avoided. The floating effect happens when the electrical circuit is not electrically connected to the ground (Earth). Without such a connection, voltages and current flows are induced by electromagnetic fields. To prevent this unknown state, a pull-up or pull-down resistor will ensure that the pin is in either a high or low state.

The next step is the value of the resistor that is needed. This value needs to be chosen to satisfy two conditions:

1. When the button is not pressed, the input pin is pulled low. The value of the pull-up resistor controls the voltage on the input pin.

2. When the button is pressed, the input pin is pulled high. The value of resistor R1 controls how much current you want to flow from VCC, through the button, and then to the input pin.

If the bed levelling option in the display (meaning the G29 command) is not activated, then the 3D printer behaves exactly like before the changes in the firmware were made.

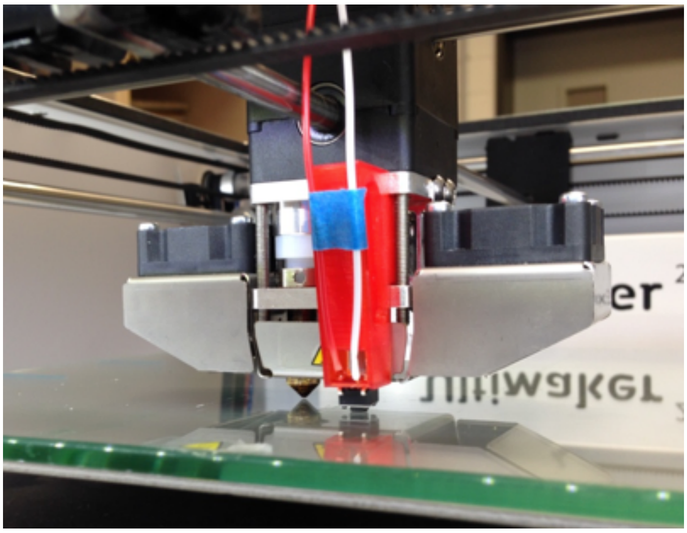


Figure 31: Final auto levelling system view I

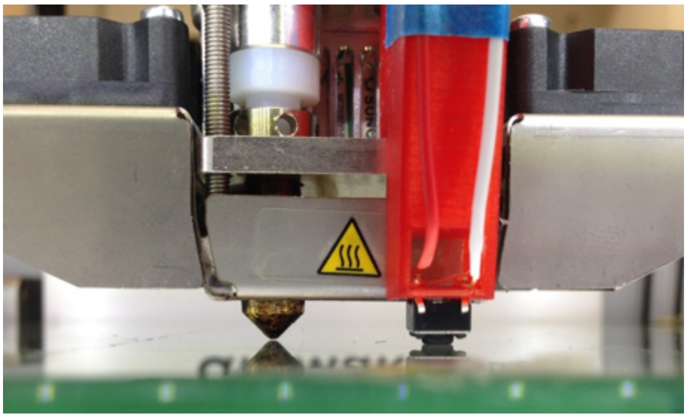


Figure 32: Final auto levelling system view II

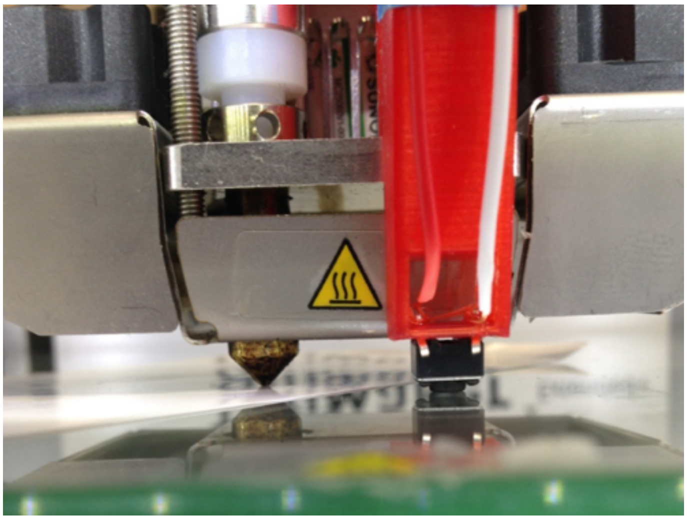


Figure 33: Final auto levelling system view III

10.12- Auto levelling using a Raspberry Pi

As mentioned before this is the more complicated option. The Raspberry Pi has to receive the micro switch signal, process this information and send it to the controller or motherboard. The printer is connected to the Raspberry Pi via USB. This option has not been carried out until the end. Here are shown some of the first steps that must be taken to install an auto levelling system using a Raspberry Pi.

10.12.1- Components and programs needed

In this section everything necessary to carry out the auto levelling system using a Raspberry Pi is listed.

Components needed:

- Starter set Raspberry Pi 2 (*http://www.elv.de/raspberry-pi-2-b-starter-set.html*) which includes: an SD card with pre-installed Noobs software (10 class and 8GB), a power supply, an HDMI cable as well as a mini WLAN stick.

- Micro switch 250 Vac 10 A (*http://www.conrad.com/ce/en/product/704558/Microswitch)*

Figure 34: Raspberry P 2 (https://www.raspberrypi.org)

Figure 35: Micro switch *(*www.conrad.de)

Programs needed:

- Latest version of Octoprint
- Putty
- SD formatter
- Apple-pi-baker or Win32

10.12.2- Set up Octoprint

Firstly, Octoprint programme has to be set up in the Raspberry Pi. OctoPrint is a snappy web interface for your 3D printer that allows the control and monitor of all aspects of the printer and print jobs. Octoprint is a free and open source software released under the Affero General Public License (AGPL). In addition, OctoPrint's powerful plugin system allows the extension of its functionality. It allows the creation of a plugin with the code programme for the auto levelling purpose.

Steps to follow to set up Octoprint on Rasberry Pi:

1- Download and install the Octoprint image on the Raspberry Pi.

2- Once the image is loaded on the SD card, it is now possible to insert it into the Raspberry Pi, connect it to a TV and with a USB keyboard and network cable (for the initial configuration) and turn it on.

3- The first settings are made following the instructions that will appear.

4- Type the IP address of the Raspberry into the browser (It will appear in the lines of text when starting the Raspberry).If all is well, when loading the page for the first time, the access control options for the Octoprint application will appear.

5- In this window, a username and password for access have to be chosen, which are not the same as the access to the Raspberry.

6- Turn it off and on again, access the Octoprint environment, and connect to the 3D printer to get started.

7- Log in, select connection port and speed (250000 by default in Marlin).

10.12.3- Read the micro switch signal

The micro switch has to be connected to the GPIO (General Purpose Input/Output) pins of the Raspberry Pi.

To control the GPIO pins of the Raspberry Pi:

1- Connect to the Raspberry either through the TV or through a terminal.
2- Type the following commands to install the wiringPi library:
- sudo apt-get install git-core
- sudo apt-get update
- sudo apt-get upgrade
- git clone git://git.drogon.net/wiringPi
- cd wiringPi
- git pull origin
- ./build

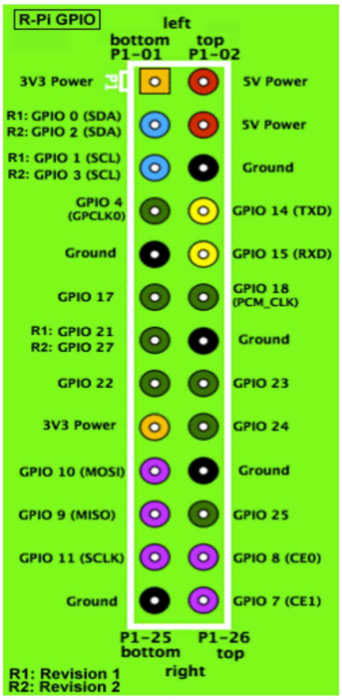


Figure 36: GPIO pins of the Raspberry Pi (https://www.raspberrypi.org)

NOTE:

- The GPIO output voltage of the Raspberry PI board is 3.3V.

3.13- Conclusions

After analyzing the crucial distance between the nozzle and the build plate and analyzing the current adjustment process, an auto levelling system was created. Two different solution to implement the auto levelling system were proposed. Implementing the auto levelling system in the motherboard directly was simpler than implementing the auto levelling system using a Raspberry Pi 2. This system avoids spending time calibrating by manually calibrating the build plate each time the printer needs to be used.

4- The speed of the printing process and the resulting quality

The parameters of layer thickness, nozzle diameter and printing head speed all influence the build time, material usage, strength, and surface roughness of the piece which is printed. All these parameters have the greatest impact on the surface quality of FDM-built parts. This study has been conducted to determine the optimum value for these parameters of the Ultimaker 2 extended + 3D printer. The focus is on the final result of the piece printed. This means choosing the values for these parameters that will improve the final result of the pieces printed while using the least amount of printing time possible. Thus, surface roughness is the main characteristic to analyze.

Moreover, if it was necessary to evaluate the piece interior structure, it would be a very complicated task. One alternative could be to use Metrotom. Metrotom uses Computer Tomography (CT) which could be a potential solution. CT technology allows non-destructive testing of damage and porosity analysis, material inspection, defect checks, etc. This technology offers an excellent tool for the evaluation of the structure of FDM prototypes.

Focusing on the final result of the pieces printed the main influential factors that affect it are analyzed.

4.1- Influential factors

Analyzing the parameters that influence the final result of a piece printed by FDM is an ambitious task. These parameters are layer thickness, diameter of the nozzle, printing head speed, extruder temperature and bed heated temperature, infill pattern, build orientation, room temperature, humidity and more. After discussing the number of possible experiments to be performed according to the time limit for this thesis, it was decided to focus on three of them. These controllable parameters are layer thickness, printing head speed and extruder temperature.

4.1.1- Layer thickness

The layer thickness refers to the height of each layer of our printed piece. Basically the layer thickness is the z axis resolution. Less layer thickness means more quality but also more layers have to be deposited which requires more time.

Three different layer thicknesses are analyzed in this thesis:

- 0,10 mm
- 0,20 mm
- 0,30 mm

4.1.2- Printing head speed

A printing head speed is a parameter which defines the quality of the piece and the time that the printer spends printing it. As soon as the printing speed is changed, (or any other print setting) Cura recalculates the duration of the print.

For this experiment the following printing head speeds were chosen:

- 20mm/s
- 50mm/s
- 80mm/s

4.1.3- Extruder temperature

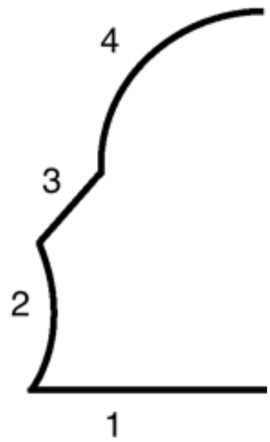
The correct extruder temperature is a crucial parameter for a successful print. Depending on the kind of plastic used, a different temperature is necessary to melt it. The temperature is also a key determining factor for the correct union of the new layer with the previous one or with the build base.

The extruder temperatures analyzed in this thesis are the lowest and highest temperatures recommended by the manufacturer:

- 190 ºC
- 210 ºC

4.2- Designing the pieces to study

Another element of this study was the design of the pieces. The design of the pieces had to be a small enough size to not take a long time to print. The shape of the designed piece needed to be chosen carefully, as it needed to be an external shape where the different combinations of the parameter could be appreciated. A revolution piece in combination with different external shapes was chosen. The following is a description of the piece´s profile.



The profile of the piece that was designed is divided into four zones. Zone One is the base of the piece. This zone is flat in order to improve its adherence to the build plate of the 3D printer. As this zone is quite large, the piece has good adherence to the build plate. Zone Two is an interior arch where the printer has to print first with a positive angle and then with a negative angle in relation to the vertical axis. No support material is used for this zone. After this, Zone Three starts. This is an inclined plane of an angle of 45° relative to the horizontal axis. This is the zone where the roughness tester is applied. Finally, Zone Four on the top of the piece is an exterior arc that forms a hemisphere when the profile is revolutionized.

Figure 37: Test piece shape

Figure 38: Test piece number one

4.3- How to quantify the final results

After designing and printing the pieces for this study, a method to quantify the final results of these pieces have to be carried out. Two ways were used to analyze the final results.

4.3.1- Non-specialized inspection equipment

In engineering the primary and most important test technique is the visual inspection. Over time this has proven to be the most effective technique of all. Therefore, visual inspection is the first method of quality control that was applied to the pieces that were printed. In this case visual inspection means the inspection of the pieces using human senses such as vision and touch.

4.3.2- Specialized inspection equipment

As visual inspection was limited in measuring surface roughness when there were tiny changes between the different pieces in this study, a roughness tester was the perfect tool to compare the final result of the pieces. Thus for measuring the surface roughness of the pieces, the Hommel Tester T500 device was applied. The roughness parameters are approved under DIN/ISO/JIS standards and the calibrated measuring elements make the Hommel Tester T500 a suitable roughness measurement device for this purpose. In the next table the technical specifications of the Hommel Tester T500 are shown.

Figure 39: Hommel Tester T500

HOMMEL TESTER T500 – Technical specifications

HOMMEL TESTER T500	
Surface evaluation parameters	Ra, Rz, DIN, Rmax as per DIN 4768 and ISO 4287/1 Ra, Rz, ISO, Rt as per ISO 4287/1 Ra, Rz, JIS, Rmax JIS as per Japanese standard JIS B601 Pc as per Euro standard 49 ANSI/ASME B 46.1 OPTION : Rpk*, Rk, Rvk, Rvk*, Mr1, Mr2 as per DIN 4776/ISO 13565 * Option applicable for devices without Datasave function.
Tolerance display for Ra, Rz, Rmax or Rt	
Cut-off lengths λc	λc (mm) 0,25 0,8 2,5
Scanning distances as per DIN 4768 and ISO 4287/1	lt (mm) 1,5 4,8 15,0
Individual measurement distances lr	1-5 selectable
Scanning speed Vt	Vt (mm/s) 0,15 0,5 1,0
The 0.25 mm and 0.8 mm cut-offs can be freely assigned to any scanning distance.	
Digital filter	Profile filter M1 phase corrector as per DIN 4777/ISO 11562
Measurement range	MR Measurement travel Resolution 1 +20/- 20µm 10 nm +20/- 60µm 20 nm 2 +40/- 40µm 20 nm +40/- 120µm 40 nm
Precision category	Class 1 as per DIN 4772
Smallest display value	0,01 µm
Probe position indicator	bar indicator and numerical value
Measurement system	µm and µinch
Interface	Standard V24 (RS232), serial
Power supply	9 V replaceable battery with plug-in mains adapter
Measurement capacity	approx. 80 measurements at lt = 4,8 mm (per battery charge)
Dimensions (length x width x height)	118 mm x 56 mm x 62 mm
Weight	330 g

Table 1: Hommel Tester T500 technical specifications (documents.tips)

Figure 40: Measuring using the Hommel Tester T500

4.4- Study the pieces printed

All pieces were printed in red transparent PLA filament which has a diameter of 2,85 millimetres and this filament is manufactured by ColorFabb company. As previously selected, the parameters for this study are the following:

Layer thickness
0,1mm
0,2mm
0,3mm

Printing speed
20mm/s
50mm/s
80mm/s

Extruder temperatures
190 ºC
210 ºC

Table 2: The different parameters analyzed in this thesis

The remaining variable parameters not studied here were kept constant. Some of these parameters are 15% of the fill density, with a shell thickness of 0,8 millimeters, the standard 0,4 millimeter nozzle diameter and no type of support structure build.

Thus eighteen different pieces were printed applying these combinations of parameters. Firstly, the layer thickness and the printing speed were chosen in the basic and advance parameters of Cura. Then Cura automatically calculated the printing time and the material it would consume. It is important to note that usually the printing time that Cura calculates is not the real time of the printing process. It tends to be more optimistic, but it can serve as a guide. The extruder temperature was selected directly in the Ultimaker 2 extended + 3D printer when it was getting ready before starting the printing process. Finally the surface roughness was measured with the HOMMEL TESTER T500 device. The arithmetic average of the roughness profile (R_a) and the maximum roughness depth (R_{max}) was taken as representative roughness parameters.

All this is shown in the Table 3:

Nº of test piece	Layer thickness (mm)	Printing speed (mm/s)	Extruder temperatures (ºC)	Printing time (mins)	Material consumed (gr)	Average roughness R_a (µm)	Maximum roughness depth R_{max} (µm)
1	0.1	20	190	479	27	9,78	39,80
2	0.1	50	190	222	27	10,21	47,04
3	0.1	80	190	174	27	12,11	57,17
4	0.1	20	210	479	27	9,52	40,32
5	0.1	50	210	222	27	10,38	48,64
6	0.1	80	210	174	27	11,76	56,63
7	0.2	20	190	239	27	11,78	48,35
8	0.2	50	190	114	27	13,25	51,37
9	0.2	80	190	87	27	13,45	59,98
10	0.2	20	210	239	27	12,10	49,40
11	0.2	50	210	114	27	12,70	49,80
12	0.2	80	210	87	27	13,18	58,86
13	0.3	20	190	179	27	15,88	60,32
14	0.3	50	190	93	27	18,78	65,02
15	0.3	80	190	75	27	N/A	N/A
16	0.3	20	210	179	27	16,08	59,22
17	0.3	50	210	93	27	18,60	66,56
18	0.3	80	210	75	27	19,96	71,14

Table 3: Results obtained from the eighteen test pieces printed

The arithmetic average of the roughness profile (R_a) and the maximum roughness depth (R_{max}) both give a good general description of the height gradient in the surface.

The data for the arithmetic average of the roughness profile (R_a) and the maximum roughness depth (R_{max}) in the fifteenth piece are not available due to the 3D printer trying to print at 9,6 cubic millimetres of filament per second. When the volume of material is more than 8 cubic millimetres it causes slipping and gaps inside the pieces. Thus, it is not possible to print with these parameters. In spite of this, these parameters were tried with an unsuccessful result.

4.5- Analysis of results

In this section the pieces of the experiment are analyzed first visually and after with the measurements of the specialized inspection equipment.

When analyzing the results by visual inspection, in which the pieces are observed in detail, it is possible to recognize the different layer thicknesses used for the same printing speed and extruder temperature. The stair stepping effect is easily recognizable in the hemisphere zone of the pieces. On a vertical surface this effect is barely noticed since the layers are stacked on top of each other. As the angle increases the effect will become more and more pronounced. This can be appreciated in Figure 41 where on the left side there is a 0,3 millimetre layer thickness printed piece and on the right side a 0,1 millimetre layer thickness printed piece.

Figure 41: Test piece number thirteen (right) and one (left)

As it can be seen, the thinner layers are able to represent the true shape in a better way. Also notice how much worse the top of the object looks compared to the lower layers. As the angle increases related to the vertical axis the rings will become more noticeable.

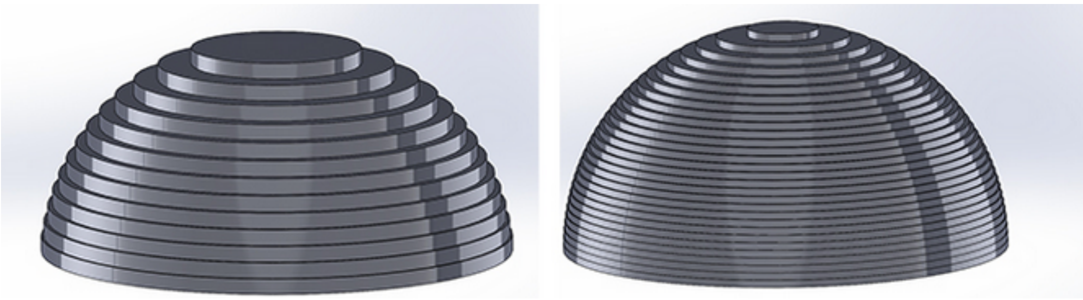


Figure 42: Stair stepping effect in the hemisphere zone (http://support.3dverkstan.se)

When the printing speed parameter is analyzed for the same extruder temperature and layer thickness, the difference between 20 mm/s and 50 mm/s of printing speeds can not be noticed by visual inspection. This is because with a 0,4 mm nozzle diameter the quality is practically the same at these speeds. If the 0,25 mm nozzle diameter had been used the difference would be considerable. However the difference between 50 mm/s and 80 mm/s of printing speeds is slightly noticeable. Nevertheless these slight changes are impossible to notice in pictures.

When the extruder temperatures are analyzed, the difference between 190 ºC and 210 ºC of extruder temperatures can not be noticed by visual inspection. Both pieces are indistinguishable.

As follows, the relations between the different parameters are analyzed by the following figures.

The variation of the printing time related to the layer thickness does not depend on the extruder temperature. This variation for each different printing speed is presented in Figures 43 to 45.

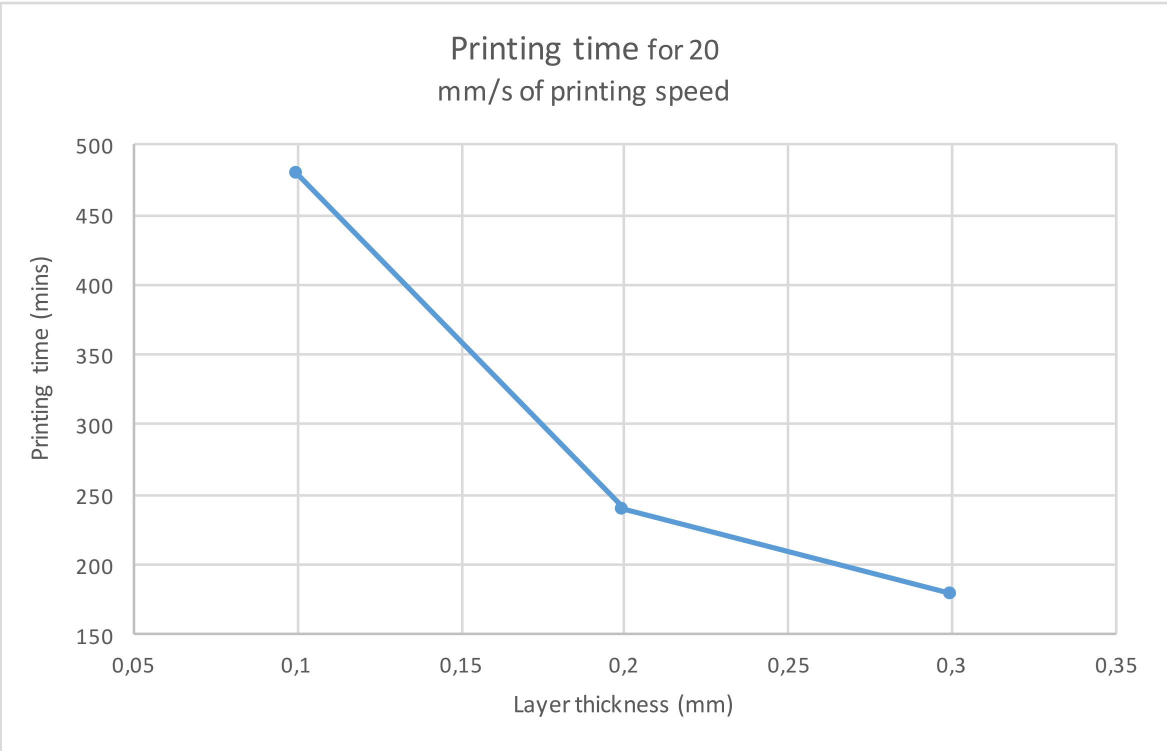


Figure 43: Printing time related to the layer thickness when it is printed at 20 mm/s

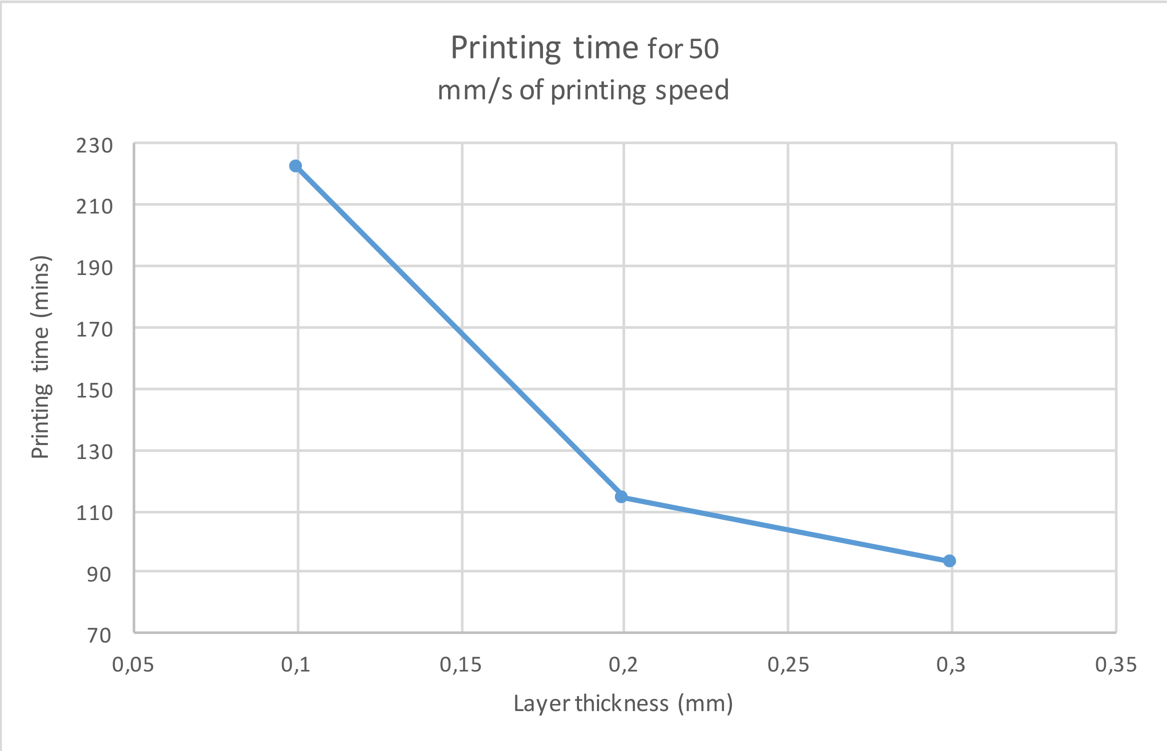


Figure 44: Printing time related to the layer thickness when it is printed at 50 mm/s

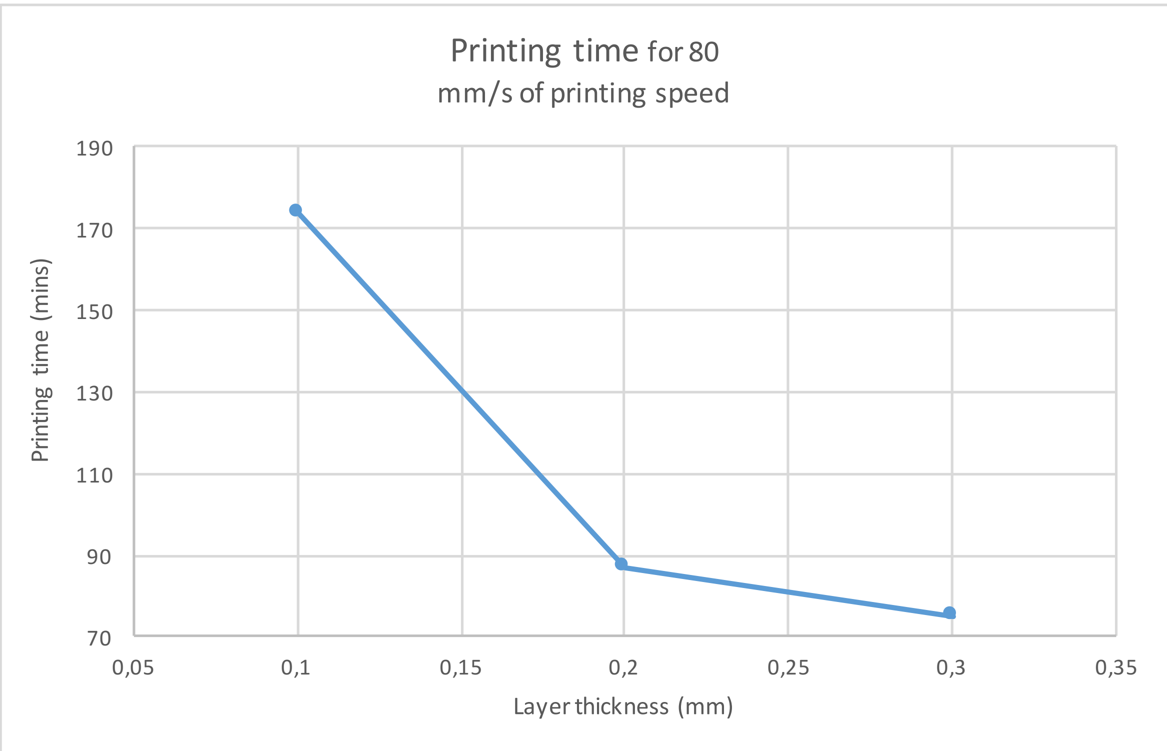


Figure 45: Printing time related to the layer thickness when it is printed at 80 mm/s

As Cura indicated, the material consumed is the same in all of the pieces. Then, it can be affirmed that the material consumed is independent of the parameters studied here.

The variation of average roughness R_a related to the layer thickness for 190 ºC of extruder temperature is presented in Figures 46 to 48.

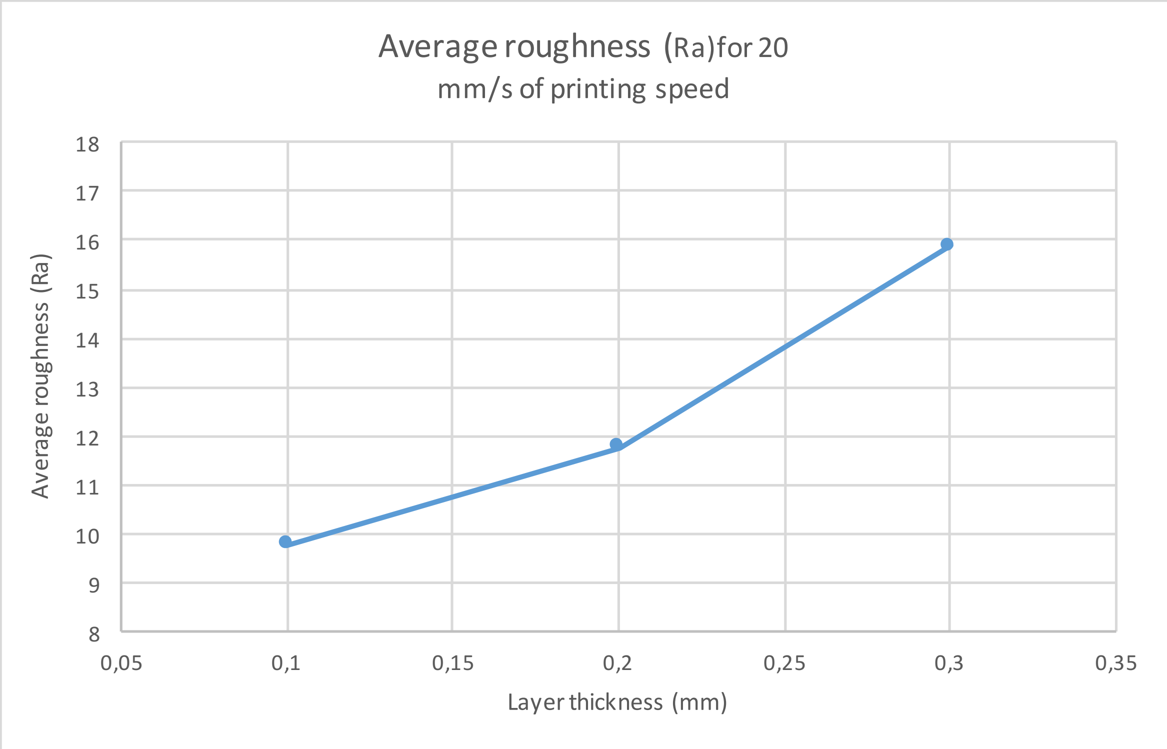


Figure 46: Average roughness R_a related to the layer thickness when it is printed at 190 ºC of extruder temperature and 20 mm/s of printing speed

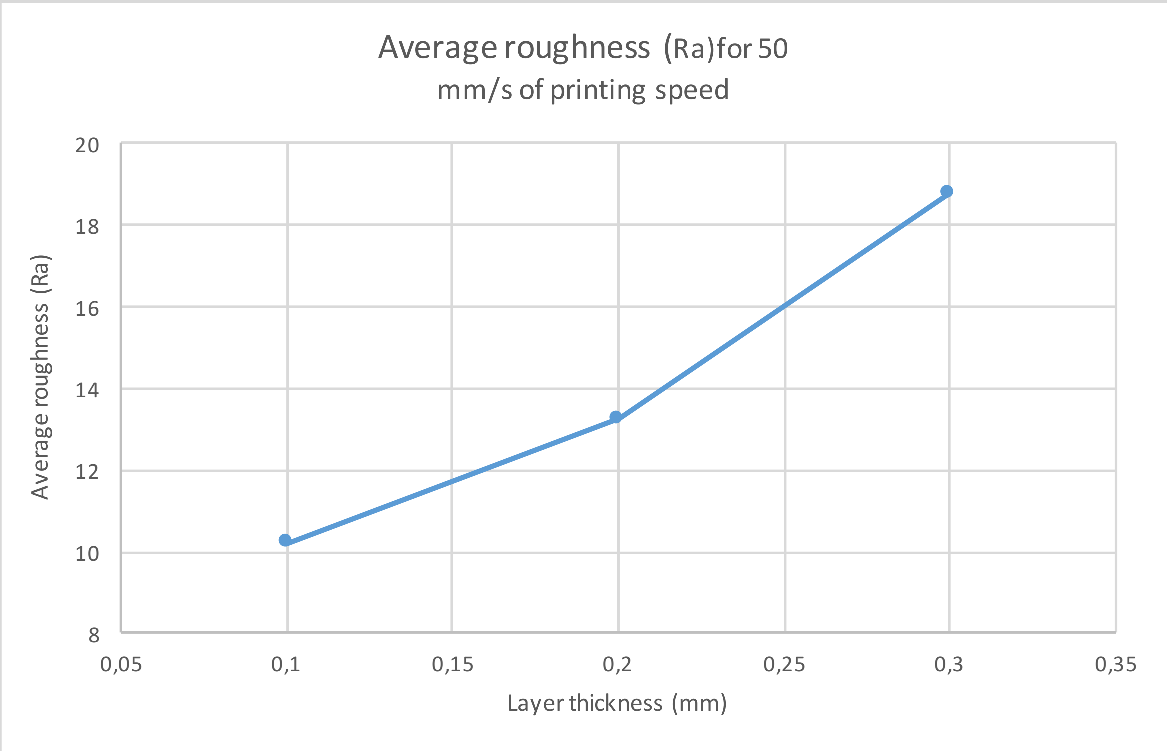


Figure 47: Average roughness R_a related to the layer thickness when it is printed at 190 ºC of extruder temperature and 50 mm/s of printing speed

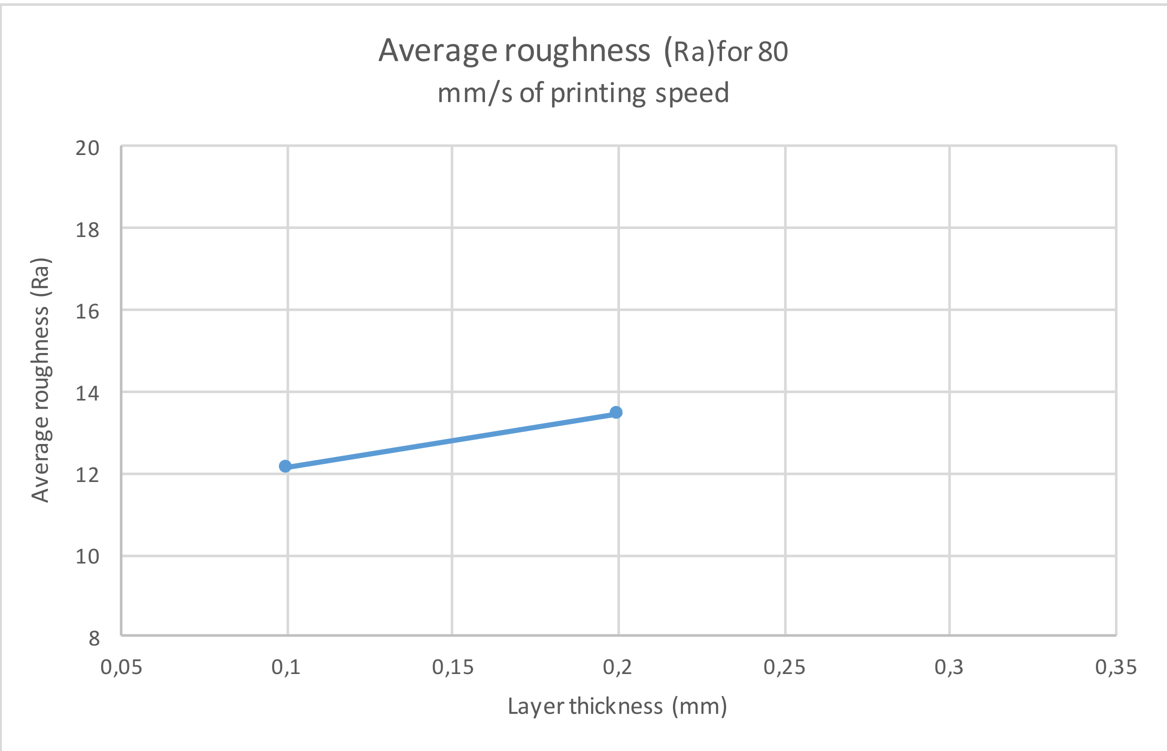


Figure 48: Average roughness R_a related to the layer thickness when it is printed at 190 ºC of extruder temperature and 80 mm/s of printing speed

The variation of average roughness R_a related to the layer thickness for 210 ºC of extruder temperature is presented in Figures 49 to 51.

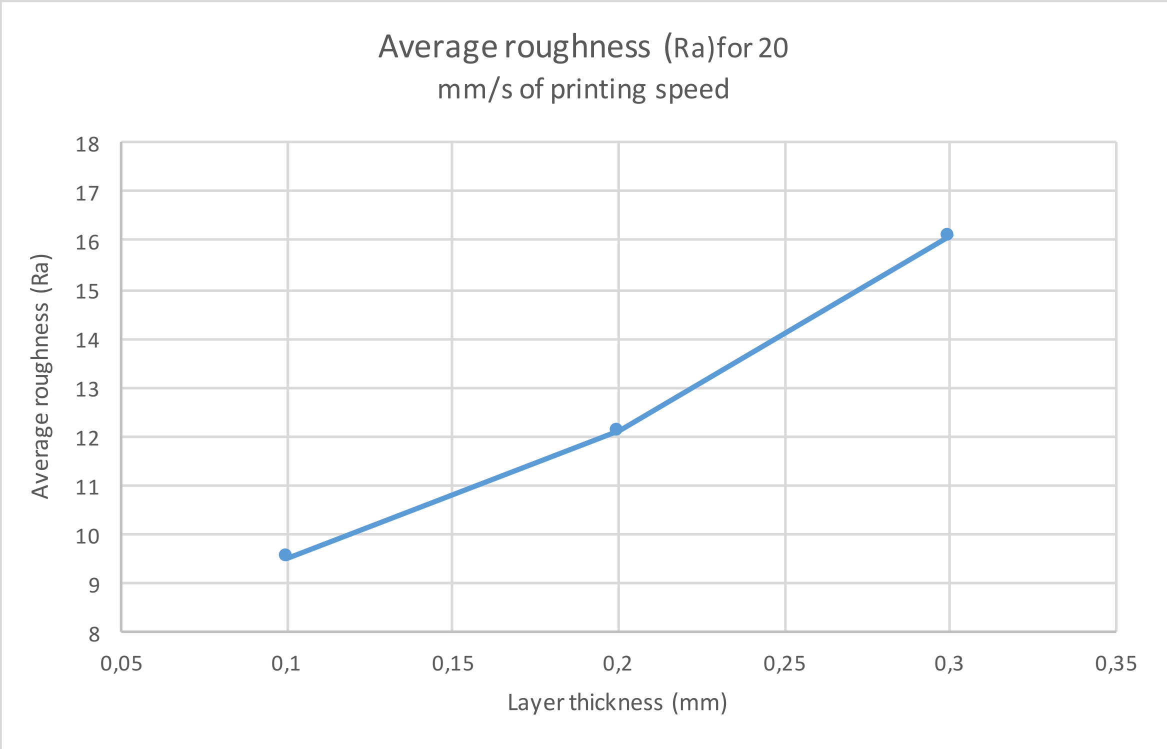


Figure 49: Average roughness R_a related to the layer thickness when it is printed at 210 ºC of extruder temperature and 20 mm/s of printing speed

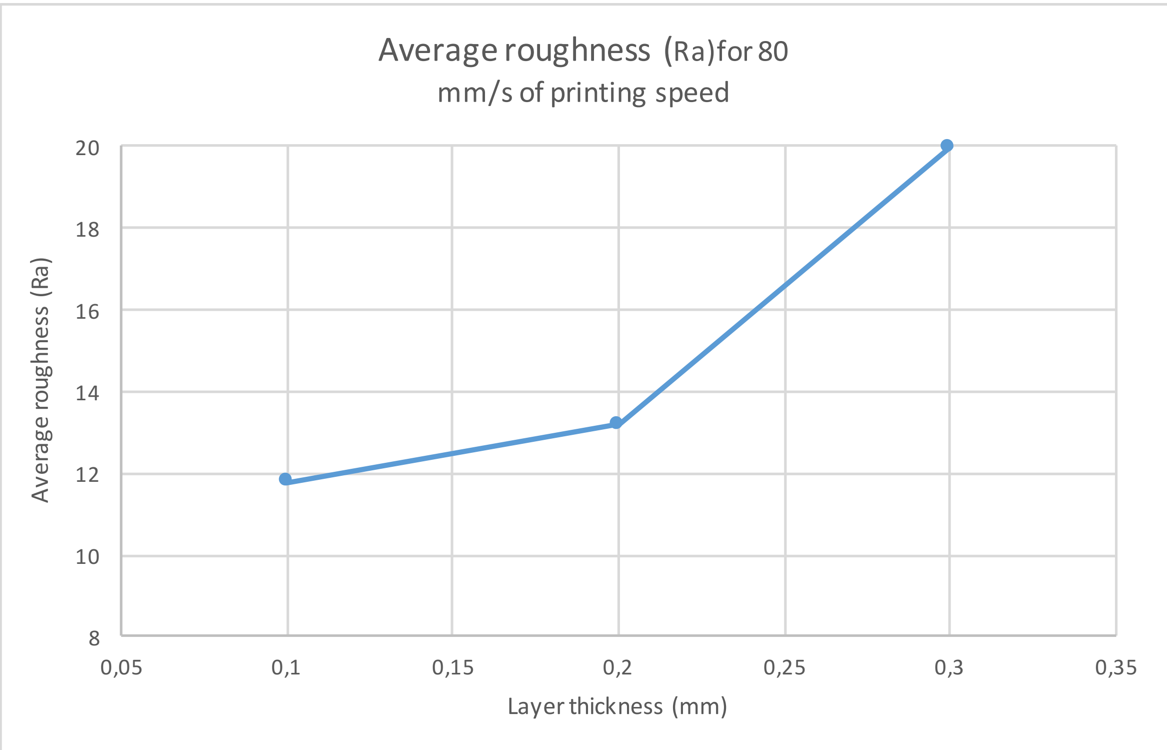


Figure 50: Average roughness R_a related to the layer thickness when it is printed at 210 ºC of extruder temperature and 50 mm/s of printing speed

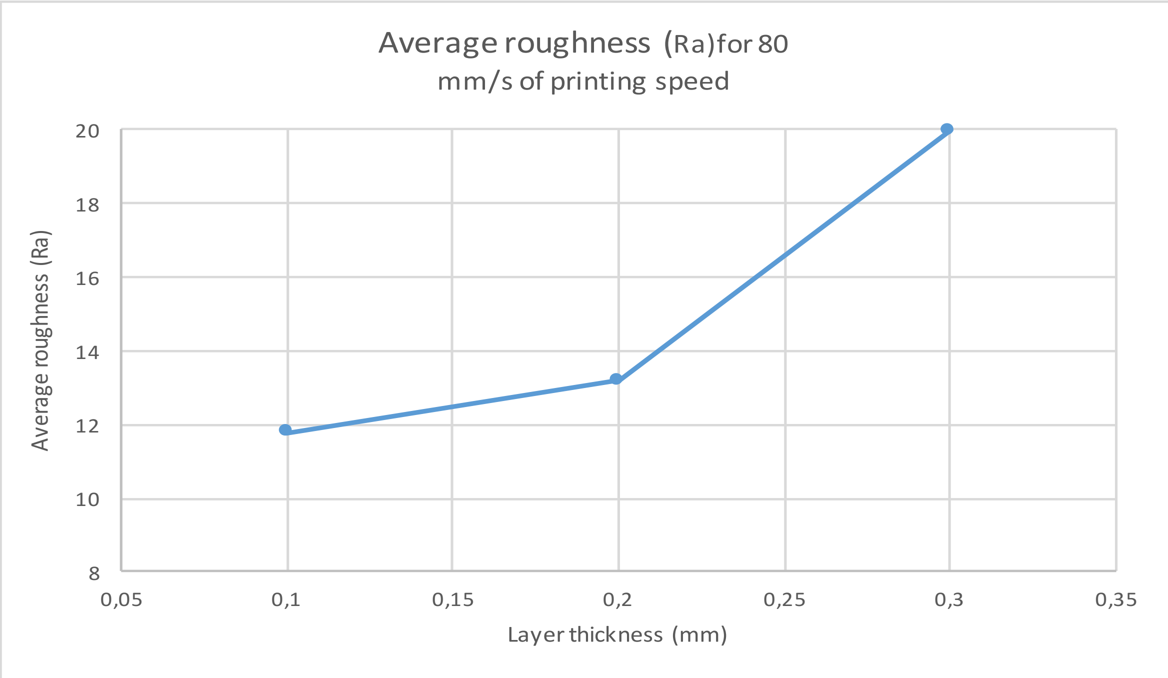


Figure 51: Average roughness R_a related to the layer thickness when it is printed at 210 ºC of extruder temperature and 80 mm/s of printing speed

The maximum roughness depth R_{max} related to the layer thickness for 190 ºC of extruder temperature is presented in Figures 52 to 54.

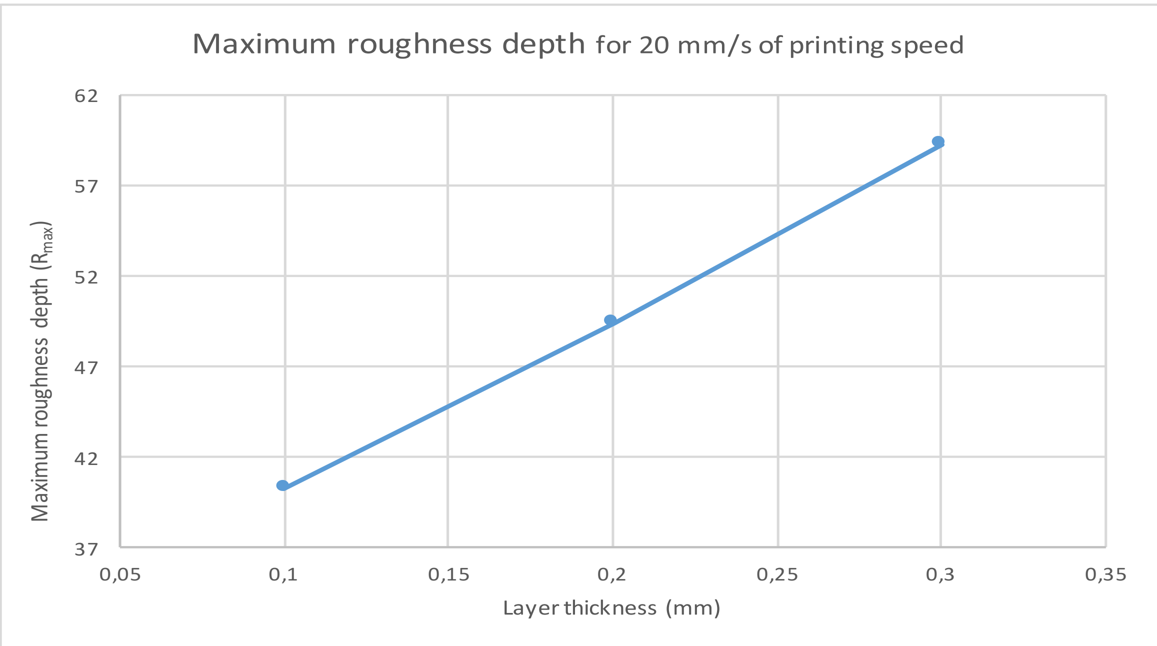


Figure 52: The maximum roughness depth R_{max} related to the layer thickness when it is printed at 190 ºC of extruder temperature and 20 mm/s of printing speed

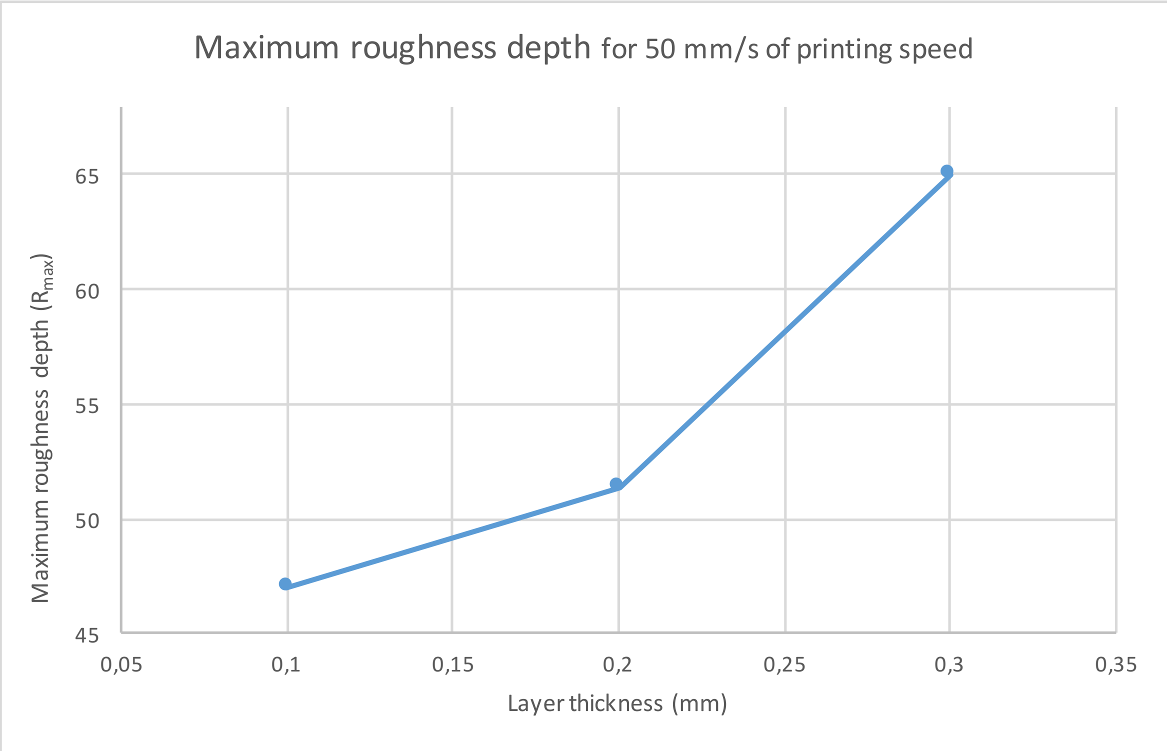


Figure 53: The maximum roughness depth R_{max} related to the layer thickness when it is printed at 190 ºC of extruder temperature and 50 mm/s of printing speed.

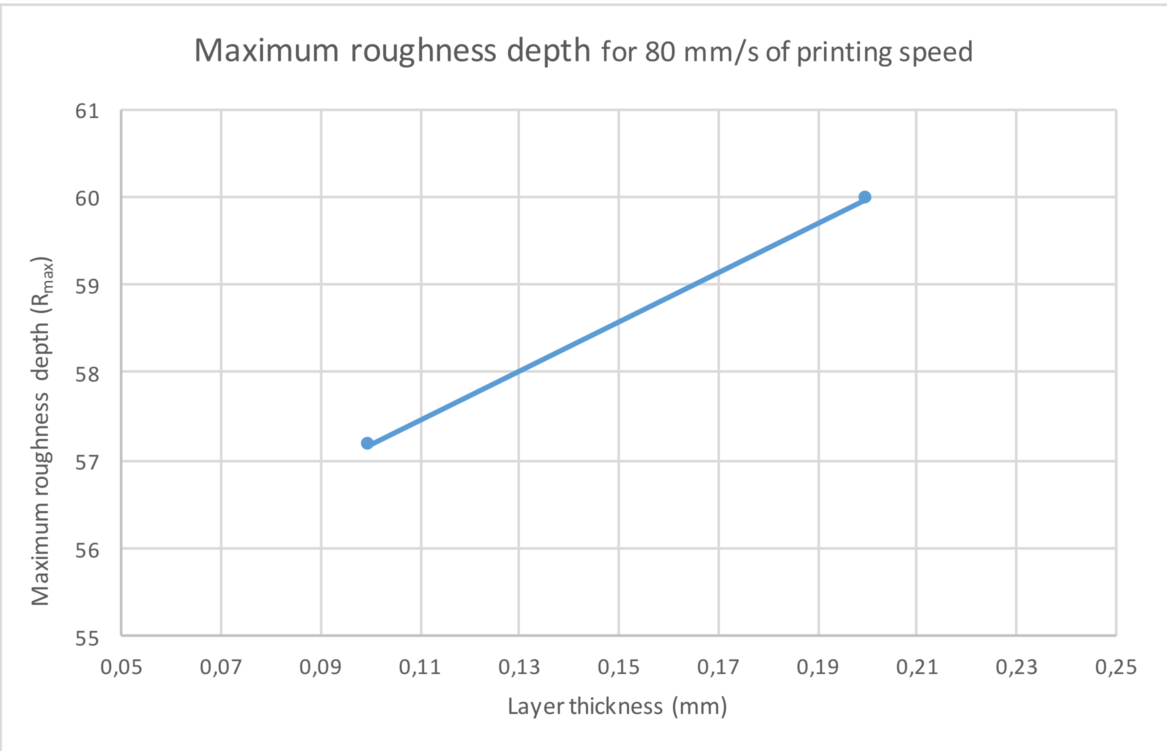


Figure 54: The maximum roughness depth R_{max} related to the layer thickness when it is printed at 190 ºC of extruder temperature and 80 mm/s of printing speed.

The maximum roughness depth R_{max} related to the layer thickness for 210 ºC of extrude temperature is presented in Figures 55 to 57.

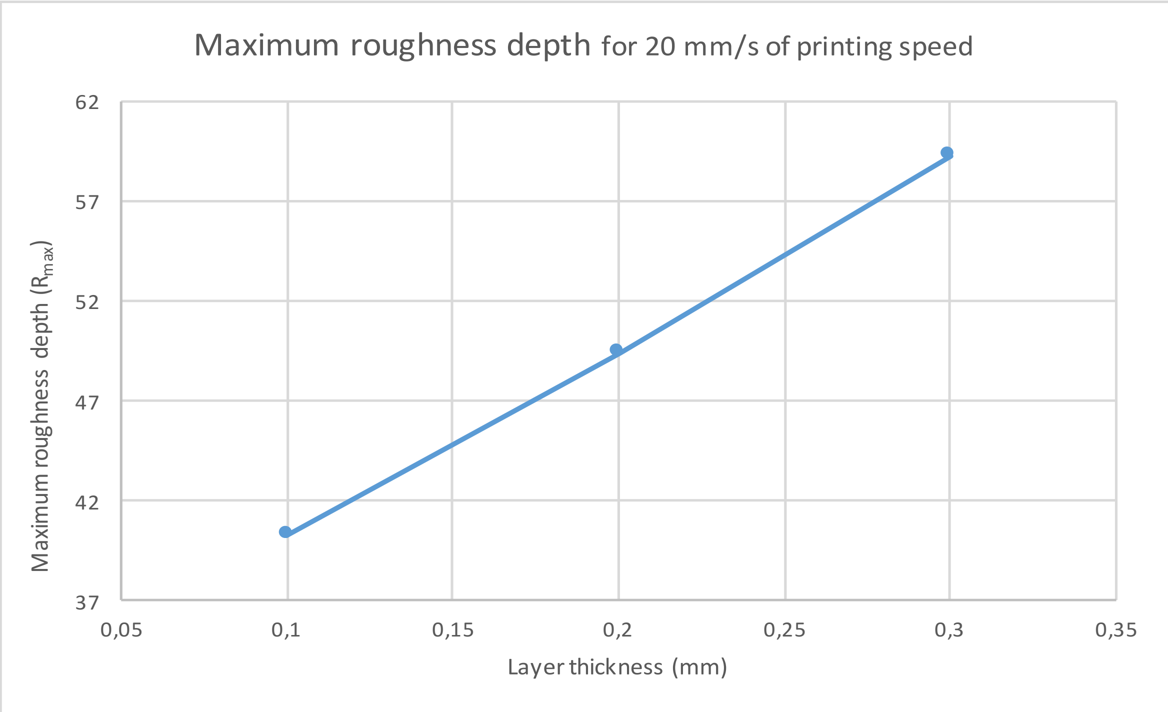


Figure 55: The maximum roughness depth R_{max} related to the layer thickness when it is printed at 210 ºC of extruder temperature and 20 mm/s of printing speed.

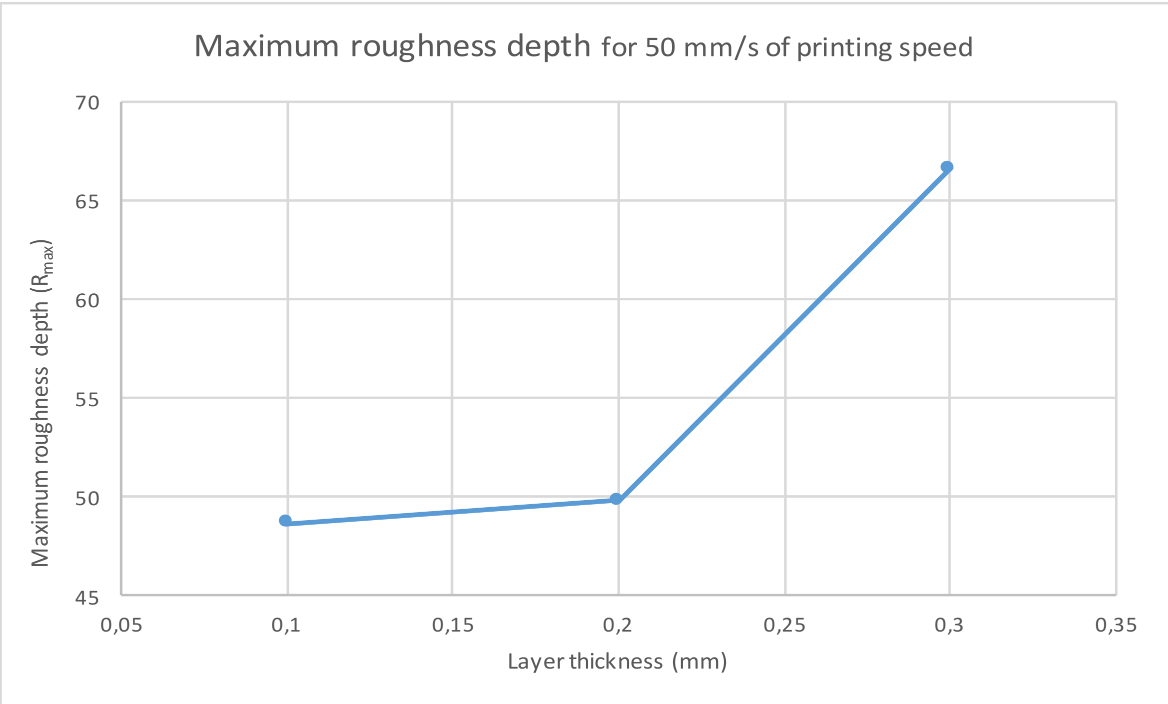


Figure 56: The maximum roughness depth R_{max} related to the layer thickness when it is printed at 210 ºC of extruder temperature and 50 mm/s of printing speed.

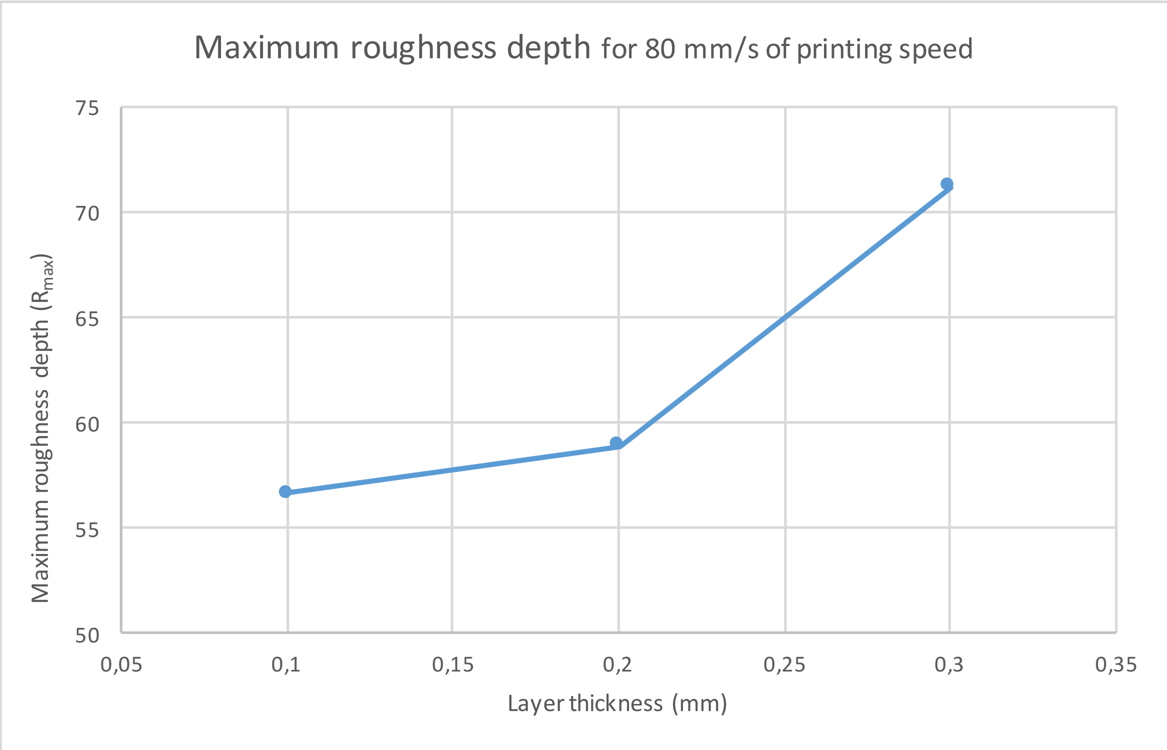


Figure 57: The maximum roughness depth R_{max} related to the layer thickness when it is printed at 210 ºC of extruder temperature and 80 mm/s of printing speed.

4.6- Conclusions

The objective of the second task of the thesis was to study the final result and the printing time of pieces built by FDM. For that reason, it is preferable to study the influence of layer thickness, the printing head speed and extrude temperature. In order to evaluate and compare how these parameters affect the roughness and the printing time, eighteen test pieces were built by an FDM printer using combinations of these parameters. Their surface roughness was measured with a Hommel Tester T500 device. All these results were summarized in Table 3. In addition, the relationship between these parameters was shown in Figures 43 to 57.

It was concluded that when the layer thickness decreases, the printing time increases and the surface roughness improves. Then a decision has to be made before printing of whether the final result is a priority or on the contrary the time is.

A direct relationship between the extruder temperature and the roughness surface was not found, with the exception of a 0,3 millimeter layer thickness and 80 millimeters per second of printing parameter when the volume of material that the printer was trying to extrude exceeded the limit allowed by the Ultimaker 2 Extended + 3D printer.

5- Evaluation of problems that appear when thin walls are printed by FDM

The main advantage of Fused Deposition Modeling (FDM) over conventional manufacturing is that complex shapes can be physically realized without elaborate tooling. However, there are some specific parts of the shape like thin walls where the application of FDM is poorly suited and may result in a lack of strength, stair-step effect (poor surface finish) or a large number of layers, resulting in higher build time.

One limit of using FDM for plastic pieces is that it is impossible to create walls thinner than the diameter of the extruder. In this case that means that the minimum thickness of the wall will be 0,4 millimetres which is the nozzle diameter used. In this thesis thin walls are considered thinner than 2 millimetres.

5.1- Materials that have been used

The materials used for this task were PLA, ABS and CPE.

An in depth description of these and others printing materials used in 3D printing can be found in the thesis of Sergio, C. A. (2016). *Characterization of 3D Printing Parameters.*

5.2- Designs to study

Several thin wall test pieces were designed. The first one was a piece with six different wall thicknesses from 0,5 to 3 millimetres. This can be seen in Figures 58 and 60.

After that a second test piece was designed. This second one has a curved base and just two walls to reduce the printing time. This piece can be seen in Figure 59 and it has been used to print in ABS. Modifications of the first design were done in order to improve the final results of the thin walls printed by FDM.

5.3- Study of the experiment pieces printed

In this section the designed pieces are shown. ABS material is expected to be the most problematic material when thin walls are built.

5.3.1- Experiment of pieces printed using PLA

In Figure 58 the PLA test piece is shown. As it can be observed there are no problems printing thin walls with PLA plastic filament.

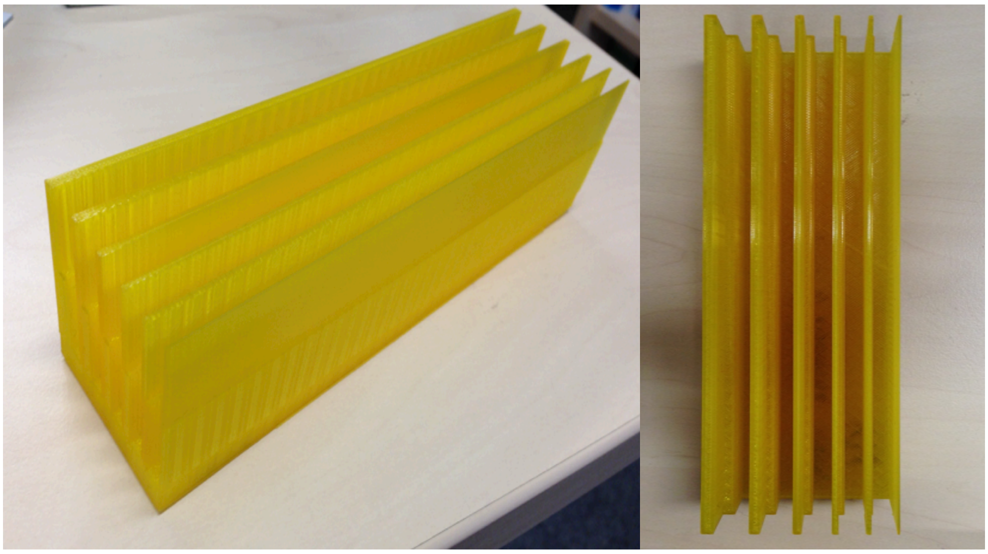


Figure 58: PLA test piece

5.3.2- Experiment of pieces printed using ABS

In Figure 59 the ABS test piece is shown. As it can be observed several problems occur when thin walls are printed using ABS plastic filament.

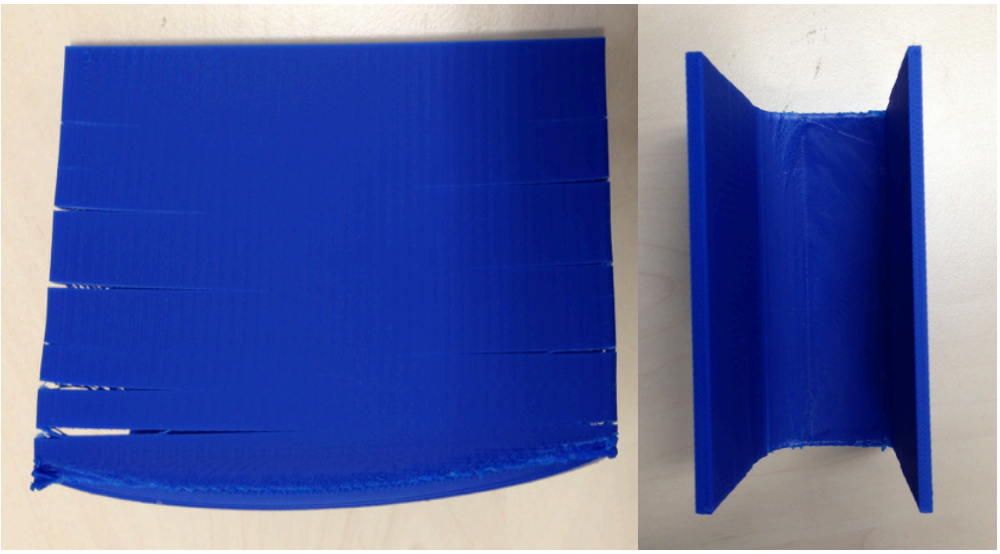


Figure 59: ABS test piece

5.3.3- Experiment of pieces printed using CPE

In the Figure 60 the CPE test piece is shown. As it can be observed there are no big problems printing thin walls with CPE plastic filament but the results are a lot better using PLA plastic filament.

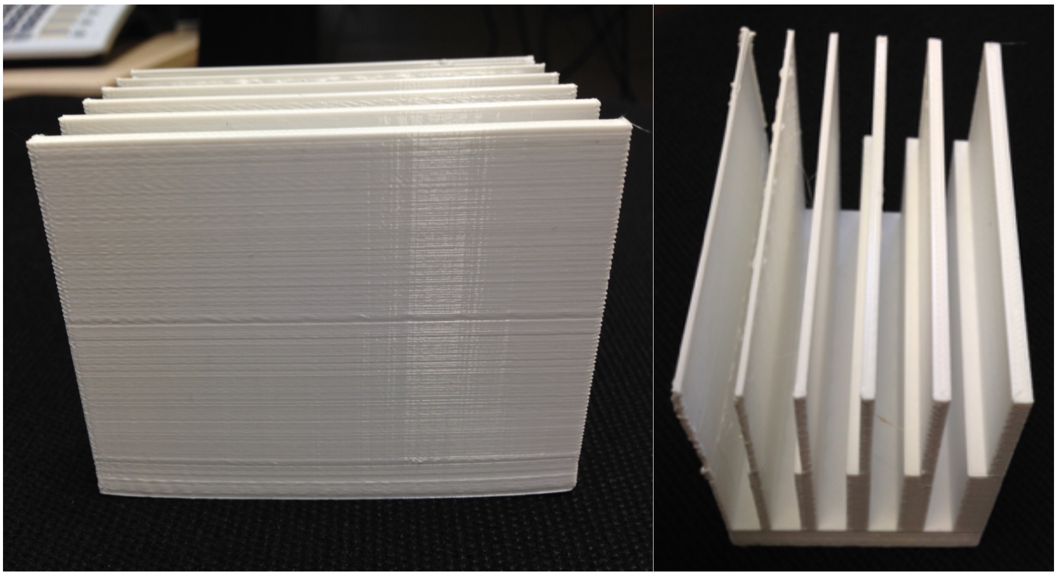


Figure 60: CPE test piece

5.4- Problems that appear

This section describes the defects that arise when thin walls are printed by FDM using ABS plastic filament.

5.4.1- Contraction on cooling

The corners of the base of the piece are separated from the build plate and deform the piece. This problem is called warping. Warping is due to the cooling and contraction of the plastic. When the plastic cools it contracts itself. As the impression passes the extruded plastic gets cold, shrinks and starts pulling the material around it. Over time the internal forces becomes so large that the printing base is bent from the build plate.

5.4.2- Separation of layers

The cracks in the pieces appear especially when the piece is long. The hot build plate provides heat for the piece but in the case of large pieces the temperature does not reach the high layers. It is here that cracks arise when a layer of another peels off.

5.5- The selection of the correct value for the printing parameters in Cura

The description of the basic and advanced Cura setting used in 3D printing can be found in the thesis of Sergio, C. A. (2016). *Characterization of 3D Printing Parameters.*

Thus, in this thesis just the expert configuration settings from Cura 15.04.6 were analyzed. In the expert configuration window it is possible to modify a lot of crucial parameters of the printing process. Analyzing and understanding one by one is the first important step.

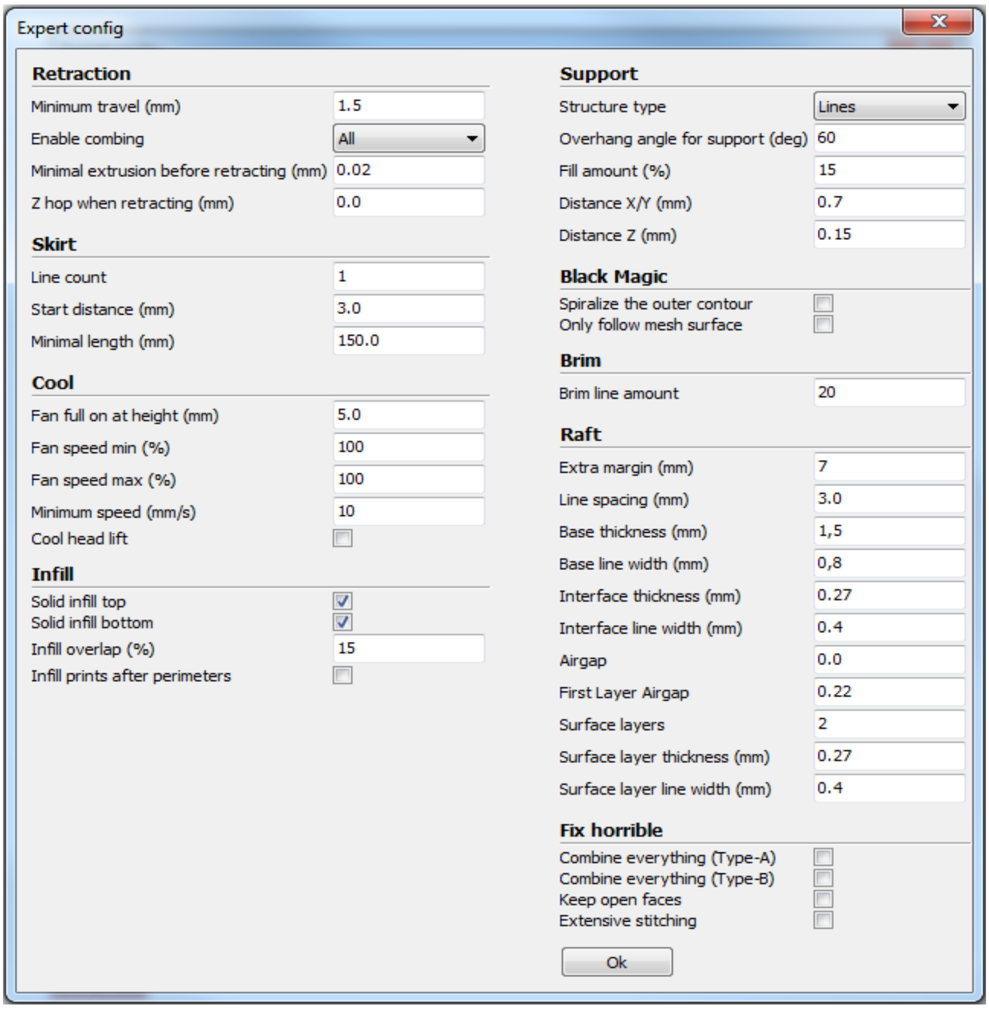


Figure 61: Expert configuration window

Cura 15.04.6 expert configuration settings:

Retraction

The printer retracts the filament whenever the nozzle has to move from one point to another without printing. This retraction is done to prevent the plastic from dripping.

- *Minimum travel*: Minimum displacement for which retraction of the filament will take place.

- *Enable combining*: In addition to retraction, the printer will prevent the nozzle from passing over the holes.

- *Minimal extrusion before retracting*: Set the minimum amount of plastic to be extruded before retraction. If at least this amount of filament is not extruded, the retraction will be ignored.

- *Z hop when retracting*: This option causes the Z axis to rise when scrolling. It is a very useful option and it will improve the quality of pieces that have small details, avoiding along with the retraction that appear threads that affect the impression.

Skirt

The skirt is a line that will surround the model to be printed. This line has 2 purposes, the first is to determine the limits where the model will be contained and the second is to clean the nozzle by eliminating possible air bubbles from the interior or dirt from the nozzle itself.

- *Line count*: Number of turns to surround the piece is being printing.

- *Start distance*: Sets the separation distance between the object and the skirt.

- *Minimal length*: Sets the minimum length that the skirt will have. In small pieces the skirt will not be big enough to clean the nozzle properly, so a minimum distance is fixed increasing the number of turns until reaching this distance.

Cool

The parameters contained in Cool affect the way the piece will be cooled.

- *Fan full on at height*: This option will completely activate the fan from the selected height. For the lower layers, the fan will operate at a proportional speed, always being deactivated for the initial layer.

- *Fan speed min/max*: These parameters set the maximum and minimum speed of the fan. It must be adjusted to ensure that the airflow is correct, as excessive flow will cool the piece too quickly and may cause cracks to appear on the piece.

- *Minimum speed*: This option set the minimum printing speed used. Never it will be slower that this minimal speed.

- *Cool head lift*: If this option is selected, the printer will raise the nozzle giving time to cool and separating it to avoid overheat the plastic.

Infill

- *Solid infill top/bottom*: Selecting these options, both the top and bottom layers will be solid and will not be affected by the fill factor applied to the design.

- *Infill overlap*: This parameter controls the amount of filler that is to be overlapped with the edges.

- *Infill prints after perimeters*: This option reduces infill from showing through the surface. If it is not checked, infill will print before perimeter lines.

Support

The supports are elements that in many cases are totally necessary to print the model, and depending on the characteristics of the the piece, it is necessary to modify the supports to adapt them as much as possible to the design. They are easily removable.

- *Structure type*: It can be selected between two types of structures, one composed of a grid and another composed of lines.

- *Overhang angle for support*: Indicates the maximum angle for which the supports will be used. This angle is taken as a vertical reference, having a vertical wall an angle of 0º and a horizontal bridge an angle of 90º.

- *Fill amount*: This parameter sets the fill to be used for the brackets. The filling will define the spacing between the support lines.

- *Distance X/Y*: Sets the separation between the edges of the object and the supports. If this distance is very small, the edges can be joined with the supports making the supports very complex to remove and influencing the final results of the piece.

- *Distance Z*: It establishes the separation in Z (height) that will be between the support and the piece. This distance is largely determined by the layer thickness used.

Black Magic

- *Spiralize the outer contour*: This option prints the outline of the object with a solid base. It converts a solid element to a hollow object.

- *Only follow mesh surface*: This option prints the surface or shell of the object, without taking into account the base, the filling or the top layer.

Brim

- *Brim line amount*: This parameter indicates the width of the visor. The greater the width of the visor, the greater will be the adhesion that the object will have.

Raft

These parameters configure the printing base. This base will improve the adhesion of the piece creating a kind of mesh on which the object is printed.

- *Extra margin*: This parameter sets the margin that will extend the base of the object.

- *Line spacing*: Sets the distance between the lines forming the mesh.

- *Base thickness*: Sets the thickness of the base.

- *Base line width*: This parameter modifies the thickness of the lines with which the base is made.

- *Interface thickness*: Sets the thickness of the middle layer that has the base.

- *Interface line width*: Sets the thickness of the lines forming the middle layer of the base.

- *Airgap*: This parameter modifies the space between the last layer of the base and the first layer of the object. This separation will influence the ease of removing the base of the object.

- *Surface layers*: Sets the number of layers at the top of the base.

Fix Horrible

The options included here are options for trying to improve or repair objects. The program makes by default modifications to the 3D layout that can result in unwanted effects and alter the original model. The options contained in "fix horrible" alone or combined with each other, change the way Cura will interpret the 3D model, solving possible problems when printing. By default, Cura usually repairs correctly all the errors of the 3D model, these options are only advisable to activate them in exceptional cases, since they can negatively affect the impression.

- *Combine everything (Type A)*: Join all parts of the model based on the normal ones trying to keep the internal holes intact.

- *Combine everything (Type B)*: Join all parts of the model by ignoring internal holes and retaining the outer layer.

- *Keep open face*: It keeps open small holes that could have the model. By default, CURA closes the small holes or cracks of the model, as it takes them as design errors.

- *Extensive stitching*: It repairs holes or cracks in the model, closing holes which have polygons that are touching.

Brim and raft are the most interesting setting for the purpose of building thin walls using ABS filament. Both require post-processing to remove it. Brim parameter is shown in Figure 62.

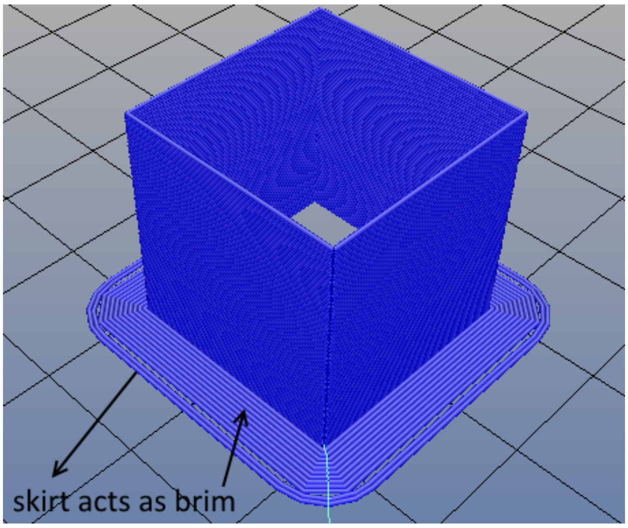


Figure 62: Brim parameter Cura view (Ultimaker. *https://ultimaker.com*)

5.6- Possible solutions

Several solutions to reduce this problem were found. It must be pointed out that these solutions help to reduce these problems that appear on thin walls but do not eliminate them completely.

5.6.1- Designing cavities in the walls to reduce internal stress

The first solution to reduce the internal stress of the pieces is to design thin walls with cavities. These cavities decrease the amount of material in the pieces therefore the contraction on cooling is much smaller. Nevertheless, this solution is not valid when the piece printed is used to contain liquids for example.

Figure 63: Seccion of thin walls with cavities

5.6.2- Installing a plugin

The second solution found was to intall a plugin that modifies the G-code of the printing process. Cura 15.04.6 has the option to apply plugins. One of these plugins called Tweak At Z 4.0.2 allows the modification of printer settings at certain z heights or layer numbers.

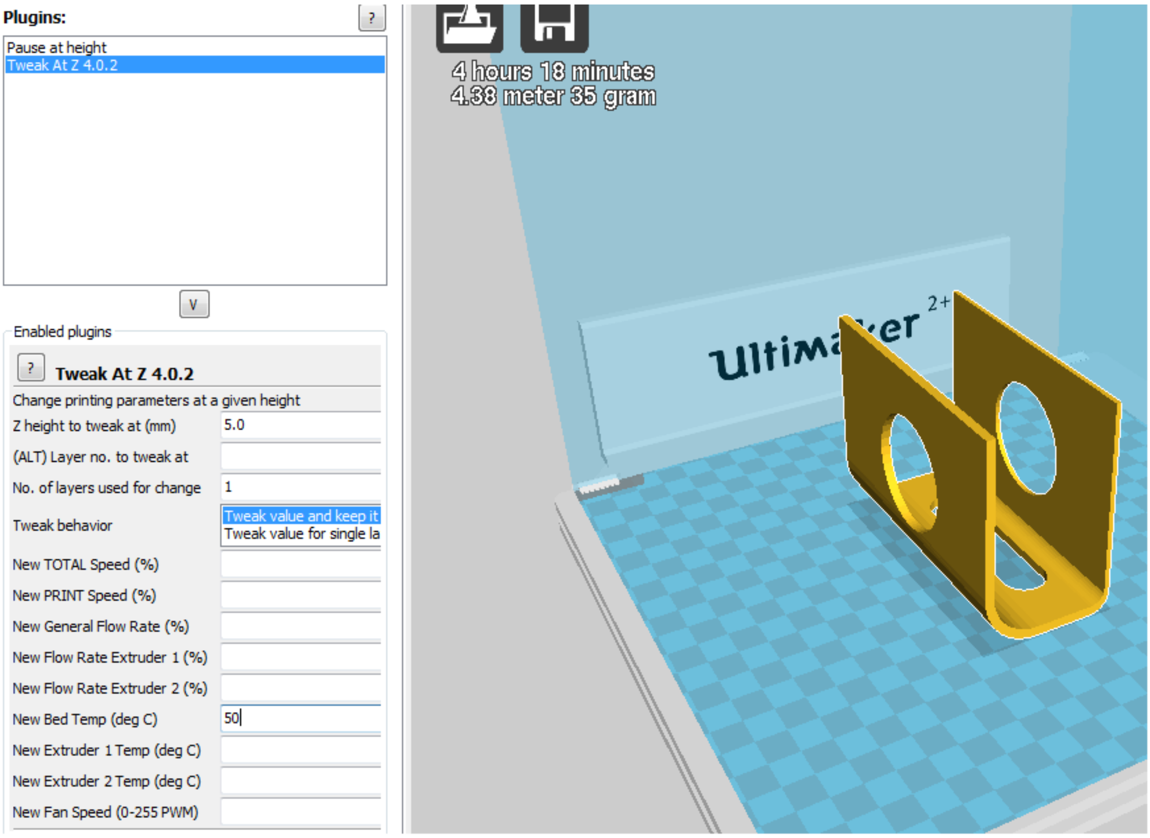


Figure 64: Tweak At Z 4.0.2 plugin window

Tweak At Z 4.0.2 plugin description:

Z height to tweak at (mm)	Specifies the tweak height in millimetres
(ALT) Layer no. to tweak at	Alternatively specifies the tweak layer number; if it is specified the tweak height from the previous input will be ignored
No. of layers used for change	Default value 1; specifies the number of layers used for a gradual / linear change of the specified printer settings
Tweak behavior	*Tweak value and keep it for the rest* changes the setting and keeps the change until the end of print / the top of the object is reached; *Tweak value for single layer only* changes the setting for only the layer specified by layer no. or by z height and resets it on the next layer
New TOTAL speed	Alters both print speed and travel speed by applying a speed factor during print
New PRINT speed	Alters print speed only by recalculating speed settings in the G-code (for G1 commands only)
New General Flow rate	Alters the flow rate multiplicator for ALL extruders
New Flow Rate Extruder 1	Alters the flow rate multiplicator for the first extruder only
New Flow Rate Extruder 2	Alters the flow rate multiplicator for the second extruder only
New Bed Temperature	Alters the print bed temperature. The bed of the printer is the build plate previous named.
New Extruder 1 Temperature	Alters the temperature of the first hotend / extruder
New Extruder 2 Temperature	Alters the temperature of the second hotend / extruder
New Fan Speed	Alters the fan speed; Full speed is 255 PWM

In this case the parameter used was the *New Bed Temperature.* This parameter allows the decrease of the build plate temperature at certain z heights. Decreasing the bed temperature over 5 to 10 millimetres of height avoids the premature contraction of the upper layers. Then the previous mentioned warping effect does not occur. The use of this plugin together with the brim parameter is the best solution to keep the piece stuck on the build plate.

5.6.3- Selecting a thin wall dimension multiple of the nozzle diameter

The third solution found is related to the wall thickness and the size of the nozzle. The standard nozzle in the Ultimaker 2 Extended + is 0.4 millimeters in diameter, therefore 0.4 is also the width with which the software has to work to make our impression. Now, suppose a wall 1 mm thick has to be created. The software generates two perimeter passes of 0.4 millimeters each leaving a gap between them of 0.2 millimeters. Since the nozzle is twice as large, the software cannot fit the nozzle between the walls to fill the vacuum. Although the latest versions of Cura solve these problems very efficiently, there will always be cases in which the software will not be able to offer the best option.

Whenever possible, the thickness of the wall must match or be a multiple of the diameter of the nozzle.

5.7- Results and conclusions

Firstly, the pieces printed on different materials have been analyzed. Then, the problems and their causes of printing ABS plastic filament have been recognized. Finally, after researching possible solutions for these problems the best solutions were exposed. As was previously mentioned these solutions just decrease the impact of these problems. Thus, if the thin wall problems need to be solved completely the solution is to use PLA plastic material. Additionally, PLA is derived from a renewable resource and is easy to recycle, therefore PLA can break down into natural elements in less than a month given the right circumstances.

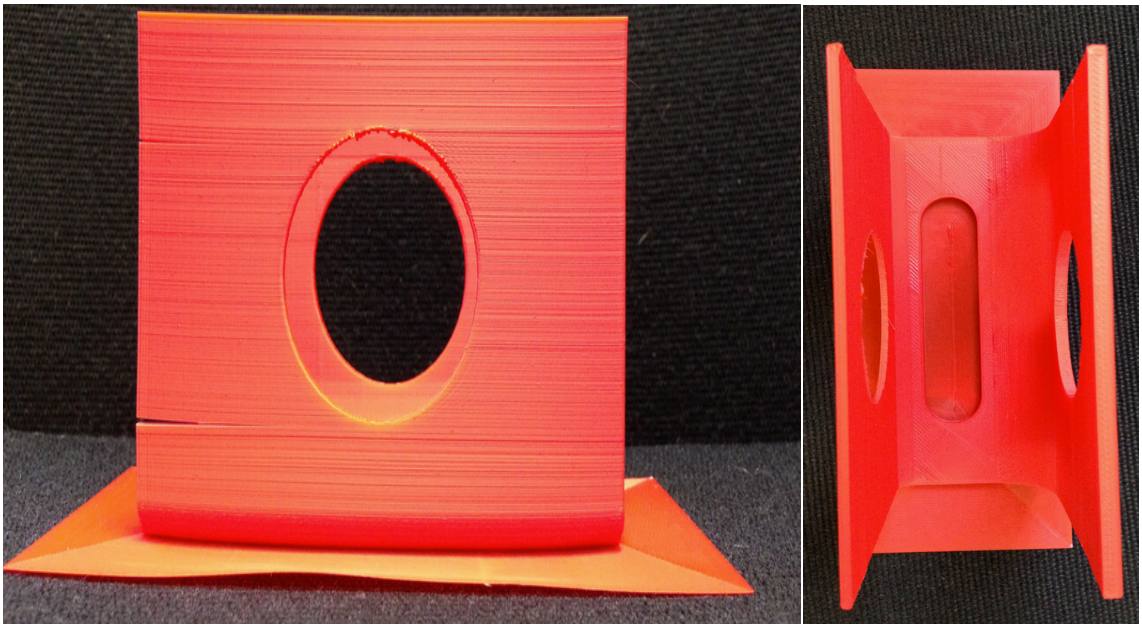


Figure 65: ABS piece printed applying all the solutions

References

[1] Thesis of Sergio, C. A. (2016). *Characterization of 3D Printing Parameters.*

[2] Ultimaker. *https://ultimaker.com*

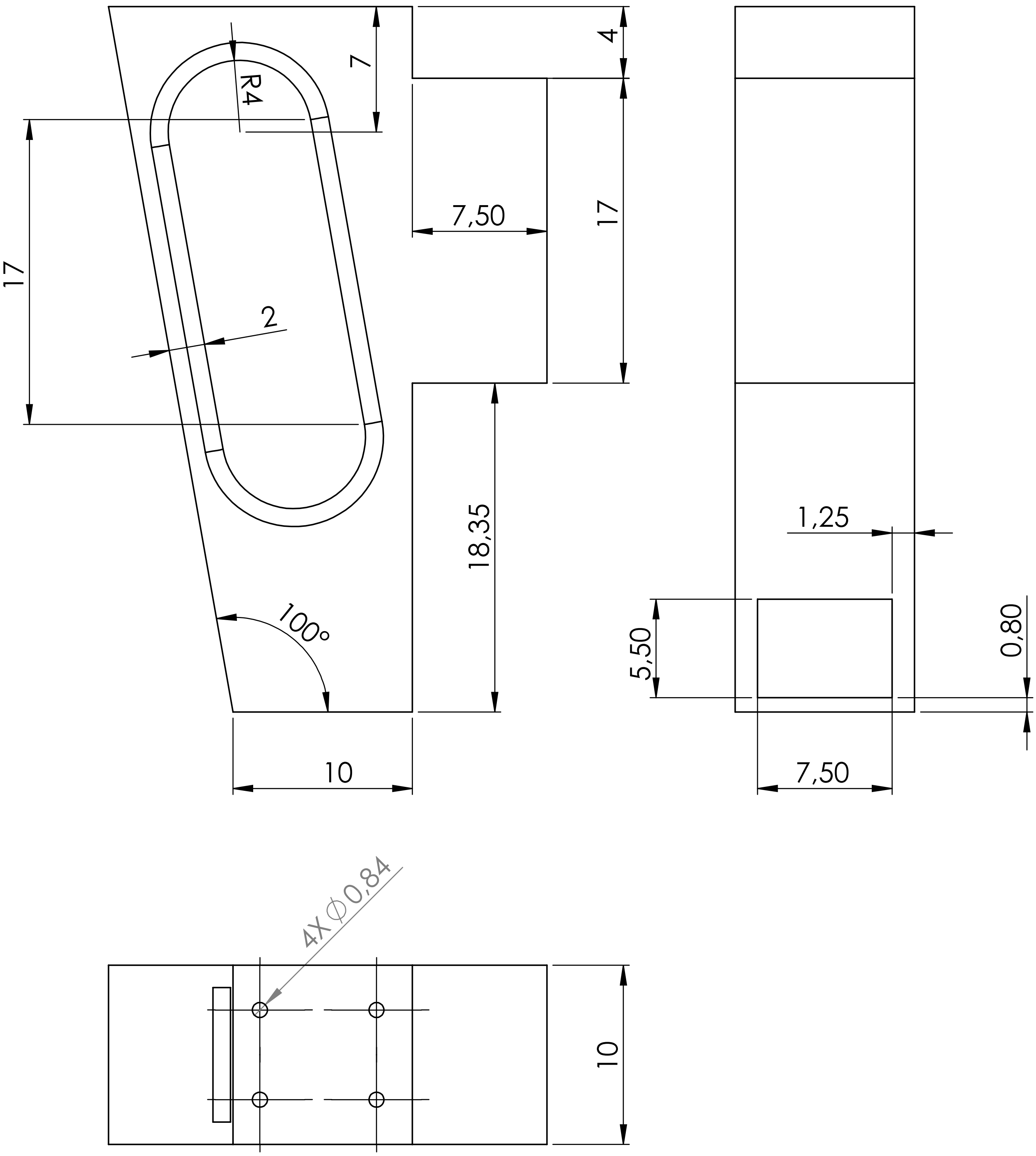
[3] GitHub. *https://github.com/*

[4] Marlin. *http://marlinfw.org/*

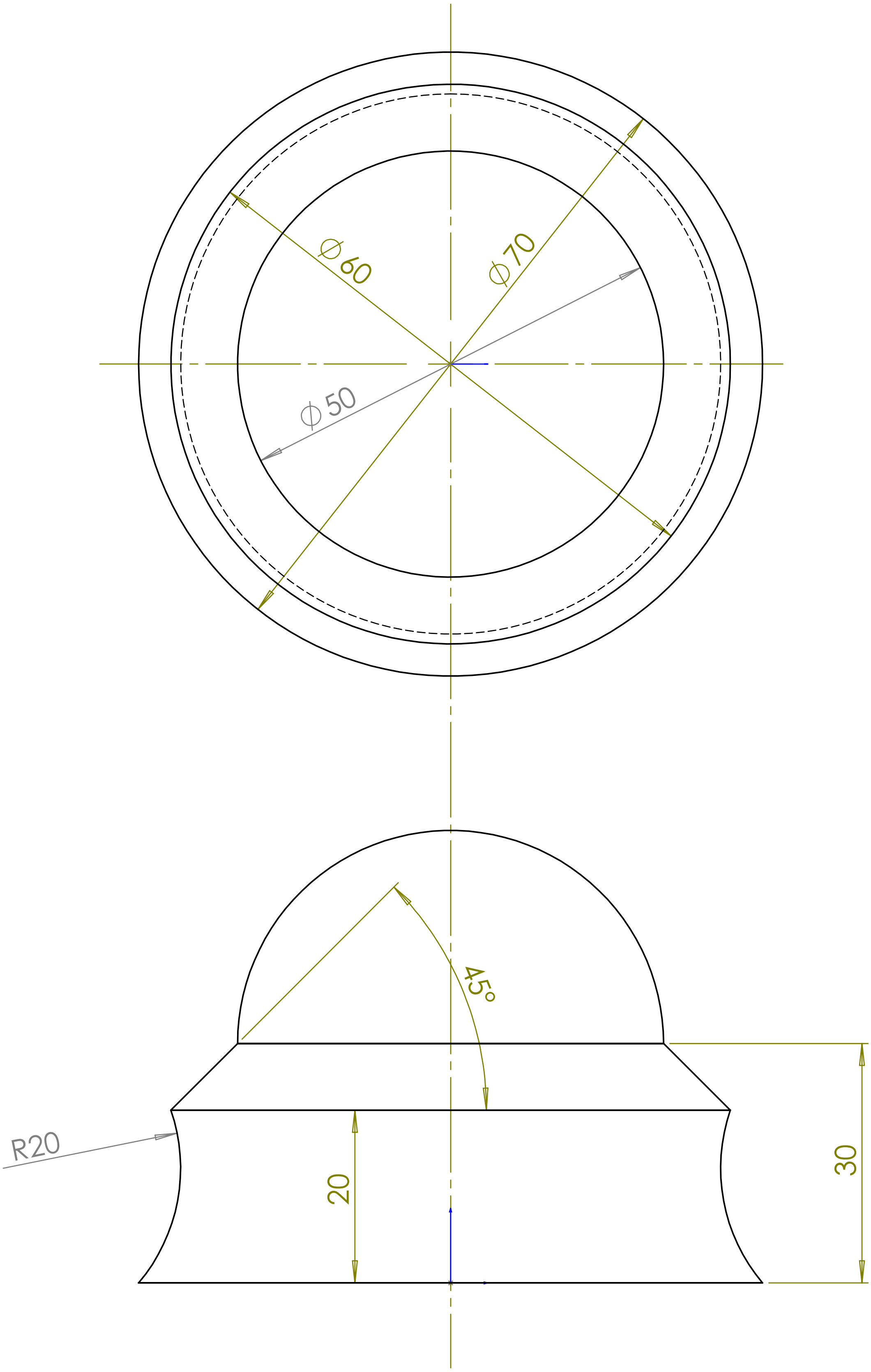
[5] Octoprint. *http://octoprint.org/*

[6] Perez, C. L. *Analysis of the surface roughness and dimensional accuracy capability of fused deposition modelling processes*, International Journal of Production Research.

[7] *http://www.engineeringtoolbox.com*



GEZEICHNET	BENENNUNG:
NAME RICARDO LÁZARO SÁNCHEZ	SUPPORT FOR THE MICRO SWITCH
DATUM 01/02/2017	WERKSTOFF PLA
ZEICHNUNGSNR. SUPPORT FOR THE MICRO SWITCH	A4
MASSSTAB: 3:1	BLATT 1 VON 1



	GEZEICHNET	BENENNUNG:	SURFACE ROUGHNESS TEST
NAME	RICARDO LÁZARO SÁNCHEZ	ZEICHNUNGSNR.	SURFACE ROUGHNESS TEST 1 — A4
DATUM 05/01/2017	WERKSTOFF PLA	MASSSTAB: 1/0,7	BLATT 1 VON 1