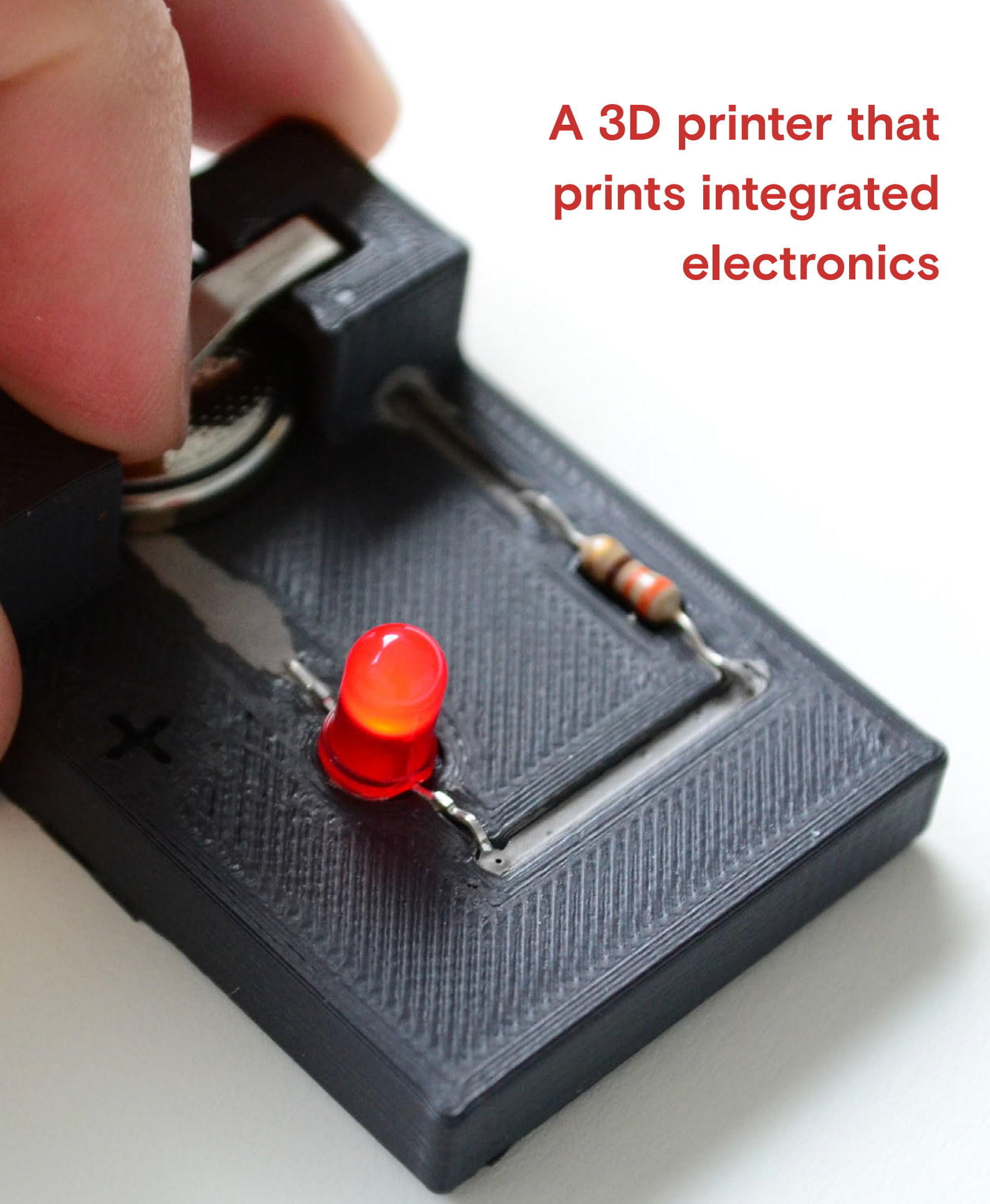


A 3D printer that prints integrated electronics

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Master Thesis
MSc Integrated Product Design
Delft University of Technology
15th of April 2020

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Preface

This thesis will be my last project conducted at the TU Delft. With this project I close off an era in my life. During the project I had a lot of support. Here I take my chance to thank everyone that helped me during this project.

First of all, I want to thank my supervisors, Sander and Wolf, who always believed in me and helped tackeling problems. I thank them for treating me as an equal person, instead of standing above the project and just saying what I should do. Their involvement in the project helped a lot, they took the time to think about the occuring problems during the project.

Second, I want to thank MTB3D, Ewoud, for providing a lot of different filaments that I could test. Without these test samples, I do not know if I would have found the right material.

Of course, I want to thank my boyfriend, Jeroen, for checking my thesis, mental support and great simple explanations of how electronics work.

Next I want to thank Jordan, a dear friend, for the regular tea and coffee breaks, where we discussed a lot about 3D printers. I thank him for being able to meet Mister Prusa on a 3D printer event.

Eva, you helped me a lot as well, I think I can always say anything to you and you will always understand. That makes the communication very easy. You helped a lot with making my thesis understandable.

I feel that this project can grow largely. I have layed the base and I am very happy that my old roommate and friend, Kasper, is continueing my project.

SRC Thor, also played a big role role during my thesis, here I was able to let my frustration go and be able to grow in rugby, with my beloved team. Thank you Bene for reading my thesis and make the sentences prettier and easier to read. Thank you Britt for being my cocaptain and easily taking over all the tasks. Thank you team for always being there.

Last but not least, I want to thank my supporting family, for being very interested in my project and for just being there.

A big supporting team was standing behind me. You all might receive some nice craft beers or chocolate.



Glossary

Acronyms

ABS	Acrylonitrile Butadiene Styrene
DIY	Do It Yourself
FDM	Fused Deposition Modelling
HT	High Temperature
PA CF	Polyamide Carbon Fiber
PCB	Printed Circuit Board
PLA	Polylactic Acid

Terms

3D printer
A machine that can make prototypes and products using agile manufacturing. The used technique for 3D printing is FDM, where a filament is pushed through a heated nozzle to build up a product layer by layer.

Active components
Complex electrical components, for instance chips.

Conductor
A material that carries electricity, for instance copper.

Extruder
Part of the 3D printer that extrudes material.

Extrusion rate
The speed to extrude material through the nozzle.

Feeder
The part of the 3D printer that moves the material through the nozzle.

Feed rate
The speed of the extruder head, moving in the x and y directions.

G-code
A numerical control programming language used for computer aided manufacturing to control automated machine tools. In FDM printing, it controls all the movements of the 3D printer.

Herman printer
A 3D printer build by Herman Broekhuizen. The printer is made with open source software and hardware and therefore easily adaptable.

Insulator
A material that resists electricity.

Integrated electronics
An electronic circuit that is printed in a 3D print.

Passive components
Simple electrical components, for instance LEDs.

Trace
The line of conductive material.

Ultimaker
A company that produces accessible and ready to use 3D printers.

Executive summary

Introduction
Within this part of the report the project scope is described. The goal of the project is formulated. The process to tackle the project is visualised.

The goal of this project is:

Building a cost-effective, compact and simple 3D printer that can print electronics for technical integration of prototypes.

This thesis is the basement of this project goal, therefore the focus was on developing the extruder that prints conductive material and how this goes together with filament.
An overview of which parts that have been developed can be seen in Figure 1.1. A 3D printer is shown, in red the extruders are shown.

Research
In the research phase, first research questions are formed to structure the research. The main research question is:

What is needed to make a cost-effective extruder printing integrated electronics?

Based on this question and on the goal of the project sub questions are made. These sub questions are answered per chapter. From the research it can be concluded that solder paste will be used as conductive material, for having a good conductivity and low price.
For the extruding method, it has been chosen to continue with the archimedes screw and plunger method. These are low cost, simple and compact solutions.
There are several thermoplastic filaments possible that might be able to withstand the heat of curing.
The shape of the trace has to be found out as this has influence on curing the solder paste.
The way of curing solder paste has to be found.
The solder paste will be cured in the oven.

Conceptualization
In this phase the two main things are explored, how to cure the solder paste and how to extrude solder paste. Three big experiments are done to find the right combination of solder paste with the thermoplastic filament and the reflow settings. Next to this, an extrusion method has been chosen.
The solder paste has the composition of: $Sn42Bi57{,}6Ag0{,}4$. The melting temperature is $138\ [°C]$.

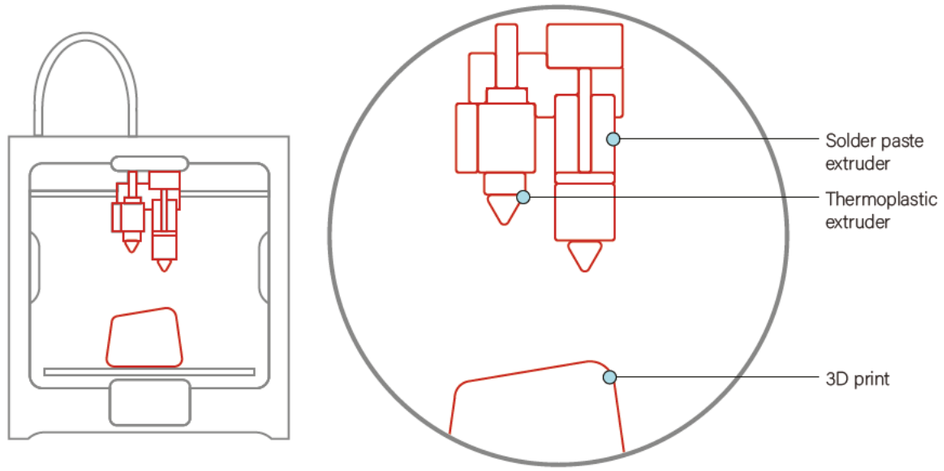


Figure 1.1: Overview of the project.

The chosen thermoplastic material is PLA X³, this filament can withstand the curing temperature. Curing has been done in the oven, heating the oven to $142\ [°C]$ with the sample in the oven. Then leaving the sample at this temperature for ten minutes, when the sample has cooled down by opening the door the electric circuit is ready to be used.

Integration
After setting all the parameters for printing electronics, it has been described with what material this has been done and how.
The prototype of the extruder head, that has been developed, has two extruders: the thermoplastic extruder and the solder paste extruder. The bracket is designed as such so the thermoplastic extruder can be lifted manually.
The printing process is as follows:

1. Design the 3D CAD model
2. How to slice and adjust the g-code
3. Preparing the printer
4. Printing the solder paste in the 3D print
5. Pick and place components
6. Curing the 3D print

Making sure to design the prototype according to a set of design guidelines. The most important guidelines are to design the electric circuit in 2D and to 3D print the circuit in the XY plane.

Validation
To proof the designed concept and settings are working a demonstrator is developed. It is wanted to create a simple prototype that easily proofs the printers capacities.
There is chosen to make a flashlight. After some iterations the final design is simple: containing a battery, an LED, a resistor and a switch.

Product vision
The future of the designed proof of concept is shown. The 3D printer can print prototypes with an integrated electric circuit at a low cost.

Project reflection
After the developed proof of concept, the project is evaluated on the basis of the design rules and design drivers. It can be said that the project goal is satisfied. A cost-effective, compact and simple proof of concept for a 3D printer that can print electronics for technical integration of prototypes is designed.
A solid base has been created that can easily be broadened and used to develop a product out of it. Recommendations have been made to develop the concept further. The most important recommendation is to further research the possibilities to 3D print the solder paste.
Finally a personal reflection on the project has been given.

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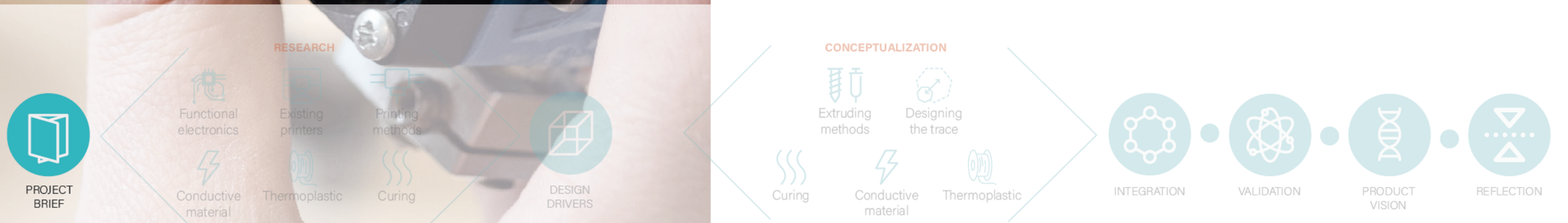
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1 Introduction

This chapter introduces the field of 3D printing integrated electronics and the opportunities that this new field can bring to designers. After defining the 3D printing method, this chapter presents the goal, as well as the boundaries for this thesis.



1.1 The project

3D printing is a relatively new method of producing prototypes and products. It is rather accessible and creates new opportunities. A new level is unlocked with the ability to 3D print electronics. How accessible is it now and what are the opportunities of 3D printed electronics?

Structural electronics is the next generation of electronics manufacturing technology. 3D printing of integrated electronic circuitries across freeform shaped architectures are innovations in structural electronics. 3D printed electronics bring the following new opportunities to designers: 1)The freedom of the designer is enabled to combine aesthetics and functions together in the design; 2) It gives the opportunity to miniaturize the design; 3) The design and manufacturing process of mechatronic products will be accelerated; and 4) It will boost the efficiency of producing customized/personalized and mechatronic/ electronic products, e.g. hospital equipment, parts of airplanes etc. Meanwhile it also poses challenges on the sustainability in the product design and manufacturing process. [1]

The focus of this project is cost-effectiveness and accessibility of 3D electrical printing. The goal is to create a next generation printer for designers who are experimenting, prototyping and testing their first concept ideas.
Making the printing method more accessible gives more users and designers the tools to develop the concept further, which will boost the technology.

In this project passive components can be printed while active components have to be added.

The project goal is to build a cost-effective, compact and simple 3D printer that can print electronics for technical integration of prototypes.

The project vision is visualised in Figure 1.1. The costs and simplicity of the 3D printer come above the performance. The 3D printer will not be designed to print high end products, but as mentioned before to build prototypes. The original project brief can be find in Appendix A.

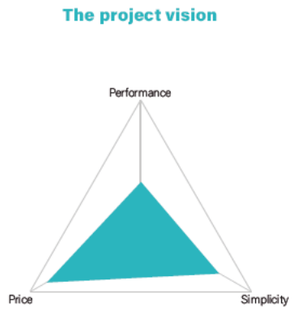


Figure 1.1: The project goal.

1.2 Approach

This graduation project will focus on the design of an extruder that extrudes conductive material together with plastic filament. To be able to conduct this project, the following boundaries of the scope are made.

3D printing is an additive manufacturing method. There are a lot of different 3D print methods. The most common 3D print method is Fused Deposition Modelling (FDM) 3D printing. In FDM printing a melted thermoplastic material is extruded through a nozzle to print layer by layer to form a 3D object. This method of 3D printing is most common as the resources are widely available and at low cost. The way of printing gives easy opportunities to adapt an existing FDM printer to print functional electronics. Additionally the way of printing is accessible for a broad range of people. Therefore FDM 3D printing is ideal for printing low cost electronics.
The second clarification in this project is to not reinvent the wheel. This means that it is focussed on designing a new method for printing electronics and not on designing a 3D printer.
In this project the used resources were made available by the Applied Labs of Industrial Design Engineering. The Ultimaker 3 has been used to print different types of thermoplastic material and the Herman printer has been used to build and test prototypes for printing electronics.

The process of this project can be seen in Figure 1.2. The start of this project is exploring opportunities for printing electronics and defining what is needed to build a 3D electrical printer. To guide the research, research questions are made. Design drivers are developed from the research. These drivers guide the ideas and concepts phase. The results from the research phase are tested in the conceptualization phase. To finalise the conceptualization phase, final choices will be made to conclude the embodiment phase. In the last phase the concepts come together and the printer is able to print functional electronics. To show the capacity of the printer a demonstrator will be designed and printed. At the end the design is evaluated and recommendations are made.



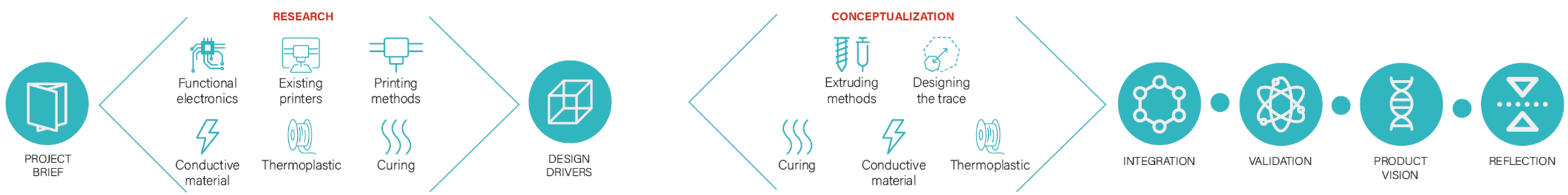
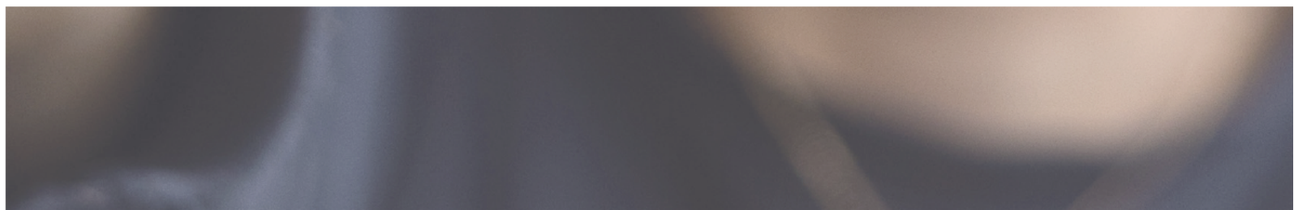


Figure 1.2: Process of this project.



2 Research

The first step of this project is the definition of the research questions. An assessment was made on the existing printers. What can they do and how do they print? This research shows which materials are currently used and which is appropriate for this project. The first set of requirements from the project goals are used to evaluate the existing printers and used materials.



2.1 Setup of the research

To guide the research phase the following main topics are researched: functional electronics, existing printers, conductive material, thermoplastic filament and paste extruders. In this chapter, the research questions are formed according to the design rules and goal of the project. What is needed to know to build an extruder that can print electronics?

Different research questions were determined to structure the study. They are all to be answered by the end of the project.
The main research question of this project is:

What is needed to make a cost-effective extruder printing integrated electronics?

The sub questions that are extruded from the main question are divided into the product vision and the technical integration.

Sub questions about the product vision:
1.1 What are integrated electronics?
1.2 How to print integrated electronics?
1.3 What printers exist and how do they print?

Sub questions about the technical integration:
2.1 What material is needed to print electronics?
2.2 How to extrude the conductive material?
2.3 What is needed to be able to print quick?

In this phase, the main research is done by gathering information from scientific publications, datasets and general websites. The information gathered for the product vision is formulated into design rules for the 3D printer. The insights gathered from the technical integration is evaluated by the project vision and formed into useful design drivers.

The next phase of the project is based on these design drivers, which will then guide the conceptualization phase.

2.2 Electronics and technical integration

In this chapter, electronics and technical integration are defined. These terms are important because they define the specifications of the printer. The sub questions 1.1 and 1.2 are answered here.

The main question of this chapter is:
What are electronics?
As electronics is a broad definition in this project we choose to have the following definition:

Circuits or devices using transistors, microchips, and passive electric components.

Conductors, semi-conductors and insulators are needed to build electric circuits. In this project microchips and transistors will not be printed, but are components to be added. The printer will be able to print the circuit.

Technical integration of electronics describes the process of using electronic components to create a functional circuit. For instance a mouse has buttons and electronic components to communicate clicks and movements with a computer. As this project focusses on integrating the circuit in the product instead of using a PCB, the products that can be printed are really integrated. Normally, a product is technically integrated when the product consists of a PCB with one or more functions that have for instance sensors on the product, like a button.
With this project the traces can be printed through the product, which is defined as integrated electronics.

To see what materials are needed to print electronics, it is needed to know the material composition of electronics. Electronics consist of insulators and conductive material. The conductor is the carier of current. To make sure that there will be no short circuit insulators are used. An insulator is a material that does not let current flow easily. In this way conductive traces can be used in non-conductive material.

The conductive material used in PCB's is mainly copper. To determine the trace width that is needed, the amount of current that has to go through the trace is important. The trace width in a PCB goes from $0.25\ [mm]$ to $6.35\ [mm]$. The trace width and thickness is about the relationship of trace area and current carying capacity. The bigger the area the more current it can take. [3]
The lower the resistance of the trace the better. Copper has a resistance of $1.68^{-8}\ [\Omega*m]$. Silver has a slightly lower resistivity. However, it is also more expensive. Therefore copper is used more often. [4]

This printer should be able to print passive components. These components are for instance: resistors, inductors and simple capacitors. These components are passive electronical components.

The goal is to be able to print simple electronics, therefore being able to print more complex electronics like chips is left out of the scope. These are not necessary in regular simple products or devices.

2.3 Existing electrical 2D/3D printers

A first research is done to understand how existing electrical printers are printing integrated electronics now. This chapter compares the existing technologies to know which one comes close to the wanted goal of this project and why. Then the main principles of this printer can be used to build upon. The sub question 1.3 is answered.

There are not many competitors on the market of electrical 2D and 3D printers. The type of printers can be categorized as industrial use, professional use and consumer use. Where industrial use are printers used in the industry and the printers used for professional use are used for printing high-end prototypes. The printers used by consumers are print low-end prototypes. The electrical printers that are used in this comparison, are found during this project, dated 2020.

Industrial use
The printer made for the high end industry is the Aerosol Jet. This printer prints with silver ink and the initial investment is rather high (***>150K euro***). [5]

Professional use
The professional use can be split into two categories, those printing in 2D and those in 3D.
2D printers are Botfactory and the Voltera. These printers print among other things silver ink on PCB's. The costs for a printer start at approximately ***€4499,-***. These printers can be used to quickly produce one PCB for a prototype or test. [6] [7]
The 3D printer in this market is a start up called EForge. This printer prints with several conductive filaments. EForge is not on the market yet. They will launch their product in July 2020. They promise that they are able to print 3D electronics with the use of 6 filaments a conductor, an insulator, a capacitor, a resistor, a N-type semiconductor and a P-type semiconductor. The final capacity of the printer is not yet known. The printer will cost around ***€7.200,-***. [8]
Another 3D printer that has been removed from the market is the Voxel8. This printer printed with silver ink. As this printer does not exist anymore it is also not taken into account in the comparison. Additional information can be found in Appendix B. [9][10]

Consumer use
For DIY electrical printing conductive filament can be used on any FDM printer. The price of the filament is around ***€50,-*** per ***500 [g]***. Printing conductive filament has not proven itself as the resistivity is rather high (Printed Protopasta ***30 [Ω*cm]***. [11] [12]

To rate the above printers on the first set of design rules that came out of the project goal is to see which printer comes the closest to the project rules. The comparison can be seen in Figure 2.2.

This project is focussed on the design rules (see Chapter 2.4). The following design rules are applicable on the existing electrical 2D and 3D printers.

The performance of the printer:
2.1 The printer should be able to at least 2D print integrated electronics and be the start of a design venture seeking to explore the 3D printing of integrated electronics.
2.2 Printing a prototype with integrated electronics should not add too much time to the original printing time, when only printing thermoplastics.
2.3 The printed conductive material should have a resistance of less than ***0.2 [Ω]***.

Cost of the printer:
3.1 The material expenses for ***100 [g]*** of conductive material should lay between ***€10*** and ***€100***.
3.2 The material expenses for ***100 [g]*** of thermoplastic material should lay between ***€1*** and ***€10***.
3.3 The retail price of the designed extruder should lay between ***€50*** and ***€200***.

Simplicity of the printer:
4.1 The printer has a straight forward system.
4.2 The printer is accessible for everyone.

Figure 2.1 shows the project goal: the printer's performance is not optimal but it is cost-effective, simple and compact, i.e. easily accessible.

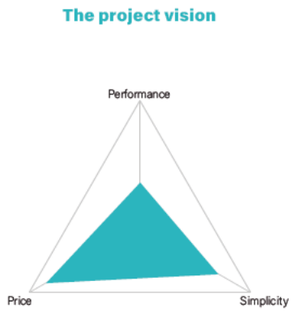


Figure 2.1: The project goal.

Insights
The Aerosol Jet does not fit the project goal at all. This printer is made for the industry and does not fit the idea of cost-effective printing, but is made for the production of high-end products and prototypes.
The EForge and printing conductive filament comes closer to the goal. The EForge has a great view on performance and the price. However, as it is a start up and the printer is not launched yet, it cannot be said how much the filaments will cost. Next to this using 8 different filaments makes the printer complex. FDM printing conductive filament will give good results in price and simplicity, however the performance of the filament is not good enough to print actual integrated electronics. Looking at the project goal the FDM printer and the 2D electrical printers come the closest to the project goal. This can be taken into account when searching for printing methods and material.

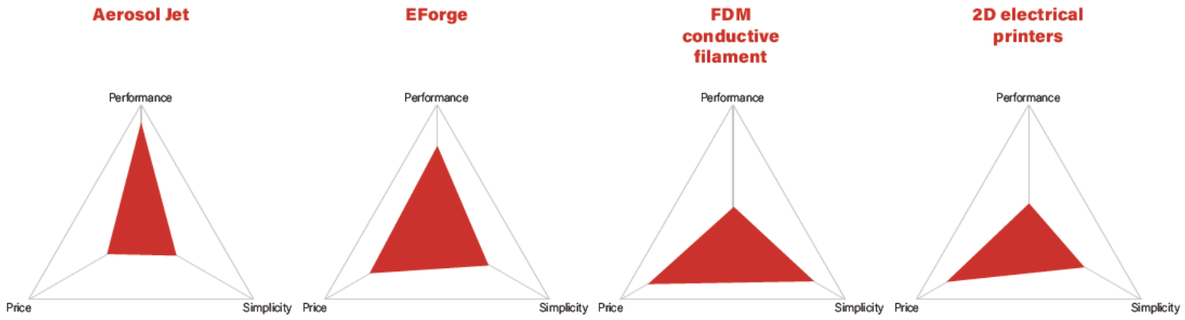


Figure 2.2: Rating the existing printers in the context of this project.

2.4 3D printer design rules

This chapter contains the design rules for this project. The rules are elaborated according to the project vision. The design rules follow from the answered sub questions 1.1 to 1.3. In this chapter the reasoning behind the design rules is further elaborated.

It is chosen in this project to work with a list of design rules instead of a list of requirements. Since the aim of this project is to work to a proof of concept rather than towards a product. The research shows that little is known for 3D printing electronics. There is a low number of competitors on the market of electrical printers. On this market a gap lays in a cost-effective, compact and simple design of a 3D printer that prints electronics. Therefore this project will focus on designing a proof of concept, creating a base for a 3D printer that can print cost-effective electronics.
Considering this, design rules are used as the guidelines of the project. They are categorized by general, performance, costs, simplicity and use.
Table 2.1 shows the list of design rules for this project. The rules are elaborated and set according to the previously conducted research.
The proof of concept is a step towards a design of an electrical 3D printer or an extruder that can print conductive material. This has been taken into account in the design rules when the printer or the extruder is mentioned.
The design rules are an extension to the project goal.

General
Design rules 1.1 to 1.3 are the direct extension from the project vision.

Performance
2.1 is a rule coming from the project goal.
Design rule 2.2 is meant to keep the prototype time as low as possible. The new electrical 3D printer should allow to print a prototype and use it to quickly iterate on the design. Therefore the time of printing should be limited.
Design rule 2.3 considers the quality of the printed electronics. As a high conductivity will lead to a higher price, the set resistivity is not the lowest possible. The desired resistivity is set to ensure the possibility of printing electronics.

Costs
The costs of prototyping and 3D printing should be low. The costs for conductive material and thermoplastic material should be doable for printing a prototype. The prices are based on what the market offers for low cost materials.

Simplicity
The rules for simplicity are set to create a printer that can be used by the majority of people: for designers and developers who are experimenting, prototyping and testing their first concept ideas. The 3D printers that can print conductive material that are now on the market, are not available for these people. These printers are made for a high-end niche, and cost too much to be used for prototypes. Moreover, these printers also need specific software to use the 3D printer. Making the 3D printer available also covers the usage of the printer. The users should be known with the 3D printing technology, however do not need to install and use complex software or slicing programs.
This proof of concept is targeting a gap in the market that will make this type of printing more accesible by making it cheaper and easy available.

Use
Conductive material can be harmful. Therefore it is important to design the extruder to be safe to use. Next to this placing the conductive material in the printer should be easy and straightforward.

Group	#	Description
General	1.1	The printer should be able to print integrated passive electronics.
	1.2	The extruder is designed to be combined with an extruder that can print at least one thermoplastic.
	1.3	The solder paste extruder is a start for a 3D FDM printer that can print electronics.
Performance	2.1	The printer should be able to at least 2D print integrated electronics and be the start of a design venture seeking to explore the 3D printing of integrated electronics.
	2.2	Printing a prototype with integrated electronics should not add too much time to the original printing time, when only printing thermoplastics.
	2.3	The printed conductive material should have a resistance of less than $0.2\ [\Omega]$.
Costs	3.1	The material expenses for $100\ [g]$ of conductive material should lay between $€10$ and $€100$.
	3.2	The material expenses for $100\ [g]$ of thermoplastic material should lay between $€1$ and $€10$.
	3.3	The retail price of the designed extruder should lay between $€50$ and $€200$.
Simplicity	4.1	The printer has a straight forward system.
	4.2	The printer is accessible for everyone.
	4.3	The printing materials should be readily available.
Use	5.1	The printer should be safe to use.
	5.2	Placing the conductive material should be easy and straight forward.

Table 2.1: The list of design rules.

2.5 The conductive material

Being able to print conductive material is essential. The type of material influences the quality, the costs and the simplicity of the products that can be printed. This paragraph details the choice of the conductive material, based on the study previously presented.

The goal is to print integrated electronics. To be able to do this, a conductive material needs to be extruded in a trace. There are several conductive materials, from pastes to conductive filaments. Conductive filament would be an accesible way of 3D printing on an FDM printer. These filaments can be easily placed on a DIY FDM printer and with adjusting the settings in the slicer, it is able to print an electrical integrated 3D print.
There are several conductive filaments on the market, from cheap to expensive.
The cheap filament comes with the disadvantage of high resistivity. For instance Protopasta: $30\ [\Omega*cm]$ with a price of $€10,-$ per $100\ [g]$. [12]
The most expensive conductive filament Electrify has a resistivity of $0.6\ [\Omega*m]$ before printing and comes at a price of around $€180,-$ per $100\ [g]$. [13]
The Aerosol Jet and other existing printers print with silver ink, which is rather expensive ($€450,-$ per $100\ [g]$.) but has an extremely low resistvity, $3*10^{-7}\ [\Omega*m]$. [1] [14]
There is also a possibility to print with solder paste. The price of solder paste compared to the resistivity is rather good. The price is $€100,-$ for $100\ [g]$, to a resistivity of around $0.002\ [\Omega*m]$ [15]

Exploring what material to use for printing conductive traces, the evaluation of each material is presented in Figure 2.4. These are compared with the project vision, presented in Figure 2.3.

The options are evaluated by the following design rules:

Performance
2.3 The printed conductive material should have a resistance of less than $0.2\ [\Omega]$.

Costs
3.1 The material expenses for $100\ [g]$ of conductive material should lay between $€10$ and $€100$.

Simplicity
4.2 The printer is accessible for everyone.

Insights (1)
It can be seen that solder paste scores medium on the three sets of requirements. The rest of the material blinks out in either one or two of them. However, comparing the project vision to the conductive materials, conductive filament 1 comes close to the project goal. However, the performance of this material is too low for the project goal. That is why solder paste is the best option to continue the project. The simplicity of printing solder paste is not that high, as printing solder paste has never happened. However the price and performance are in line with the project goal. For this reason, solder paste is the favorite option and will be used for this project.

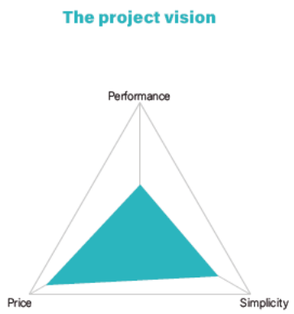


Figure 2.3: The project vision.

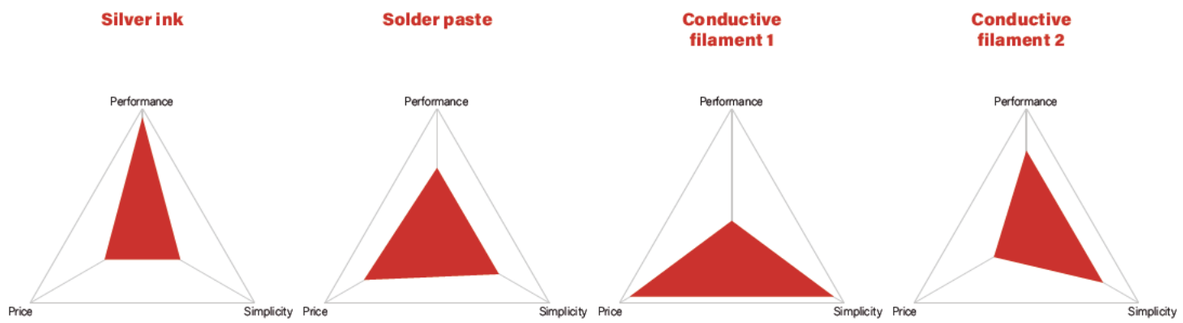


Figure 2.4: The evaluation of the conductive materials.

2.6 Extruding conductive materials

How to print conductive materials? The way of printing conductive materials is important, because it has influence on the quality, the price and the speed of the printing. This chapter presents ways to extrude solder paste, the material which has been chosen as best suited in the previous chapter.

As presented in chapter 2.3, no printer is currently printing solder paste. However the Aerosol Jet and the Voxel8 print with silver ink. Silver ink is a paste comparable to solder paste. Therefore the used printing methods could also be used for printing solder paste. Details can be find in Appendix B. The Voxel8 prints with a trace width of ***0.2 [mm]***, the size of the nozzle is ***0.250 [mm]***. The Voxel8 uses a pneumatic system. [9][10]

There are multiple other ways of pushing out the material (see Figure 2.5):

- Using an archimedes screw
- Using a plunger
- Using pressed air (a pneumatic pump)
- Using an aerosol jet

Two experiments are conducted to find the most suitable solution to push the material out. First, a method comparable to the plunger is tested. Second, a method with the screw is tested. Details can be find in Appendix C.
The Aerosol Jet is used in the Optomec printer, which is a complex printer. To push out the material three steps in the process are needed, as can be seen in Figure 2.5C.
The pneumatic pump of the Voxel8 also influences the build size of the printer. However is a less complex product.
In Figure 2.7 the four different methods are compared with Figure 2.6, the project vision. As the complexity and influence on build size are low when using a screw or a plunger these methods are worth considering. As the tests were only done manually, it is important to automate these methods and then compare the test results again.
However the methods are still comparable using the design rules. In this way a choice of method or several methods can already be made.

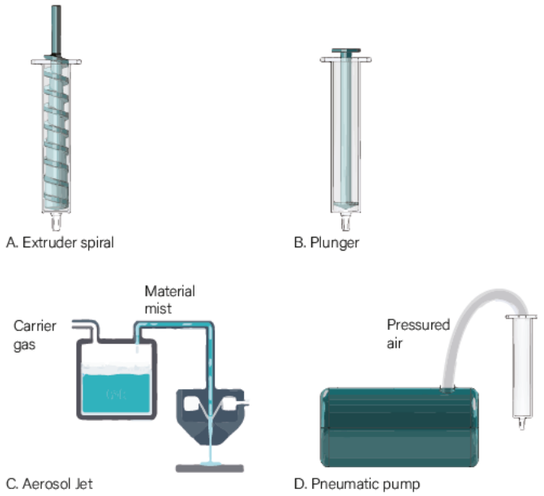


Figure 2.5: Different extruding methods.

The following set of design rules is taken into account:

Performance
2.2 Printing a prototype with integrated electronics should not add too much time to the original printing time, when only printing thermoplastics.

Costs
3.2 The retail price of the designed extruder should lay between ***€50*** and ***€200***.

Simplicity
4.1 The printer has a straight forward system.
4.2 The printer is accessible for everyone.

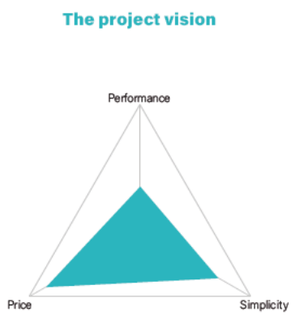


Figure 2.6: The project vision.

Insights (2)
Figure 2.6 shows the vision of this project. Figure 2.7 shows the comparison of different extruding methods. The Aerosol Jet scores high in performance, but low on the other requirements. The pneumatic pump scores low on the simplicity, on the contrary to the archimedes screw and the plunger method. These are closer to the project vision. For this reason, the archimedes screw and plunger are chosen for the continuation of the project.

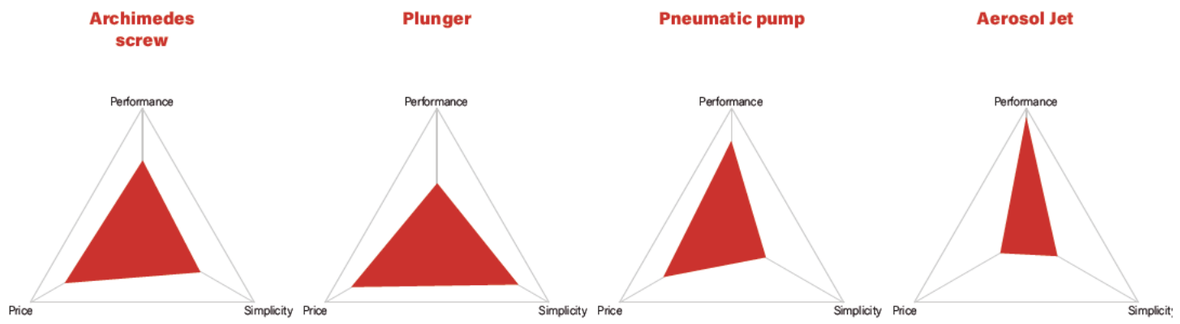


Figure 2.7: The evaluation of the extruding methods.

2.7 Curing solder paste

Solder paste is a conductive material that is used on PCBs. The solder paste is designed to reflow. It is not conductive until it is heated to a certain temperature. In this chapter, the different curing methods are studied. Finally, a method is chosen for the continuation of the project.

Method
There are several methods to cure solder paste. In this project, it is a wish that it can be done while printing. This provides the opportunity to produce a final prototype or product in one go. Research and small tests will be done to see which option is the best. The following options are being considered: oven, induction, soldering iron, infra-red, microwave and a laser. The challenge is to cure the solder paste while printing without deforming the thermoplastic. First, the method to cure the solder paste is researched. Second, the suitable thermoplastic material is researched. The first experiment was conducted with the solder paste $Sn96.5Ag3Cu0.5$, which has a melting point of $217\ [°C]$.
The solder paste first needs to be heated. The reflow diagram of the paste can help optimise and accelerate the process, but this is not considered here. The general reflow diagram is shown in Figure 2.8.
The different curing methods can be categorised either for industrial use or for consumer use. The main difference between these categories are the quantity (how many PCB's can be cured at once) and the price. The curing products made for the industry are at a price level, which is not relevant for this project. This project is therefore focussing only on the consumer usage options. More details can be found in Appendix D.

Oven
A reflow oven heats up the sample with convection. The heat of the oven heats up the solder paste to a temperature above the melting point of the solder paste. At that point the solder paste starts to reflow. The heat is uniformly distributed through the product. [16]
To be able to use this principle in a 3D printer, the printer can be enclosed and function as an oven too. Otherwise on side curing is not possible. However, printing in an enclosed printer becomes more popular as it gives the printed part better adhesion and quality.

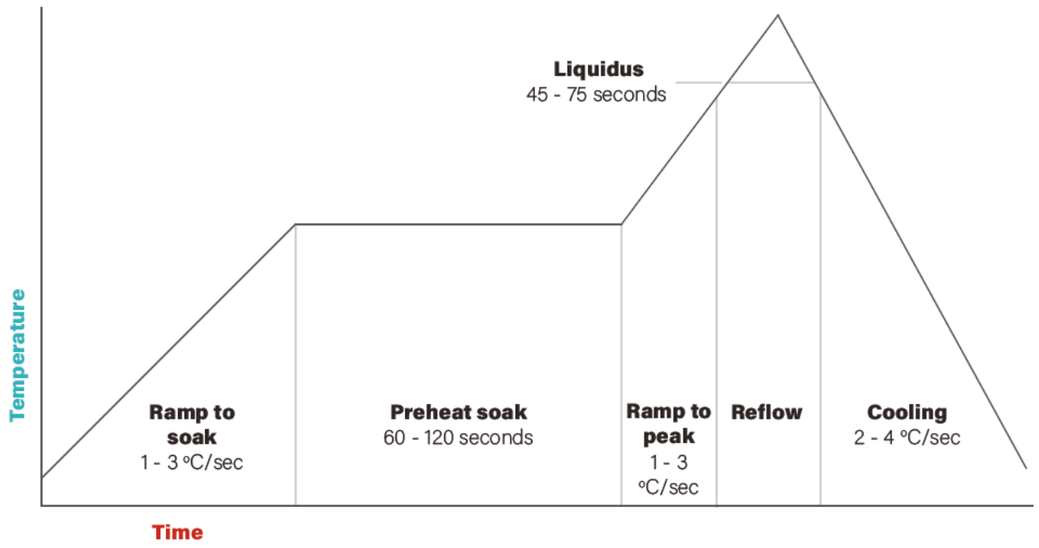


Figure 2.8: Reflow diagram

Soldering iron
A soldering iron is generally used to solder components to a PCB. The soldering iron gets very hot to be able to reflow the solder.
The solder iron is a tool that can be used to cure the solder paste. The heated point of the solder iron goes over the printed trace. In that way the solder paste could be cured. A drawback of this idea is that the solder paste can stick to the tip of the solder iron. [16]

Diode laser
Reflowing a PCB happens also with a diode laser. In this project a laser beam that is concentrated on one point could create enough heat to cure the paste. As the laser can be small, it becomes easy to attach it to the 3D printer. [16]

Heat up in nozzle
Why not cure the solder paste in a heated nozzle which can then be printed simultaneously? To be able to do this the material should be less pasty and more solid to be able to load it into the nozzle.
Right now, there is a kickstarter project (EForge) that has several conductive materials to be able to print electronics. All their material is heated up by a nozzle and then printed.
This project heats up the conductive material to $265\ [°C]$, which would be too high for solder paste. Indeed, it becomes very fluid at that temperature, and would make the printing harder. [8]
Another drawback of using a heated nozzle is that the conductive material behaves very abbrasive and the nozzle wears out very fast, giving unreliable printed traces in width and depth. [17]

Insights (3)
The main accesible curing methods can be found above. The diode laser can be a very good option to use. Heating the conductive material in the nozzle results in worn out nozzles. This option is therefore not a reliable option. The oven is a reliable option and easily available. Soldering irons are very accessable for consumer curing. However the biggest problem is that there will be contact with the material. This wears the tip of the soldering iron. To begin testing the reflow of solder paste there will be worked with an oven. It has to be explored how solder paste has to be cured and how the thermoplastic material will behave.

2.8 Thermoplastic filament

Curing a solder paste that has been printed in thermoplastic filament implies that the filament endures high temperature. The type of plastic should be able to withstand this heat. The solder paste with the lowest temperature that was found has a melting temperature of 139 °C.

To be able to cure the solder paste, it is important that the thermoplastic that is used can withstand high temperatures. The temperatures that the thermoplastic has to withstand depend on the solder paste and its reflow temperature. A widely available solder paste ***Sn42Bi57,6Ag0,4*** has a melting temperature of ***139 [°C]***, which means that the reflow temperature will be around ***145 [°C]***. [15]
The thermoplastic material should withstand this temperature for a short period of time.
There are three temperatures that influence the state and form of the thermoplastic. Two of them are directly related to the properties of the material, those are the glass temperature and the melting temperature. Above the glass temperature the material can deform. The material will start melting at the melting temperature.
The third temperature is the service temperature, which is a maximum and a minimum temperature at which the material can be used. The definition of the service temperature according to CES Edupack [18] is: "at which the material can reasonably be used without oxidation, chemical change or excessive deflection or "creep" becoming a problem."
There are four thermoplastic materials that have a melting temperature above the ***200 [°C]***. The glass temperatures differ from ***44*** to ***199 [°C]***. These materials are:

- PA ***44 - 66 [°C]***
- PET ***59 - 86 [°C]***
- PTFE ***116 - 132 [°C]***
- PEEK ***143 - 199 [°C]***

[17]

Using a material above the glass temperature is a risk, however it is not sure that it will be a problem. The materials can get stronger without deforming. This is called annealing. [19]

Working above the melting temperature the materials will deform definitely. Only a small range of temperatures are possible for the working conditions. Too high melting temperatures of filament cannot be printed on a regular 3D printer. This is the case with PEEK. Unfortunately, the printer and the used material must be easily available. Therefore PEEK is not a good option.
As the range of working temperatures is small, materials with a lower glass temperature than ***145 [°C]*** were also considered.
A thermoplastic like Nylon (PA) has melting temperatures between ***220*** to ***260 [°C]***, but glass temperatures of ***44*** to ***66 [°C]***. Therefore this material can be used in an oven. There are several Nylon filaments. Testing with these is the next step.
There is a difference in using the material filament and the pure material. For printing additives can be added to make the printing easier. This can result in lower melting temperatures. The printed material can also behave differently and have different glass and melting temperatures.
Nylon filaments that are sold vary with a melting temperature between ***125*** to ***190 [°C]***. There are nylon filaments with added glass fibers from an Italian company FiberForce, where the melting temperature is ***180 [°C]***. The heat deflection temperature is ***160 [°C]***. This filament can be a suitable material.
There is no PTFE filament for consumer usage. Only one printer can print PTFE, this is a printer from 3M. This makes this material moderately available, so not preferable in this project. [21] [22]

PET is a material that can be printed in the version of PET-G where additives are added to make it printable. This material could be an option.

Next to this, ColorFabb has some high temperature filaments. These filaments are blends of different materials and can be interesting as well. [20]

All the materials are evaluated according to the following design rules:

Simplicity
4.1 The printer has a straight forward system.
4.2 The printer is accessible for everyone.

Insights (4)
Figure 2.10 shows the comparison of the four thermoplastics. PA and PET come very close to the project vision. (Figure 2.9)
The next step is to conduct experiments with curing and the temperatures that the 3D prints can withstand.
As previously stated, ColorFabb also has designed high temperature resistant filaments. These will be tested as well.

Performance
2.2 Printing a prototype with integrated electronics should not add too much time to the original printing time, when only printing thermoplastics.

Costs
3.2 The material expenses for ***100 [g]*** of thermoplastic material should lay between ***€1*** and ***€10***.
3.3 The retail price of the designed extruder should lay between ***€50*** and ***€200***.

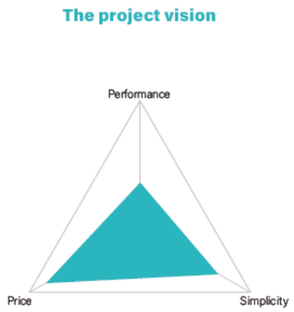


Figure 2.9: The project vision.

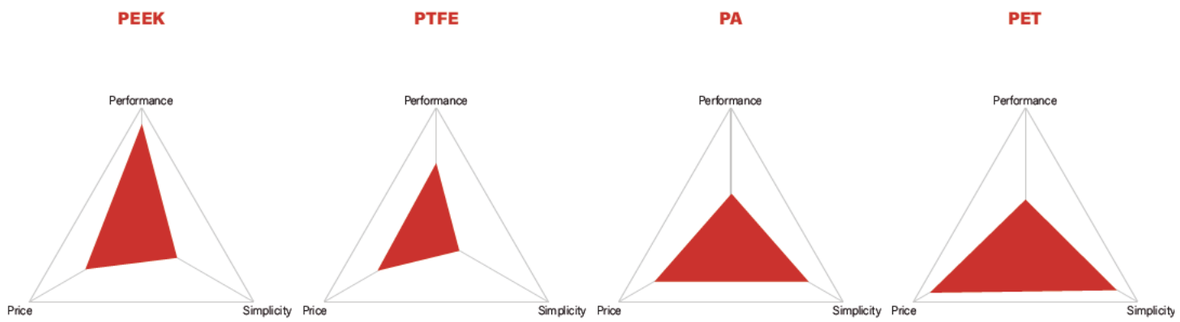


Figure 2.10: The comparison of four possible thermoplastics.

2.9 Design drivers

In this chapter the design drivers that came out of the research are described, per driver the specific insight leading to this information is given in brackets. These design drivers give a specific direction for further research in practice. These are the base for creating ideas and concepts for the 3D printer that can print electronics. The design drivers are divided into extruding solder paste and in curing the solder paste.

2.9.1 Curing solder paste and the effects on thermoplastic

The solder paste should be cured so it can behave as a conductive material.

How the solder paste will behave when being cured is influenced by the following parameters: the cross section of the trace, the used thermoplastic material, the temperature and time of curing and the method of curing. The temperature, time and method of curing will also influence the thermoplastic material.

Solder paste
The composition of the solder paste is important for the reflow temperature. However it also influences the safety of the solder paste. Several safety regulations are already in place for uncured solder paste. The composition influences this, so it is important to choose for a relatively safe product.
(1)

Thermoplastic material
The melting temperature should be above $200\ [^oC]$, to make sure the material will not deform when the solder paste is being cured. The glass transition temperature can be lower than the curing temperature. PET and PA are possible thermoplastics that are able to keep form when being heated. However other specifically designed filaments can be an option too.
It has to be taken into account that after being printed the material can behave differently and that the material has different melting temperatures and glass temperatures.
(4)

Shape of the trace
Solder paste is a material designed to reflow. Therefore the shape of the trace will have influence on how it is cured and on the conductivity of the trace. The width and depth will influence, as well as the overall shape.
(3)

Temperature of curing
The reflow diagram is made to quickly reflow the solder paste. However time in this case is not as important. It might be that the temperature can be set lower, using a slower reflow time. This has positive effects on the range of thermoplastics that can be used when a lower temperature for curing is possible.
(3)

Methods of curing
There are two most suitable options for curing solder paste: the oven or the diode laser. These methods will not touch the solder paste and therefore will not be wearing out the materials, for instance with a solder iron. First the oven will be tested to see how this method influences curing the solder paste.
(3)

2.9.2 Extruding solder paste

The extrusion method should be cost-effective and simple.

According to the previously presented research there are two methods suitable for this project, extruding with a screw and extruding with a plunger. In the next phase the following parameters have to be studied:

- Having enough strength to extrude the material.
- The control over the extruded line.
- Being able to print in 3D.

(2)

Archimedes screw
The design of the screw is important for the capabilities of the method. There are a lot of variables in the design of the screw.

- The design of the screw should be studied and its influence on the extruded line.

(2)

Plunger
The plunger is less complex than the design of the screw. The main design aspects of the plunger are the parameters of the control of the plunger.
The following aspects influence the plunger:

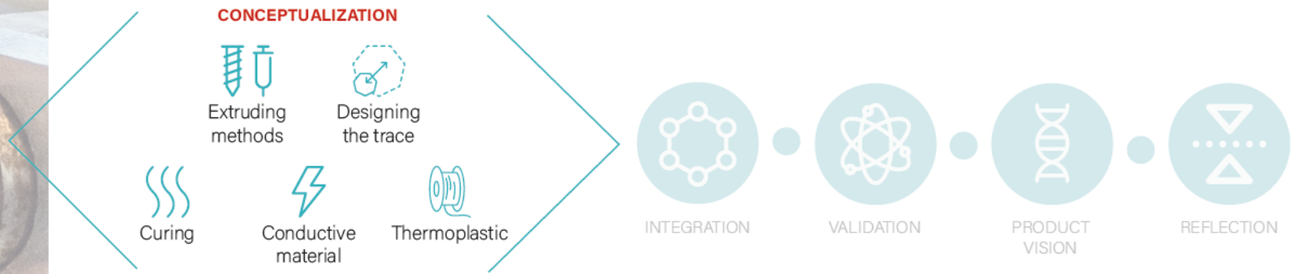
- Strenghth of the motor operating the plunger.
- Design of the retraction.

(2)

3 Conceptualization

After the research phase, choices are already made to narrow down the scope. The ideas are tested to further finetune the used materials and methods. All the testing is done by trial and error. The tests are therefore carefully documented to be able to redo them.





3.1 Concept directions

This chapter describes the steps taken in the conceptualization phase. The concepts that are developed are found by several experiments.

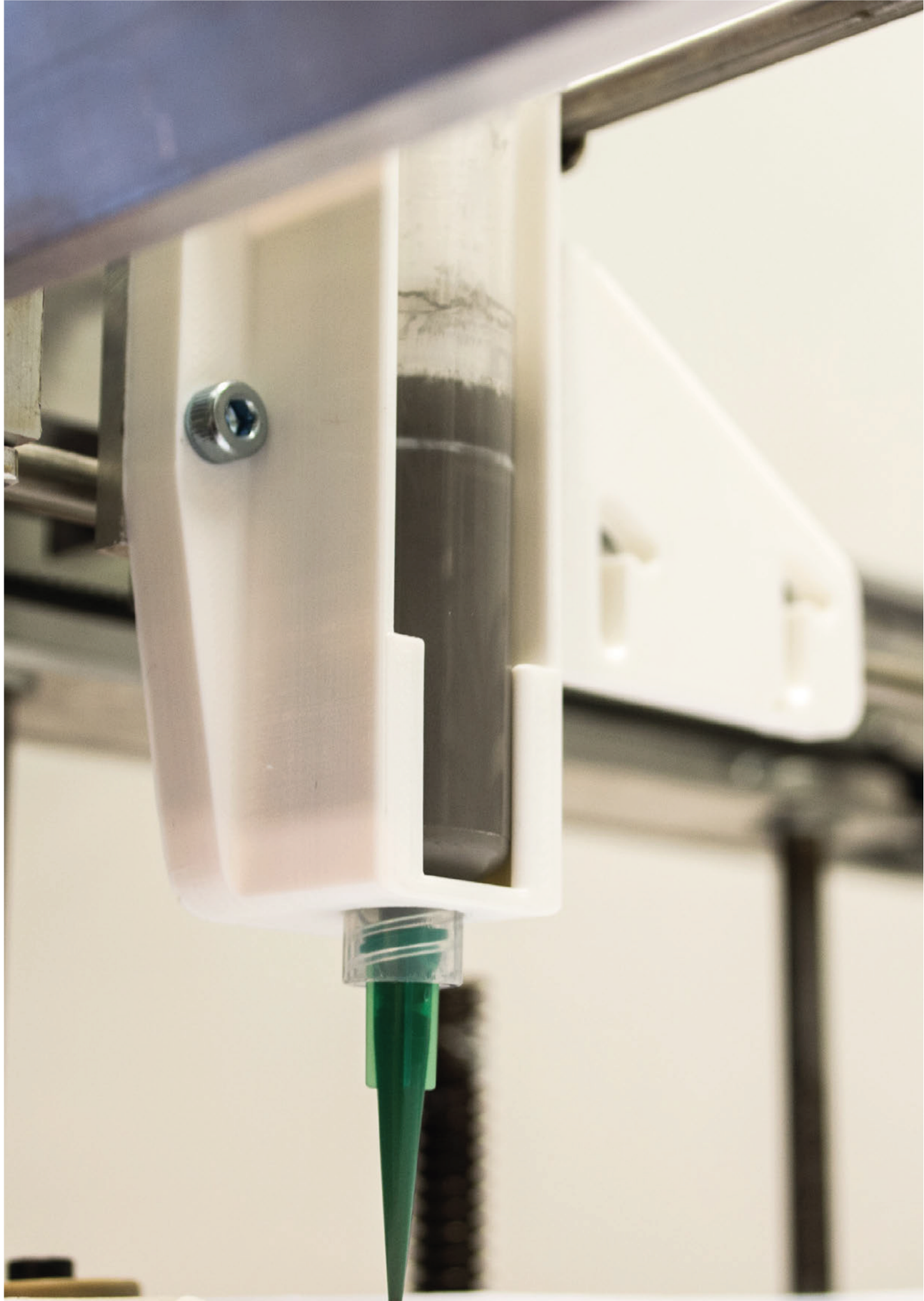
The concept directions are driven by the design drivers. It is discovered which steps need to be taken to achieve a proof of concept. The two main directions are:

Curing solder paste

Extruding solder paste

Per direction several parameters have to be studied. For curing solder paste a lot of parameters influence each other. The goal is to find the right combination of parameters to make the curing of the solder paste work.

For extruding solder paste research gave two promising solutions. These solutions, the archimedes screw and the plunger method, have to be studied. The goal is to extrude a consistent line of solder paste.



3.2 Curing solder paste

This chapter shows the experiments done with different kinds of solder paste, different trace shapes, different curing temperatures and reflow schemes. This is tested with trial and error. An overview of these experiments is presented.

Curing solder paste in a 3D print never happened before. Understanding the response of the solder paste and the connection between the solder paste and the thermoplastic is crucial for the development of the project. Besides, the type of solder paste has to be chosen, the right thermoplastic has to be chosen and the method of curing has to be chosen and tailored as well. It is important that the trace of solder paste is continuous and conductive.
In this chapter the experiments are described to find out the best combination of the above parameters.

On the next page, Figure 3.3 shows the overview of the experiments with curing solder paste and two kinds of thermoplastics and Figure 3.4 shows an extension of the experiments with different thermoplastics. The vertical axis presents the temperature of curing in $[^oC]$, whereas the horizontal axis presents the trace shape and measurements in $[mm]$, the used thermoplastic, the solder paste and the time in minutes of curing.
In the graph, check marks are added to indicate which traces are conductive over the full trace length.

The samples are 3D printed in an Ultimaker 3. The solder paste has been added by hand. The heating of the samples was done in a drying and heating oven. The oven is a Binder FP 115. Pictures of the oven are shown in Figure 3.1 and Figure 3.2.

The sample has been placed in the oven at room temperature and is heated up within the oven to the set temperature. It is important, following the reflow diagram of chapter 2.7, to not preheat the oven, but to let the sample warm up with the oven. At the set temperature the sample stayed in the oven for the given time and is cooled down afterwards, by opening the door of the oven.



Figure 3.1: Overview of used oven.



Figure 3.2: Settings of the binder..





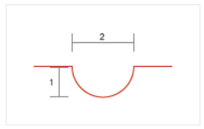
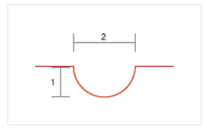
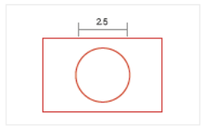
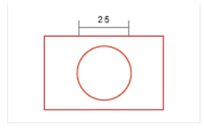
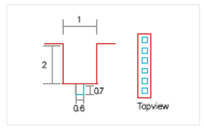
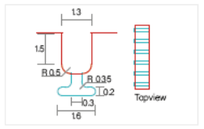
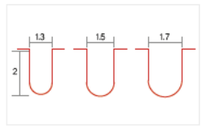
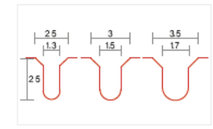
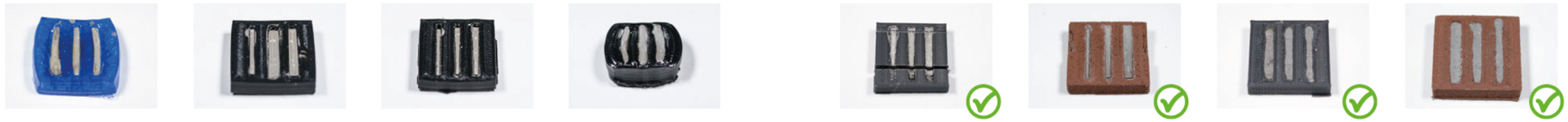
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Intersection of trace (in mm)								
Thermoplastic	ABS	HT filament	HT filament	HT filament	HT filament	HT filament	HT filament	HT filament
Solder paste	Solder paste A	Solder paste B	Solder paste B	Solder paste B	Solder paste B	Solder paste B	Solder paste B	Solder paste B
Curing time	2 minutes	2 minutes	2 minutes	2 minutes	2 minutes	2 minutes	2 minutes	10 minutes

Figure 3.3: Visualisation of the experiments with curing the solder paste.

Temperature in [°C]

142



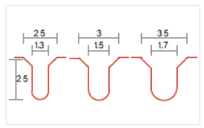
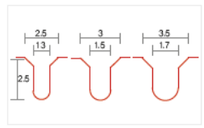
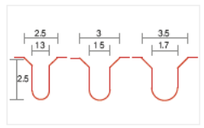
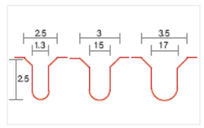
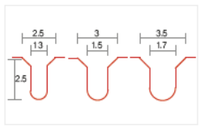
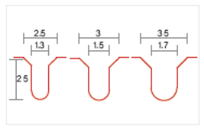
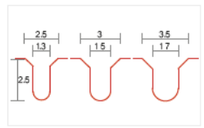
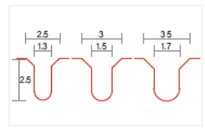
	Sample 9	Sample 10	Sample 11	Sample 12	Sample 13	Sample 14	Sample 15	Sample 16
Intersection of trace in [mm]								
Thermoplastic	*FF Glass HD*	*PC*	*Ngen*	*XT filament*	*PLA X3*	*Copper filament*	*PLA X3*	*Copper filament*
Solder paste	*Solder paste B*	*Solder paste B*	*Solder paste B*	*Solder paste B*	*Solder paste B*	*Solder paste B*	*Solder paste C 10*	*Solder paste C 10*
Curing time	*10 minutes*	*10 minutes*	*10 minutes*	*10 minutes*	*10 minutes*	*10 minutes*	*minutes*	*minutes*

Figure 3.4: Visualisation of the experiments with curing the solder paste and the behaviour of different thermoplastics.

3.2.1 Shape of the trace

Figure 3.3 shows the evolution of the trace shape. As can be seen in sample 2 the solder paste tends to form into a sphere. The creation of a mechanical bond by adding a pattern of pockets to the trace, is tried to prevent this phenomena, as is presented in Figure 3.5 and Figure 3.6.
However, the pockets did not work, as can be seen with samples 5 and 6. The trace width is considered being too small. It is therefore chosen to try a deeper trace than in sample 1 and 2.
As sample 7 shows, the solder paste is laying on top of the printed material. Therefore it is chosen to make the trace at the top wider, so the material can reflow in the trace and not on top of the print.

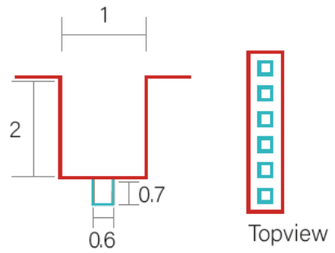


Figure 3.5: Intersection of a trace with mechanical bond.

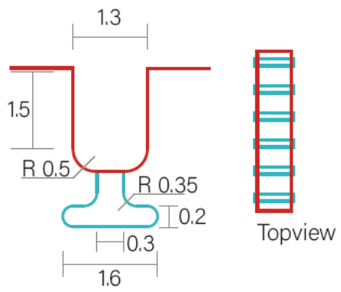


Figure 3.6: Intersection of a trace with mechanical bond.

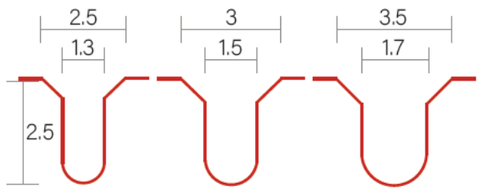


Figure 3.7: Extra space for reflow.

Conclusion
The best working shape turned out to be the form shown in Figure 3.7. All three widths have a good conductivity. The form has a wider top to let the solder paste stay in the trace. The form is deep and wide comparing to the previous forms, the widened top of the trace makes sure the solder paste stays in the trace. This shape of the trace improves the reflow of the solder paste. Three different widths of the shape were tested. There is no difference in conductivity between the different widths. Therefore the smallest width and form has been chosen for the continuation of this project.

3.2.2 Solder paste

The melting temperature of the solder paste highly depends on its type. A low melting temperature is handy for two main reasons: it expands the working framework for using a thermoplastic filament. Next the electrical components in the 3D printer will not be damaged by the heat (when the curing method is an oven).
After some research, three types of solder paste were selected for the low melting temperature that can be an applicable option in this project. Their composition and melting temperature are as follows:

- ***Sn18Pb32Bi50 98 [°C]***
- ***Sn42Bi57,6Ag0,4 138 [°C]***
- ***Sn42Bi57 138 [°C]***

The first option is unfortunately toxic as it contains lead. However, it is a good starting point to see how it cures and if it is a good combination with the used thermoplastic. Unfortunately this solder paste is hardly available and the price for just one syringe of ***10 [mL]*** is ***€50,-***.
The last two options differ in the added silver. The added silver gives the solder paste a better mechanical structure, improves wettability and strengthens the fatigue resistance, therefore the second option was chosen too to use in the experiments. [23][24]
The following solder pastes are used in the experiments. The composition, melting temperature and price per ***10 [mL]*** of the solder pastes are:

A. ***Sn96.5Ag3Cu0.5 217 [°C] €37,-***
B. ***Sn42Bi57,6Ag0,4 139 [°C] €33,-***
C. ***Sn18Pb32Bi50 98 [°C] €50,-***
[15] [25] [26]

Solder paste A has been used as this solder paste was readily available in the Applied labs. A solder paste with a low melting temperature is preferred, therefore no further tests with solder paste A are conducted.
Figure 3.4 shows the extended experiments with solder paste C. It can be seen that this solder paste does not shrink as solder paste B. The three solder pastes used in the experiments are compared in Figure 3.8.

Conclusion
Solder paste C is scarce, toxic and more expensive than the two other solder pastes. Solder paste A is slightly more expensive than solder paste B. Solder paste B is way less toxic than C and comes the closest to the project vision. Therefore there is chosen to work with solder paste B.

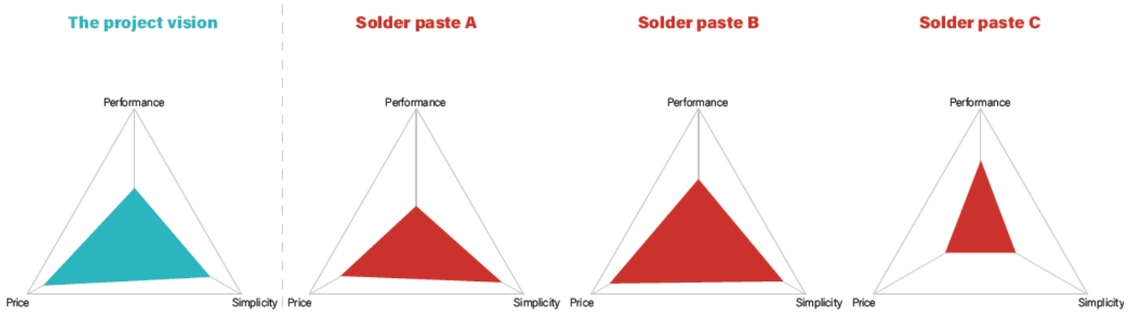


Figure 3.8: The comparison of solder paste A, B and C.

3.2.3 Thermoplastic filament

As seen in chapter 2.8 not many thermoplastics can withstand high temperatures. It is therefore needed to find the threshold of temperature that the filament can withstand. As previously mentioned, materials have a melting temperature, a glass temperature and also a service temperature. The filaments that are tested have been searched to have a high melting temperature. Next to ABS and HT filament seen in Figure 3.3, Figure 3.4 shows other filaments tested at the temperature where solder paste B reflows the best. In Figure 3.4 the check marks give the indication that these thermoplastics are not deformed by the heat.

Testing different filaments

The filaments are printed on an Ultimaker 3. The printed blocks have three traces where solder paste is added. The blocks are heated up in an oven. ABS is heated up from 120 to $160\ [^oC]$. See Sample 1 in Figure 3.3. Further details can be found in Appendix E.
The HT filaments are heated from 130 to $160\ [^oC]$. The rest of the filaments and the HT filaments are tested with the right situation of curing the solder paste. These are tested at $142\ [^oC]$ for ten minutes. Seen in Figure 3.4.
The following filaments are tested:

- ABS
- HT clear filament from ColorFabb
- HT light grey filament from ColorFabb
- PA CF filament from ColorFabb
- PLA X³
- Copper filled filament
- Glass HD
- PC
- Ngen
- XT filament from ColorFabb

The effects of heat on ABS is deformation at $130\ [^oC]$. This is plastic deformation, but the material stays rigid.
For the HT filament, the effect is different: it softens at $160\ [^oC]$. When the material is now touched it will deform. It is plastically deformed when cooled down. At $150\ [^oC]$ the material starts to slightly deform.
The effect of heat on PA CF is that the material gets less flexible. After reaching the temperature of $160\ [^oC]$, the material becomes less bendable.

Metal filled filament

Solder paste contains little metal particles that form the conductive trace. During curing the flux melts with the particles in it. The paste is made to reflow very well on other metal plates, like on PCBs. Therefore the possibility of using metal filled filament, which is non conductive, is also explored. The filament that is used has 80% copper particles in PLA. The traces are cured using slow reflow. The solder paste stays in a flat line and is properly cured. The difference with using copper filled filament and PLA X³ is the flux that is laying on top of the trace. However, this does not give different results in conductivity.

Conclusion

Figure 3.4 shows that PLA X³ and the copper filament are able to withstand the heat. To see which material best fits the project vision, both materials are compared in Figure 3.9. The copper filament looks different from other 3D printed parts. It is very brittle and comes in only one color. Next to this it is an abbrasive material and wears out the nozzle a lot quicker than PLA X³. PLA X³ has better aesthetics, is easier to print and does not wear out the nozzle fast. For continuation of this project there is chosen for PLA X³.

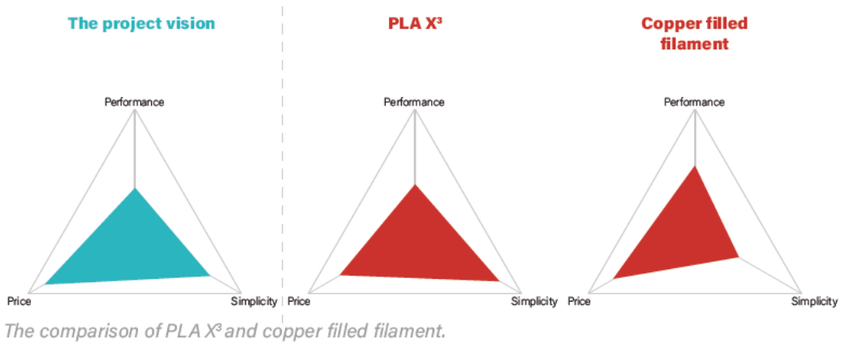


Figure 3.9: The comparison of PLA X³ and copper filled filament.

3.2.4 Temperature and time of curing

The different solder pastes have the same reflow diagram, however at different temperatures. The first experiment is done by testing the temperature at which the solder paste is conductive. This has been done with ABS prints and solder paste A, with a melting temperature of $217\ [°C]$.
The full experiment can be found in Appendix E. The conclusion of this experiment was that the solder paste becomes conductive before the melting temperature. However, the resistivity below melting temperature is around $0.8\ [\Omega]$. When the solder paste has been cured above melting temperature the resistivity is at most $0.2\ [\Omega]$.
Later experiments showed that when the solder paste is being cured the material becomes a sphere, it does not stay in the printed trace.
Figure 3.3 shows that above $150\ [°C]$ the solder paste is creeping and not staying in the trace. Therefore an experiment with slow reflow and more specific temperatures between 140 and $146\ [°C]$ has been conducted. Solder paste B can be cured, with a good conductivity and smooth trace, when slowly heating up to $142\ [°C]$ and staying at this temperature for $10\ minutes$.

Conclusion
Slow reflow showed an improvement for the cured solder paste. The paste stayed in the trace and became conductive. To continue this project slow reflow has been chosen for curing the solder paste.

3.2.5 Methods of curing

The experiments are conducted with a drying and heating oven of Binder, model FP 115. In order to meet the most important aspects of the defined scope (see Chapter 1.1) a deliberate choice has been made to perfect the succesfully demonstrated heating method with the drying and heating oven and to not test other curing methods (laser, soldering iron). The oven method cures the sample uniformly. This method cannot be compared to other methods, as no other methods were tested. However, this method has been proven to work. For the continuation of this project the drying and heating oven will be used.

3.2.6 Evaluation of the resistivity of the trace

The curing method, curing process and used thermoplastic are decided. It is needed to evaluate the resistivity of the trace. To do this one meter of the trace is 3D printed. On both ends of this meter, hard core copper wire is placed. On these spots the multimeter can measure the resistivity over one meter.
The meter of solder paste is presented in Figure 3.10 and Figure 3.11.
The measured resistivity is $2.0\ [\Omega*m]$.

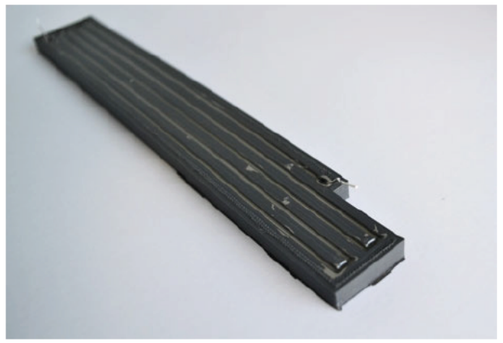


Figure 3.10: A 1 meter trace of solder paste.



Figure 3.11: A close up of the 1 meter solder paste.

3.3 Extruding solder paste

This chapter shows the experiments conducted with two extruding methods, the archimedes screw and the plunger method. This is tested by combining scientific knowledge and practical skill in an iterative approach. These experiments are presented in a clear overview.

The goal of these experiments is to figure out which method of extruding works best for the achievement of the project goal. The experiments target to print a constant and continuous line of solder paste, which can later be printed in a 3D print.

3.3.1 The archimedes screw

The next page Figure 3.15 shows the overview of the experiments with extruding solder paste. The vertical axis shows the different g-code configurations and the printed traces. The horizontal axis shows the iterations of the design of the screw. Appendix G shows the used g-codes.
Figure 3.12 presents the initial setup. A NEMA 17 stepper motor is used with stepper drivers with 1/16 microsteps. The NEMA 17 has a 1.8^{o} step angle and a holding torque of $0.48\ [Nm]$. The nozzle is a taper tip 18, the diameter is $0.838\ [mm]$. Subsequent iterations are shown in Figure 3.13 and Figure 3.14.
G-code is used to control the screw and the feed rate.

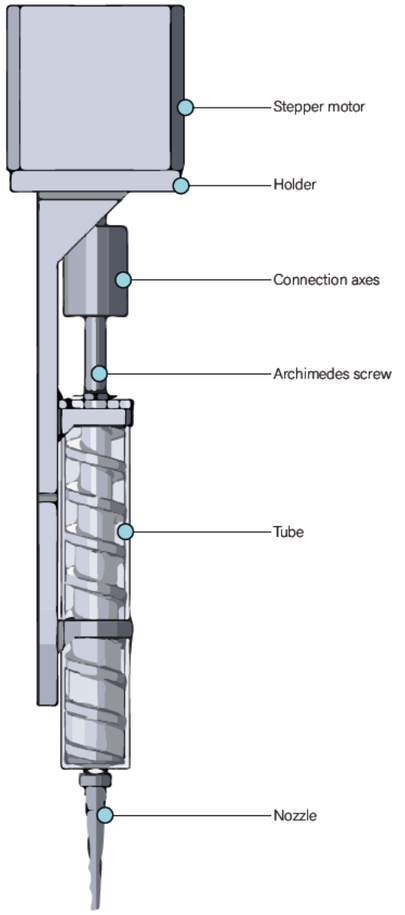


Figure 3.12: The setup of the archimedes screw.

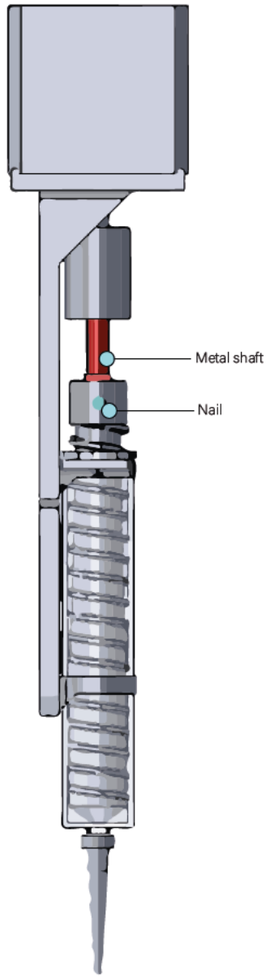


Figure 3.13: The adapted setup of the archimedes screw.

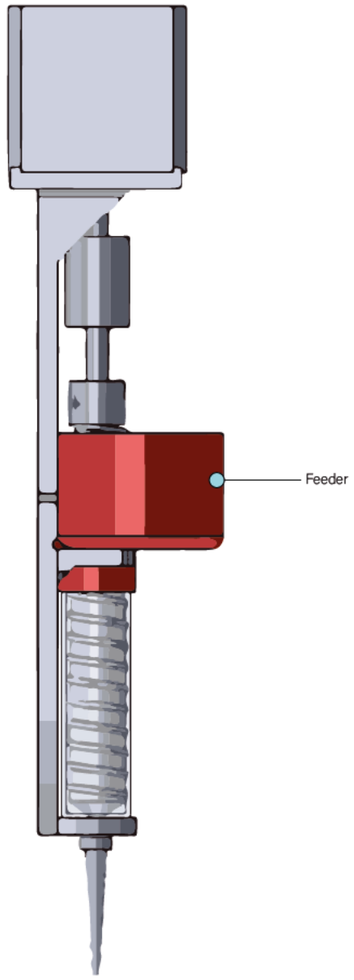
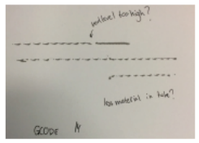
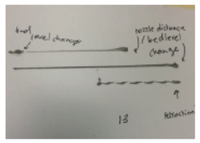


Figure 3.14: The setup of the archimedes screw.



Lines
G-code 4



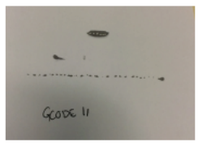
Lines
G-code 3



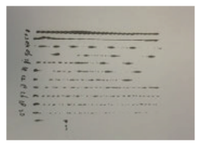
Square
G-code 1



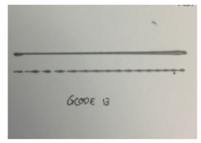
Lines
G-code 2



Lines
G-code 2



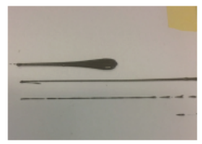
Linear advance
G-code 5



Lines
G-code 3



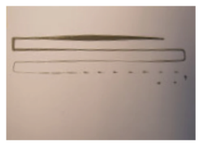
Printing mosterd
G-code 7



Lines
G-code 3



Continuous line
G-code 6



Continuous line
G-code 6

Iterations

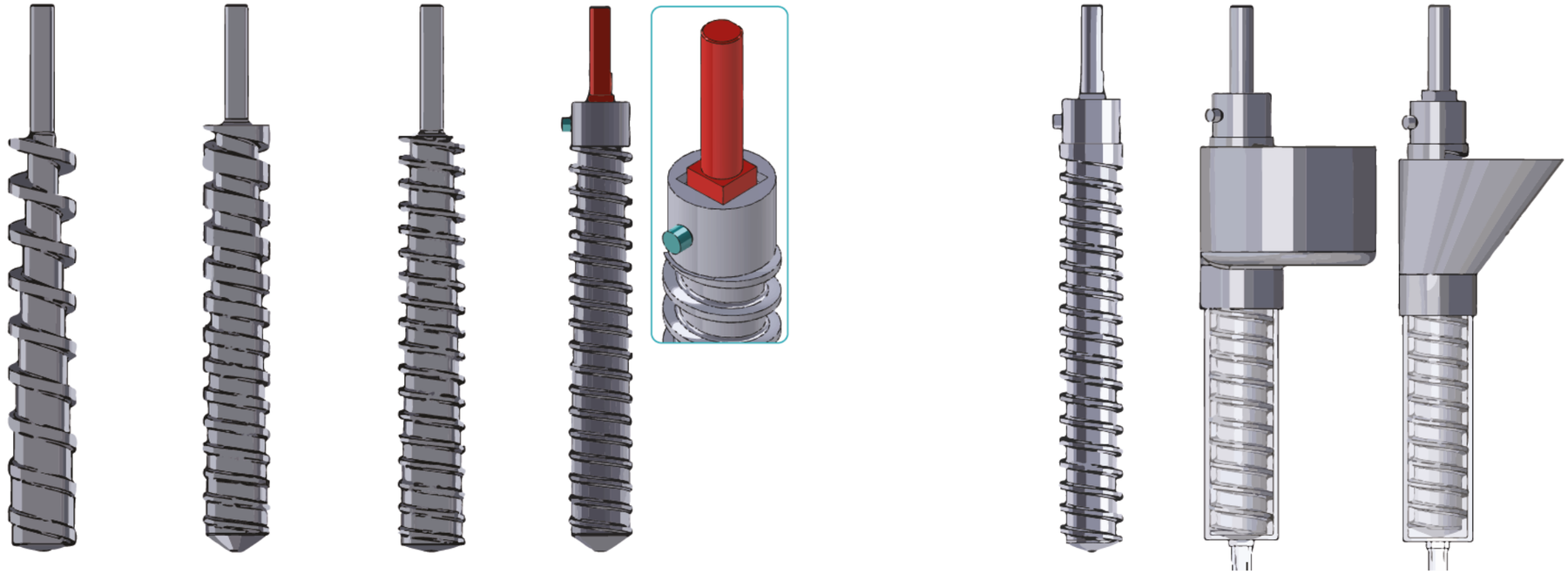


Figure 3.15: Visualisation of the experiments with extruding solder paste.

Screw design
The design of the screw is based on an extrusion screw of plastic injection moulding. A simplified geometry of this screw can be seen in Figure 3.16. The screw has three areas: the feeding area, the compression area and the metering area. [27]
In the experiments the screw is optimized to print a constant and continuous line of solder paste. The conical design of the screw results in a high compression rate of the material. The motor is on its maximal torque and not able to turn quicker. The iterations of the screw are into lowering the compression rate of the material. Next samples show a smaller pitch and a slightly less conical design. Lateron it was decided to rule these parameters out and choose a straight screw, to release the compression and pressure build up. The final design has more windings to have less torque on the motor. Less material is moved downwards so the motor is able to turn faster.

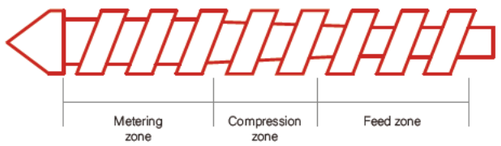


Figure 3.16: Screw for injection molding.

Nozzle size
A 0.8 nozzle is chosen for the syringe. This nozzle came with the syringe and is a taper tip 18.
The feed rate and speed of printing will be different when using different nozzles. When the printer is able to print a constant line of solder paste and all the parameters are known it is possible to choose a smaller nozzle.

Connection of the screw
The screw is slipping in the connection part. Therefore the axis of the screw has to be optimized. At this moment the connection of the screw is 3D printed with the screw as one single part. However the coupling part will connect better if the connection is made from metal.
A new design is made to connect the screw with the coupling, presented in Figure 3.15 and Figure 3.17. This design has been tested and the screw does not slip anymore.

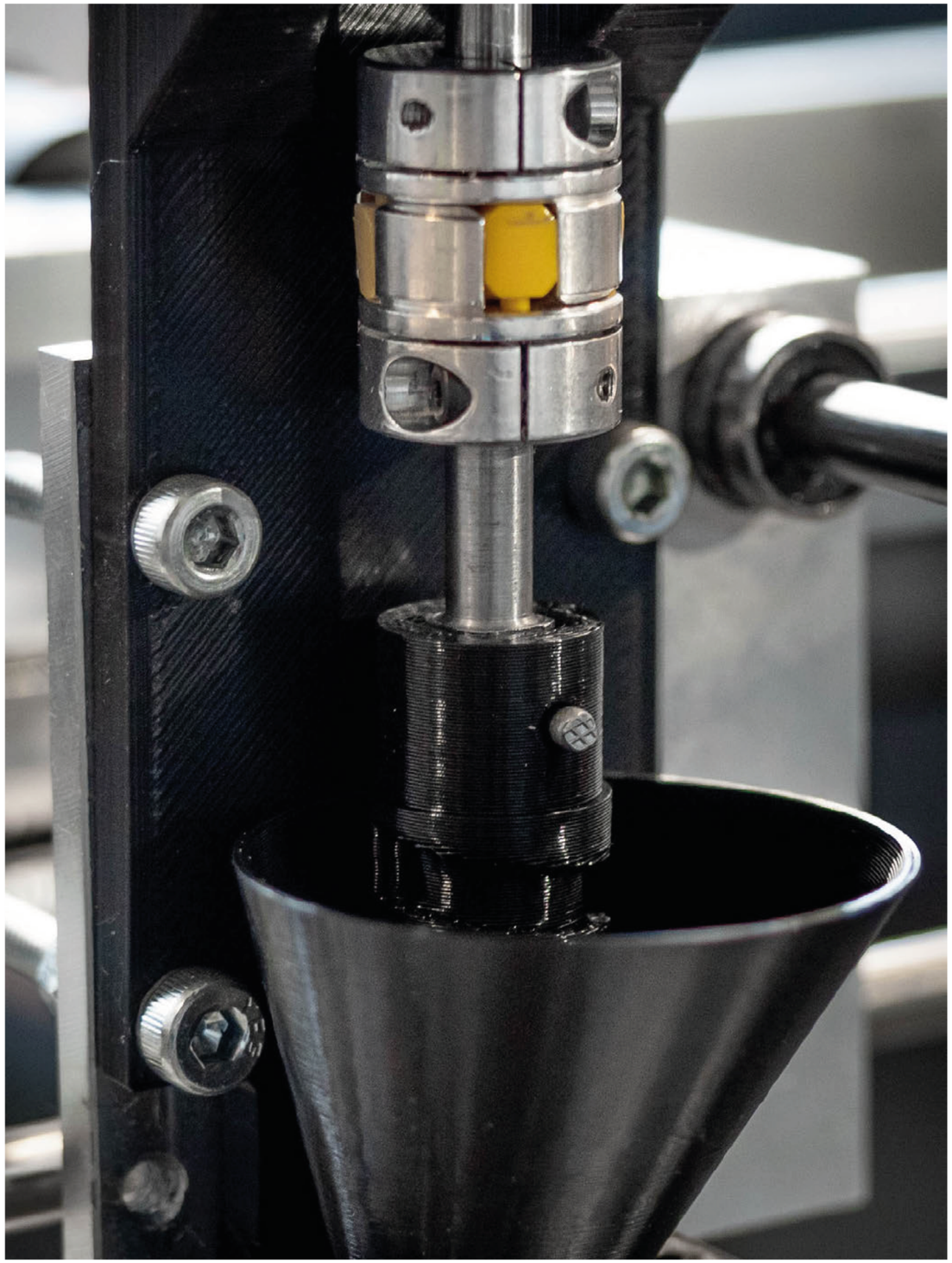


Figure 3.17: Metal connection to the screw, secured with a nail.

Troubleshooting

As it can be seen in Figure 3.15, the previously optimised setup does not allow to reach the target of the required line. To be able to troubleshoot the problem the viscosity of the solder paste will be studied, as this seems one of the problems. To see if the method works with less viscous materials, it was chosen to test the most viscous material below solder paste. The last print has been printed with mosterd. This material is less viscous than solder paste, however very viscous compared with other materials. [28] The full experiment can be found in Appendix F.

Printing with mosterd gave better results than with solder paste, however air is dragged in to the setup and therefore prints a non-continuous line, see Figure 3.18.

The mosterd is being dragged in the screw by using the feeder, and solder paste is not. The solder paste sticks to the sides of the feeder and does not slide in, see Figure 3.19.



Figure 3.18: Printing solder paste.

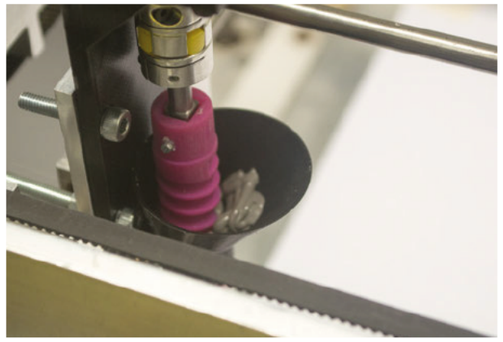


Figure 3.19: Sticky solder paste in the feeder.

Conclusion

Solder paste turns out to be a difficult material to work with. It is extremely viscous and differs from other fluids as it is compressable. Solder paste consists out of flux and little metal balls, it is a suspension. Another difficulty is that the thread of the screw cannot be calculated. Therefore in the previous experiments it has been based on a extrusion screw for injection molding. However, the materials and use of the screw are different. The iterations of the screw designs are based on logical reasoning. The ideal configuration of the design of the screw has not been hit with this experiential approach. This does not mean that the idea of using the screw will not work. A working design of the screw did not appear in the search area. Finally lines have been printed with the screw, but the thickness of the lines was not continuous.

Other difficulties lay in the amount of parameters that influence the printed line. Controlling the screw with different feed rates and extrusion rates could not be optimised. Considering that the design of the screw was not optimal, the goal using the archimedes screw was not reached.

3.3.2 Plunger method

The first setup is shown in Figure 3.20. The stepper motor is a NEMA 17 running at a stepper driver with 1/16th microsteps. The NEMA 17 has a 1.8^{o} step angle and a holding torque of $0.48\ [Nm]$. An iteration on this setup is shown in Figure 3.21. This setup is designed to control the plunger in a more accurately. The second setup has a screw length of $100\ [mm]$, it has a double thread of M5 with a pitch of $1\ [mm]$. A different motor was used during the second iteration. The motor is a NEMA16 with a holding torque of $20\ [g*cm^2]$. The full step angle is 1.8^{o}. The same stepper driver with 1/16th microsteps is used. The NEMA16 is a non-captive actuator, the screw is moving through the motor.

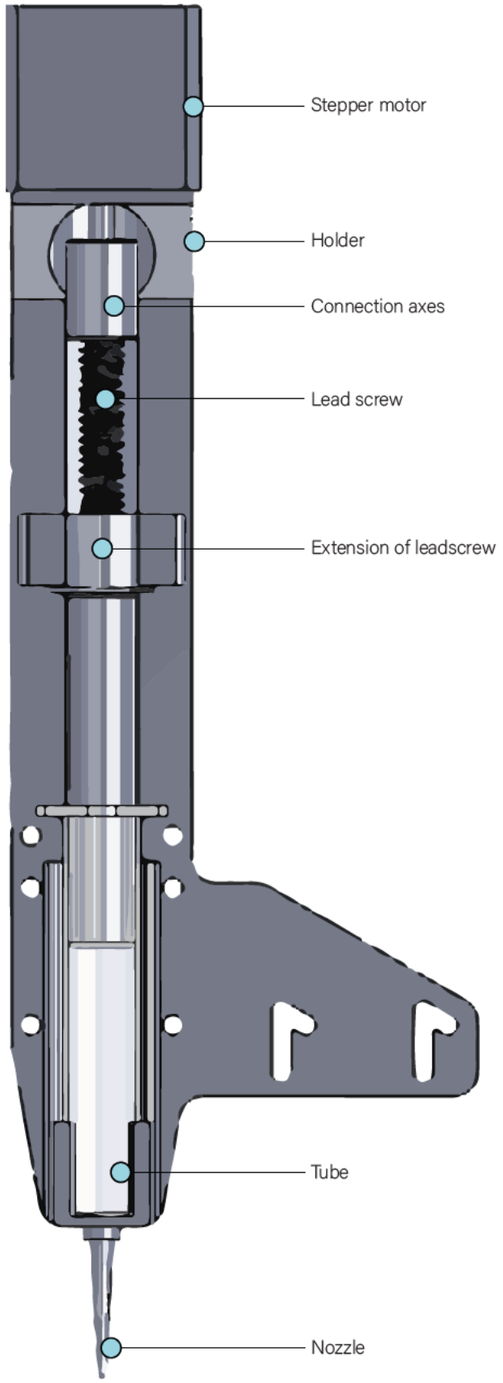


Figure 3.20: The first setup of the plunger method.

Volume

G-code is used to control the extrusion motor, this is done by using values for E. (See Appendix I for an explanation of g-code) The E-value is how many millimeters the plunger is moving down or upwards. Slicer programs, used to slice a 3D model into g-code, calculate the volume that has to be extruded and turn it into the E value, how many millimeters the extruder has to move the filament. [29]
The theoretical extrusion profile is a circle, which can be used to calculate the volume of the line of solder paste that needs to be printed. [30]
Same can be done using the plunger. This has been calculated as follows. See Figure 3.22 for the visualisation. The extrusion profile of the line that will be printed has a radius of $0.4\ [mm]$. The length of the line is 100 mm. The volume of the printed line is:

$$V1 = Pi*(0.4)^2*100 = 50.24\ [mm^3]$$

This volume is further defined as the baseline volume. The E value in the g-code defines how much the plunger moves downwards. This means that the E value can be calculated. The inner radius of the tube is $7.75\ [mm]$.

$$V2 = Pi*(7.75)^2*E$$

As the volume of the printed line and the volume that is coming out of the tube has to be the same, it can be said that $V1 = V2$.
In that way the E value can be calculated:

$$E=V1/Pi*(7.75)^2$$

This calculation serves as the base of the printing settings.
The g-code has been tested with several percentages of the calculated volume. See Appendix H.

Printing settings

The goal is to print a continuous and constant line of solder paste. The movement of the plunger, extrusion rate (E value) and feed rate have influence on this. See Figure 3.23 for a visualisation of this matter. Several experiments with these parameters are done. Based on the conclusion of these experiments the search area for a good extruded line has been set.
First the different volumes are tested at a feed rate of $300\ [mm/min]$. As calculated in the previous paragraph the 100% volume for a $10\ [cm]$ line is $50.24\ [mm^3]$. The percentages of the baseline volume are tested from 100% to 1000%, with steps of 100%. With a volume percentage of 900% different feed rates are tested, from 50 to $500\ [mm/min]$ with steps of 50. The results are shown in Figure 3.24 and Figure 3.25.

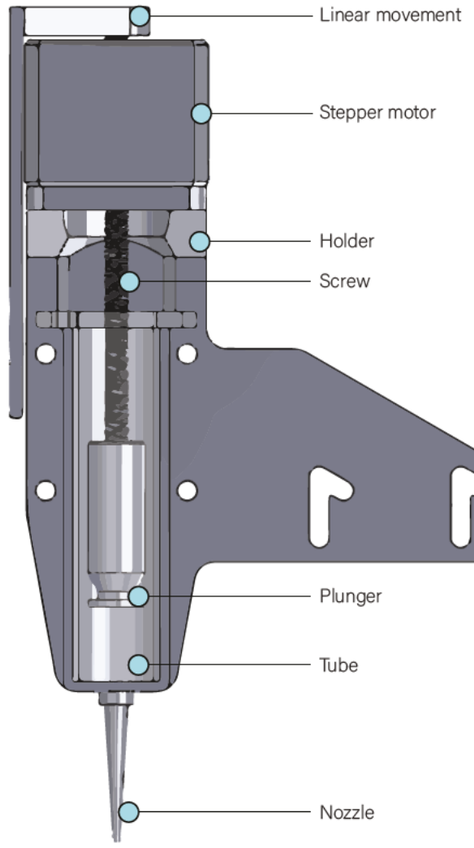


Figure 3.21: The second setup of the plunger method.

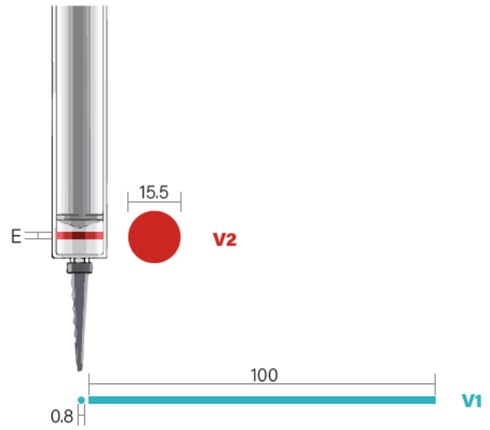


Figure 3.22: Visualisation of the volume (measurements in mm)

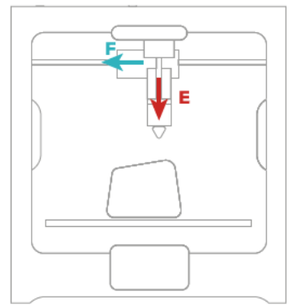


Figure 3.23: Visualisation of feed rate and extrusion rate.

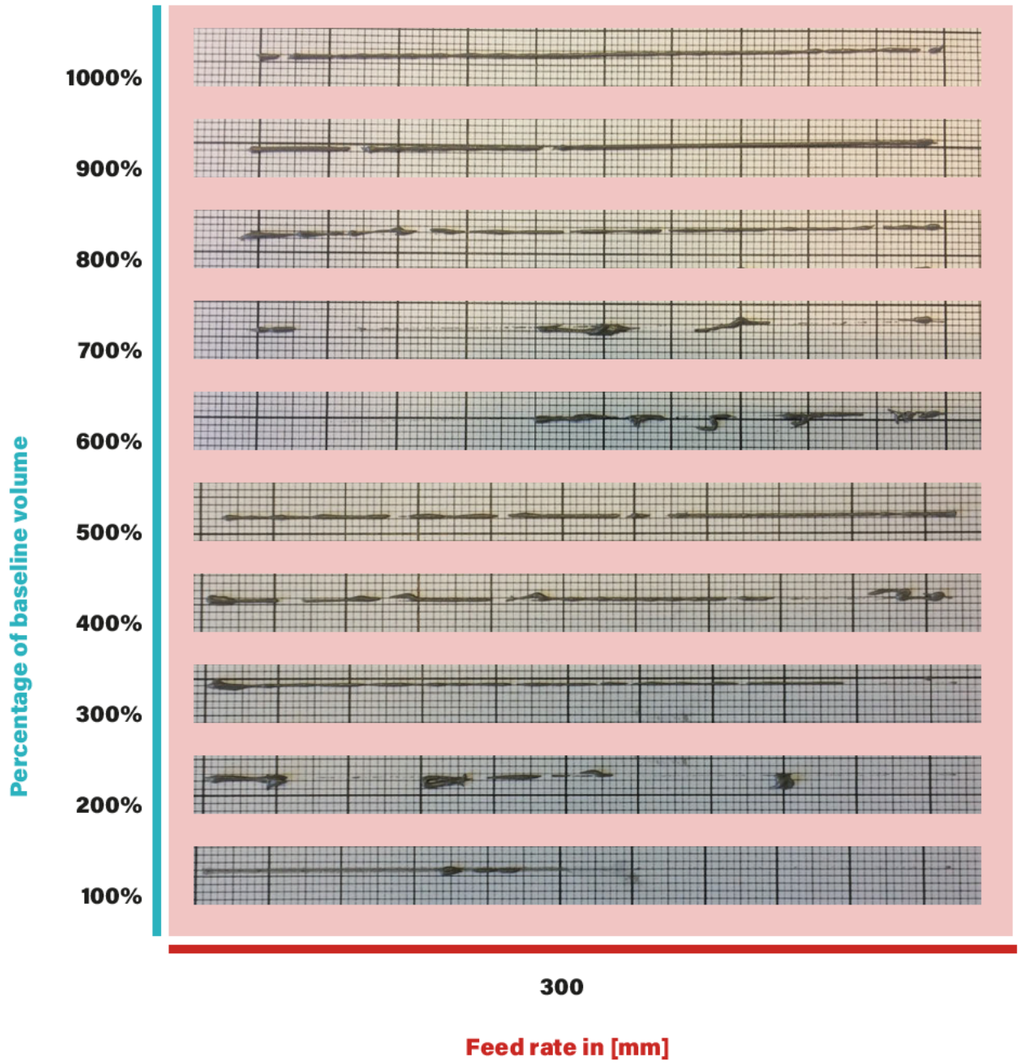


Figure 3.24: Graph of tested percentages of the baseline volume.

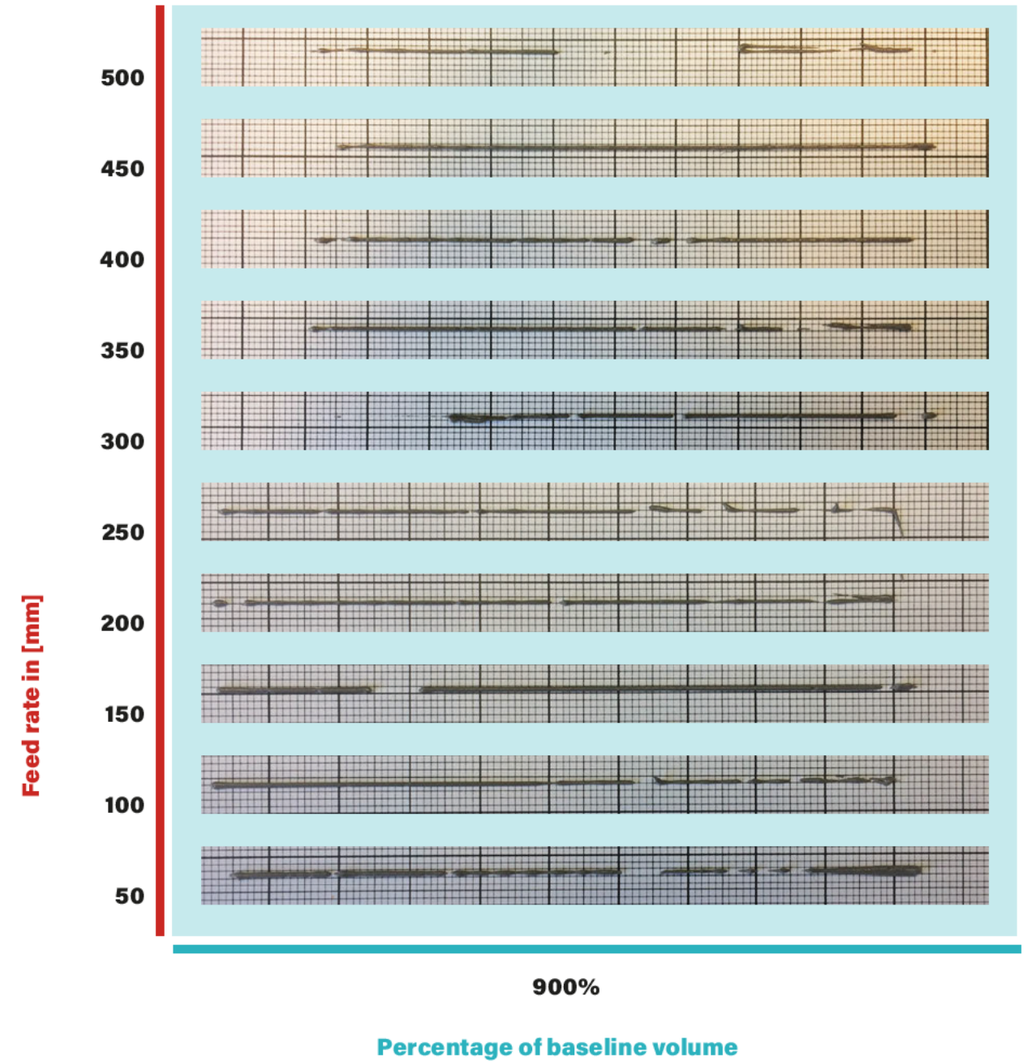


Figure 3.25: Graph of tested feed rates.

Results of the plunger method
The results of testing different volumes and feedrates are shown in Figure 3.24 and Figure 3.25. The configuration of these tests is shown in Figure 3.26. Not all combinations have been tested, however the tested configurations give an indication of which parameters could be the best.
Seen in the experiment the line printed at ***900%*** at a feed rate of ***150*** has a constant thickness. The only problem is that a gap appears in the line.
Higher feed rates, above ***300*** give lines that are not fully printed from start to end.
Lower volumes than ***900%*** do not give a good result, the lines are not straight and not continuous.

Conclusion
The perfect line has not been printed in the previous tests, however it can be said in which area of feed rates and extrusion rates can be researched.
A low feed rate has positive effects on the printed line. A high volume as well. The search area is shown in Figure 3.26.
This project will continue with the configuration of ***900%*** and a feed rate of ***150 [mm/min]***.

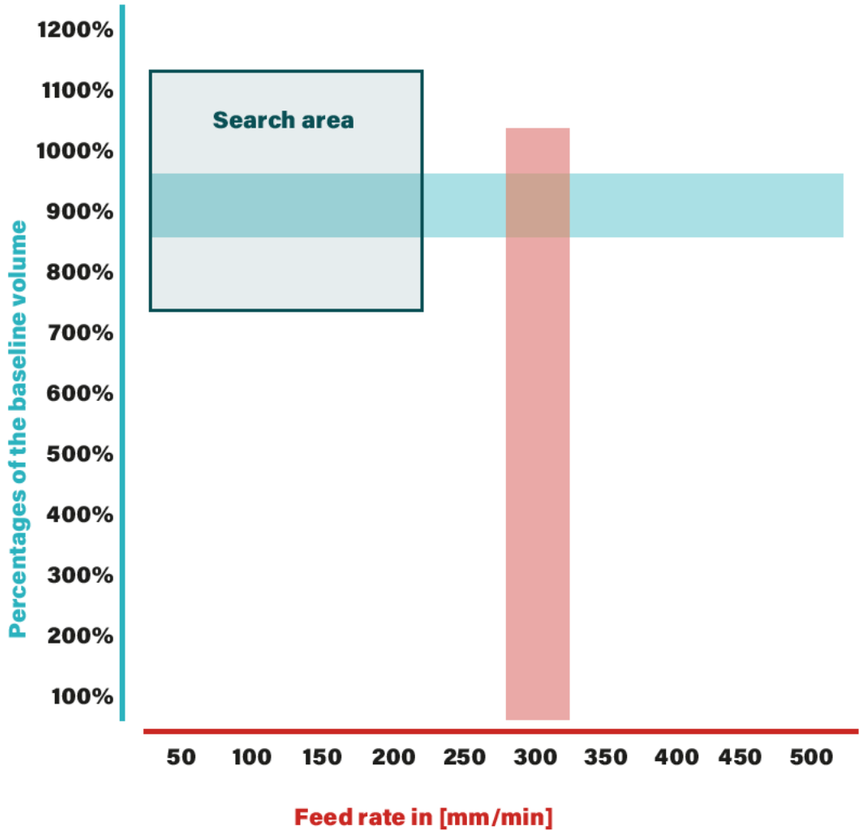


Figure 3.26: Graph of both tests.

3.3.3 Comparison of the archimedes screw and the plunger method

Two solder paste extrusion methods are prototyped and tested. This has been done to find out how the methods are extruding the solder paste, how controllable the methods are and if the methods are able to extrude the solder paste. Both methods are not extruding the solder paste perfectly, however both have potential to print the solder paste.
The methods are compared to the goal of this project, presented in Figure 3.27.
It can be seen that the plunger method gets closer to the project goal than the archimedes screw.
This is mainly because the archimedes screw is a more complex method than the plunger. The design of the screw and controlling of the screw comes very precise. What's more, the archimedes screw method, the screw has to be added to the solder paste, to prevent contact with the solder paste. With the plunger method this is significantly simpler. The solder paste comes in a enclosed tube where the plunger part, which is added to the screw, can be plugged into the tube, without touching the solder paste.

For a final design the screw has to be sold within the solder paste tubes, which makes this method also more expensive.
However the precision of extruding is possibly better using the archimedes screw. The exact precision of printing is not needed to reach the project goal, as the price and simplicity are more important, the plunger fits the project goal better. For continuation of this project there has been chosen for the plunger method.

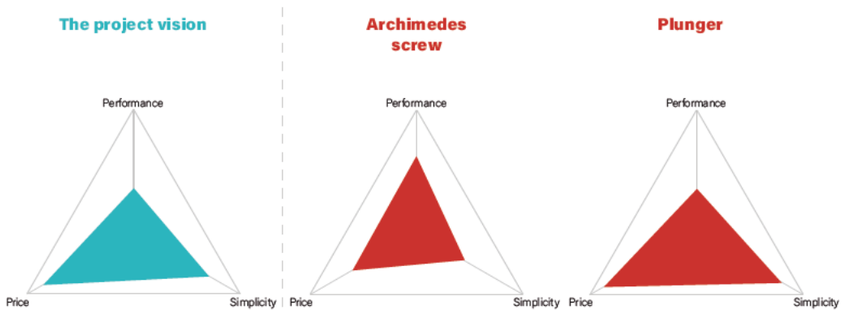
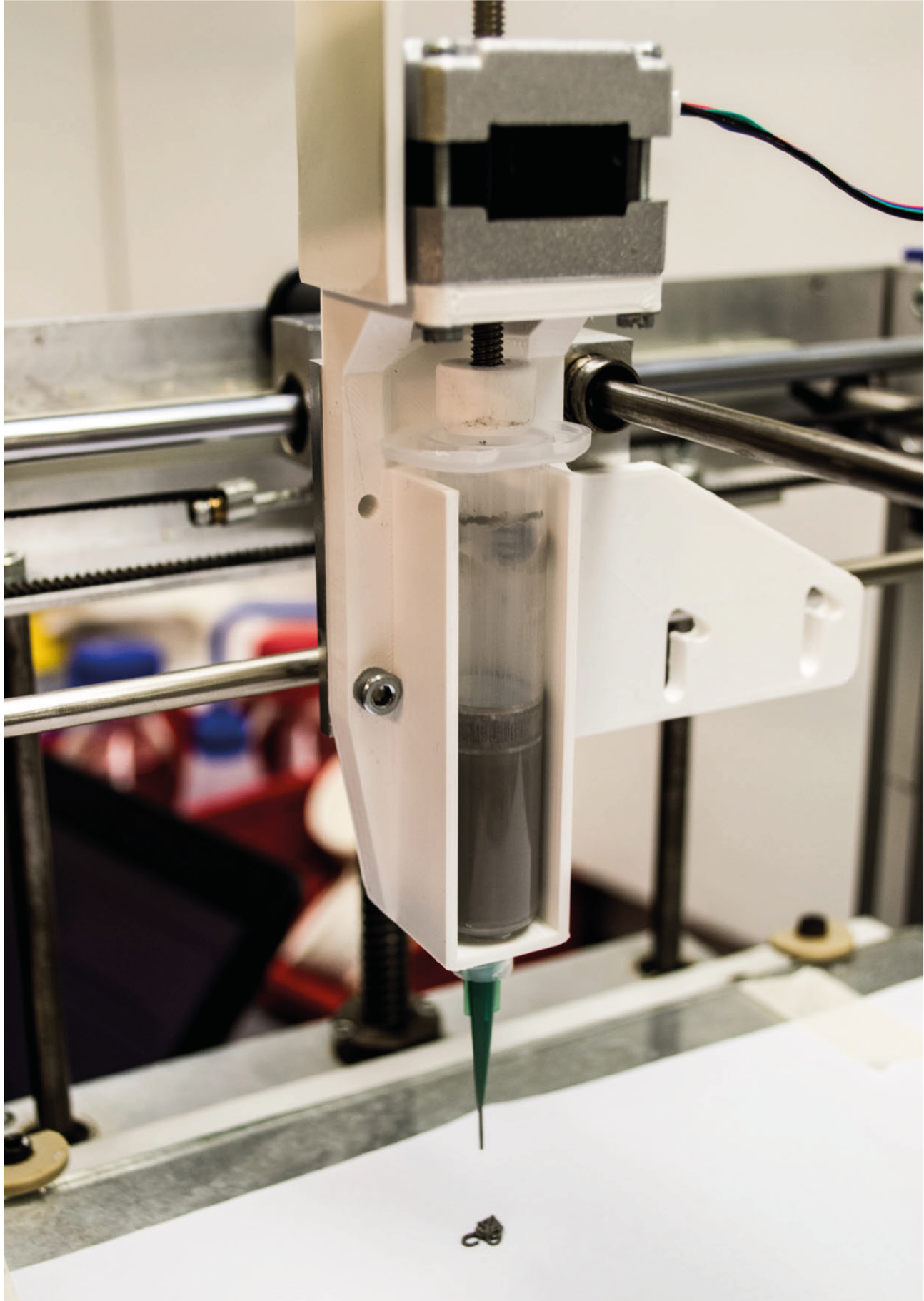


Figure 3.27: The comparison of the archimedes screw and the plunger method.



3.4 Final print settings

In this chapter the final print settings for printing solder paste are described and established. It describes the final choices and conclusion of chapter 3.2 and 3.3. For a clear overview, the print settings are divided into subsettings according to the previous design drivers.

3.4.1 Curing solder paste and the effects on thermoplastic

The solder paste should be cured, in thermoplastic material, so it can behave as a conductive material.

A combination of thermoplastic material and solder paste has been found. The curing method and time and temperatures have been optimised. Next to this the shape of the trace has been found. All these parameters have been researched until the combination of right settings has been found.

Solder paste
It has been found that solder paste B, composition ***Sn42Bi57,6Ag0,4***, is working good for this project. It has a melting temperature of ***139 °C***. The composition does not contain lead and is therefore safer than other options. The material still has to be used with care.

Thermoplastic material
Two thermoplastic materials showed no deformation after being cured. These thermoplastics are PLA X³ and copper filled filament. The copper filled filament is abbrasive and does not have regular looks of either plastic or a 3D print. According to the goal of this project the two thermoplastics are compared, where PLA X³ comes the closed to the goal. PLA X³ is chosen for continuation of this project.

Shape of the trace
Many experiments have been done in finding the right shape for the conductive trace. The final intersection of the trace can be seen in Figure 3.28. In the last experiments three different sizes of this shape were tested. It is chosen to work with the smallest form of this intersection, as no difference in resistivity has been found.

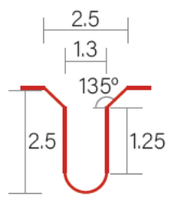


Figure 3.28: Measurements (in mm) of the intersection of the trace.

Temperature and time of curing
In the experiments it is found that a slow reflow has positive effects on the solder paste and the temperature can be lower. The final settings are a ten minute reflow at ***142 [°C]***. The sample is placed in the oven at room temperature, the sample heats up with the oven. This takes approximately ***15 minutes***. When the oven has reached ***142 [°C]***, the sample stays in the oven for ***10 minutes***. After this time the sample can be taken out and cooled down back to room temperature.

Methods of curing
The proposed curing method is to use a drying and heating oven, in this case the Binder FP115. Using this method, the process of printing is extended. The prototype is placed in the oven after printing. Several other methods for on side curing might be a good option for further research.
In this project, using the oven, the sample is heated gradually and evenly through the material. For continuation of this project the drying and heating oven will be used.

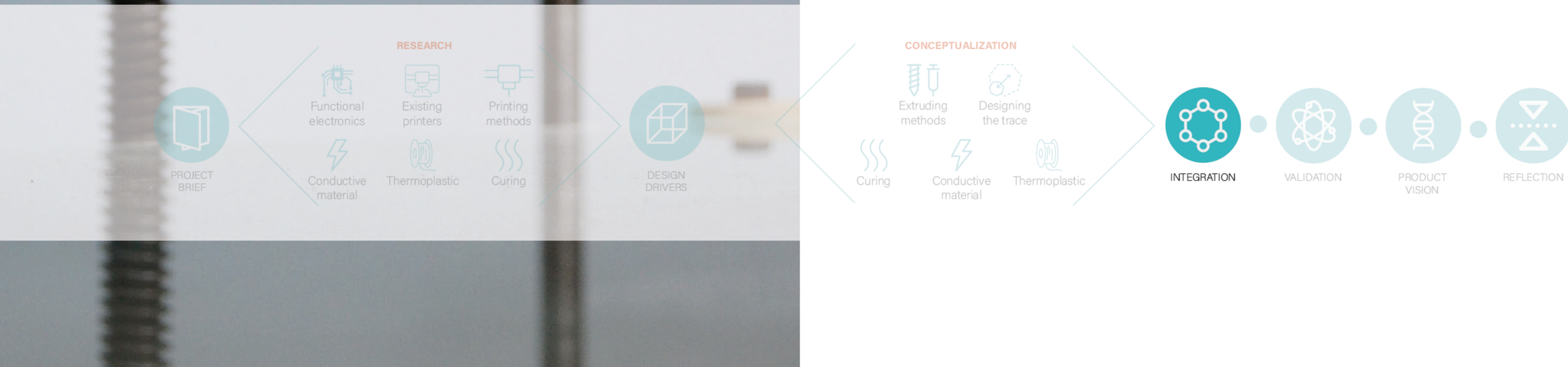
3.4.2 Extruding solder paste

The extrusion method should be cost-effective and simple.

The previous experiment presented in chapter 3.3 are conducted to find the most suitable method to extrude solder paste. Both methods are being prototyped and used on a 3D printer. The most important parameter for both methods was to find out if they are able to extrude a continuous and constant line of solder paste. After the conducted experiments the methods are compared to the project goal. It has been chosen to continue with the plunger method.

4 Integration

Combining all the results from the previous chapter will lead to new insights. New issues will appear, although at a more detailled level of the embodiment of the proof of concept. The lessons learned from these insights will provide recommendations for the continuation of the project.



4.1 The proof of concept

This chapter gives an overview of the design of the solder paste and thermoplastic extruder. This includes the design of the holder for both extruders. As this project is based on finding out the basics for a 3D printer that can print cost-effective electronics, this is a first prototype for the printer and can be later redesigned to function better.

This prototype is designed to 3D print electronics. The prototype for the dual extruder is described. Besides, the used hardware and software is described.

4.4.1 Dual extruder

The final design of the bracket is 3D printed. Figure 4.3 and Figure 4.2 provide an overview, here a plunger (without solder paste) and the thermoplastic extruder are attached to the bracket (printed in white PLA).
The bracket holds the extruder for the thermoplastic and it is designed to click in the tube with solder paste. The NEMA16 is screwed on top of this bracket. The bracket is attached to the x and y axes of the 3D printer.

When using a double extruder on a 3D printer, the nozzles have to switch during printing. When the solder paste is being printed, this nozzle has to be the lowest, so the thermoplastic extruder has to set in rest position. When the thermoplastic is being printed, this nozzle has to be lowered. In the design of this bracket this has to be done mannually. Figure 4.4 shows that the nozzle of the solder paste extruder is lower than the thermoplastic extruder, the solder paste extruder is in its active position.
Figure 4.5 shows the active position of the thermoplastic extruder.
Using this double extruder the build volume is x by y by z, 100 by 150 by 200 $[mm]$, see Figure 4.1. Using these two extruders the build volume is decreasing. This can be improved in a future design, which is out of the scope of this project.

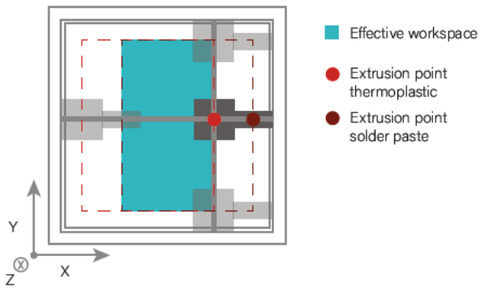


Figure 4.1: Effective workspace.

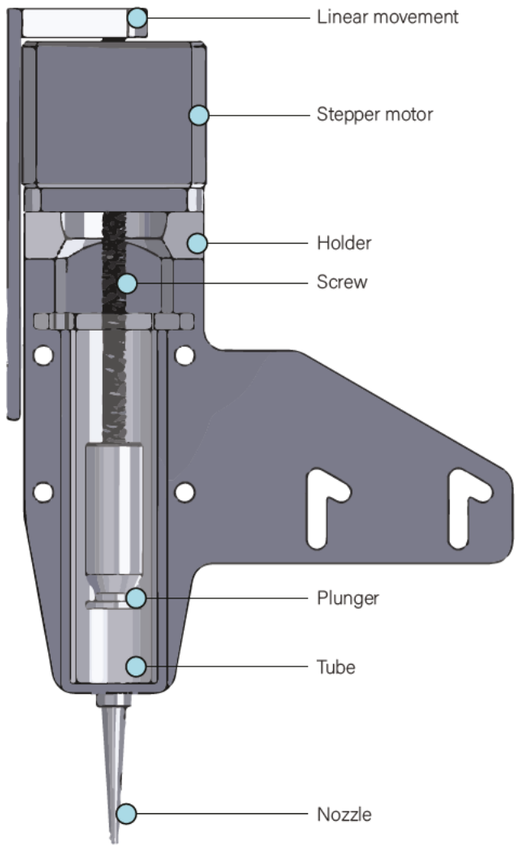


Figure 4.2: The final setup of the plunger.

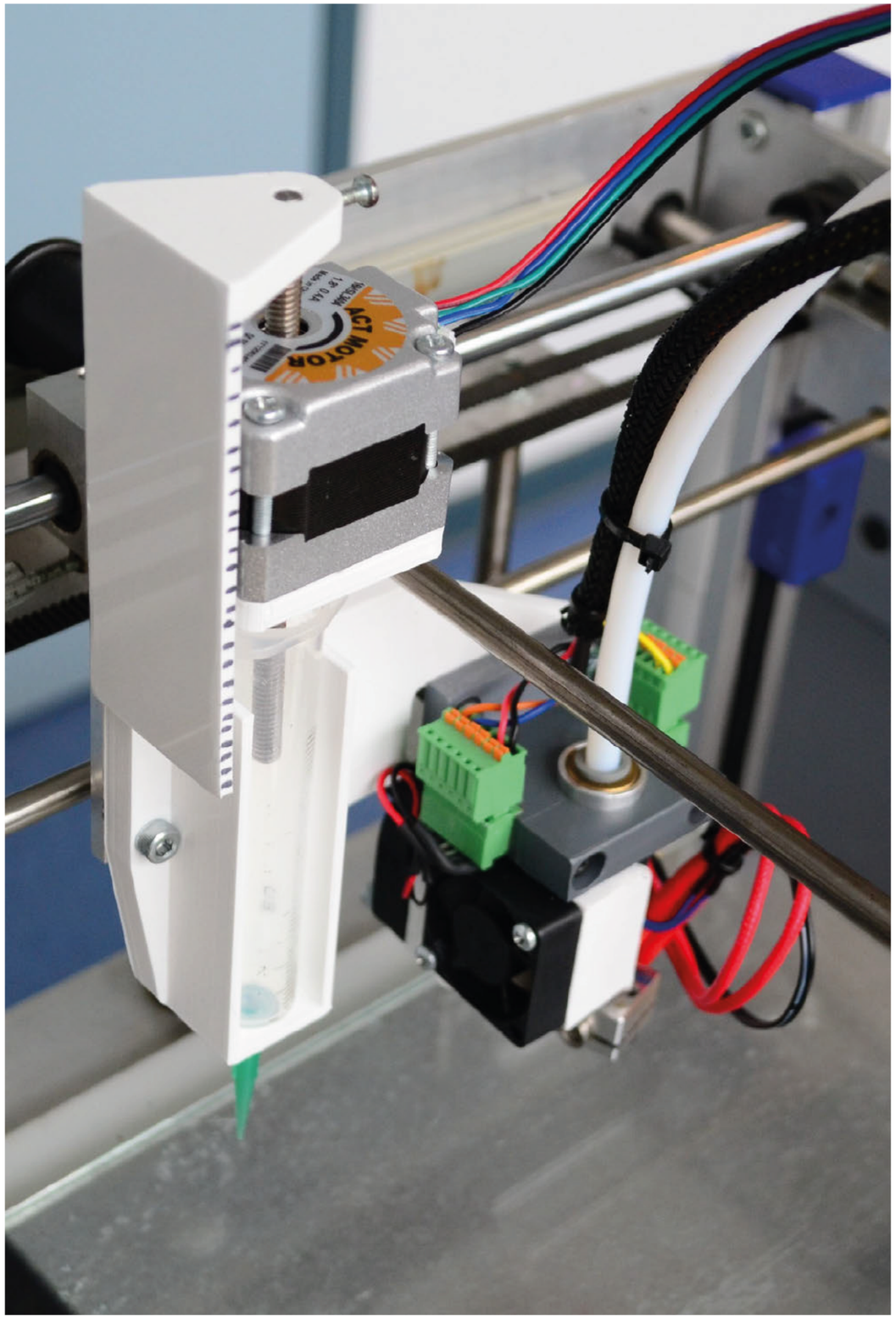


Figure 4.3: Overview of the setup.

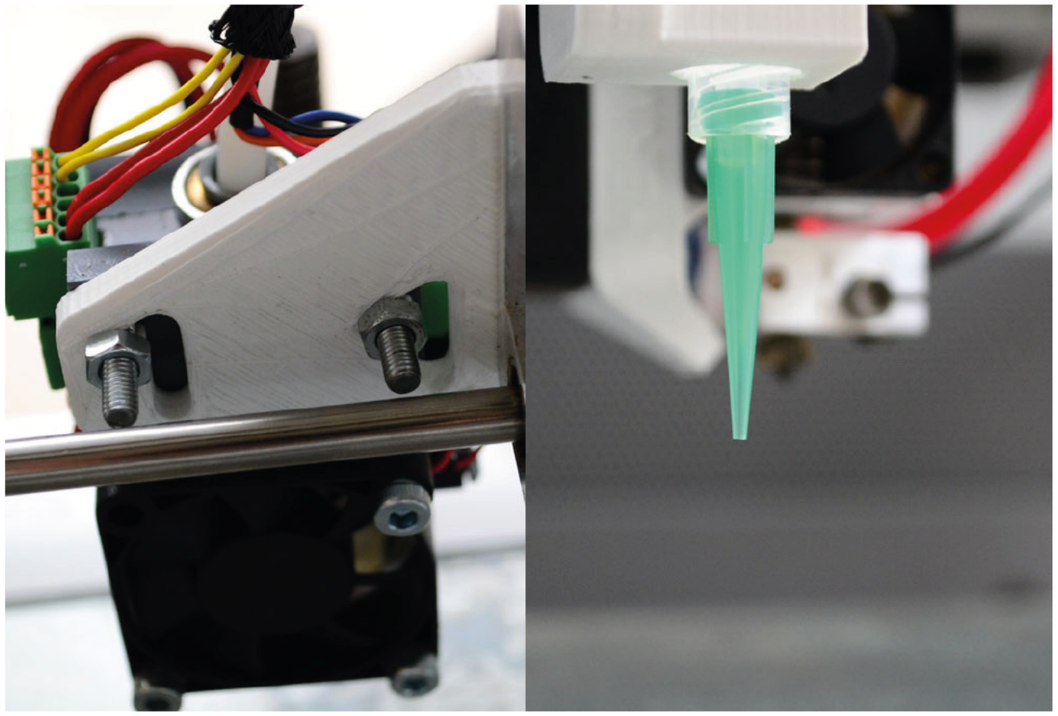


Figure 4.4: Thermoplastic nozzle in rest position, solder paste extruder in active position.

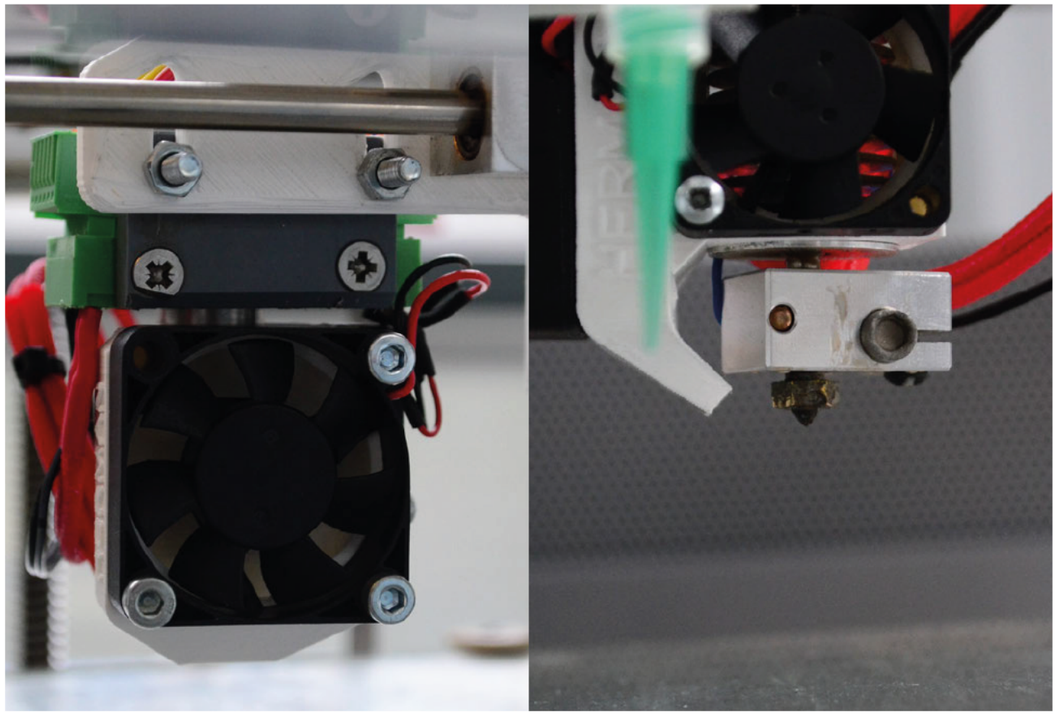


Figure 4.5: Thermoplastic nozzle in active position.

4.1.1 Hardware and software

The extruders are controlled by the Bigtreetech SKR v1.3, presented in Figure 4.6. The used software is the open source Marlin firmware. The dual extruder is used on the 3D printer designed by Herman Broekhuizen.

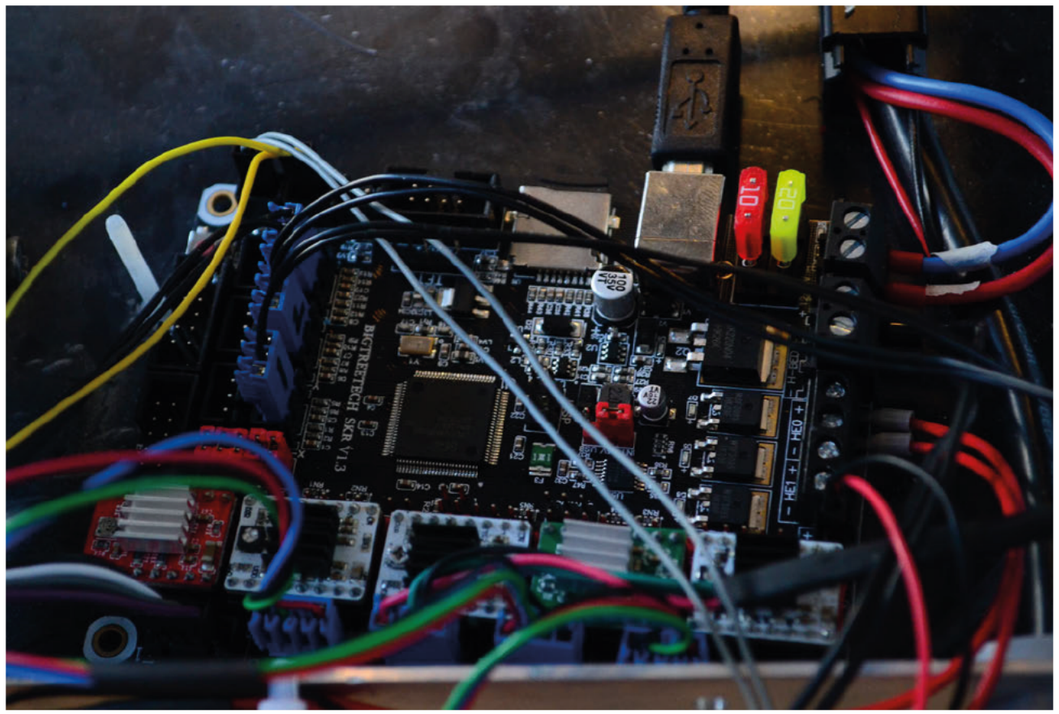


Figure 4.6: The Bigtreetech SKR v1.3.

4.2 Process of printing solder paste

The full process of printing a 3D print with conductive traces is explained step by step. How to use the slicer and adapt a g-code to use the printer. Every step is written down, from the start to the end.

The steps are as follows: design of the 3D CAD model, slicing the model and adapting the g-code, preparing the printer, printing, pick and place components and curing. The process of printing solder paste has not been automized, therefore it is assumed to be familiar with 3D printing, before printing solder paste.

4.2.1 3D CAD model

By modelling the 3D CAD model it is important to take the following guideliness into account.

1. The solder paste can only be printed in the xy plane.
2. The measurements of the trace are shown in Figure 4.7.
3. When integrating electrical components to the print that contain wires, add a gap of dimensions (L x W x H) ***1.3 [mm]*** by ***1.3 [mm]*** by ***5 [mm]*** from the top of the print into the trace, as presented in Figure 4.8 and Figure 4.9.
4. When adding a different sized component, make sure to add a big enough tolerance of at least ***0.5 [mm]***. [29]
5. Make sure the conductive traces can connect to every component and to the battery.
6. The solder paste will shrink in the trace, it is possible to cure and print over the solder paste again to make sure it is level with the print. See Figure 4.10 presents an example of this step.

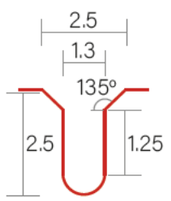


Figure 4.7: Measurements for the intersection of the trace.

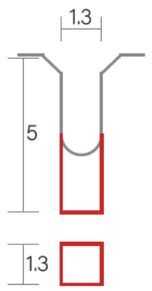


Figure 4.8: Measurements of the component gap in mm.

4.2.2 Slicing and g-code settings

After converting the 3D CAD model to a STL format, the model can be sliced. This converts the STL into g-code. In this g-code only the lines for the thermoplastic are present. To understand g-code more precisely read Appendix I. To print the solder paste the following steps have to be followed.

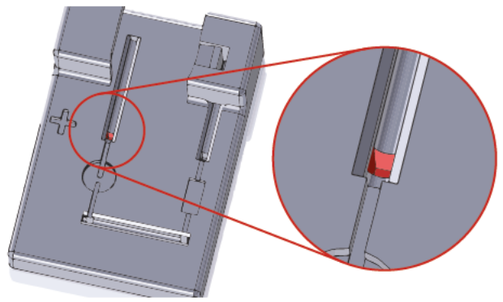


Figure 4.9: Illustration of the gap for components.



Figure 4.10: Encircled double cured solder paste.

1. Find the height of where the traces are fully printed in the g-code.
2. Let the printer pause at this point by adding ***M0*** in the g-code.
3. At this point the g-code for the solder paste can be added. Start with a tool change: t1.
4. Measure the length of the lines and decide the starting point: ***X0 Y0***.
5. Calculate the volume (***V1***) that has to be printed, per printed line and layer.
6. Multiply ***V1*** with 9.
7. Use the following formula to calculate how much the extruder has to move down.
E=V1/Pi*(7.75)²
8. The starting point for each line is the coordinates where the nozzle has to start. Here is an example:
G1 X0 Y0 F6000
9. The next step is to make sure the distance to the print is good. Add the following:
G1 Z0.100 F600
10. To make the plunger ready for printing it will prime a little solder paste. Add:
G1 E0.100 F200
11. Add the following to make sure the extruder is reset:
G92 E0
12. Add the to printed line to the g-code, use the following system:
G1 X0 Y0 F200
G1 X10 Y0 E0.1
The above g-code is one line from point 0,0 to 10,0, the extruder is moving ***200 [mm/min]*** and the plunger moves ***0.1 [mm]*** down.
13. End the to printed line with:
G92 E0
G1 E-1 F200
G1 Z0.4 F600
14. Follow steps 8 to 13 to add extra lines.
15. Retract the solder paste by adding the following line to the g-code.
G1 E-1.0 F300
16. If the printer will be printing thermoplastic after printing the solder paste, add a second pause to be able to switch nozzles. Add ***M600*** to the g-code.

Now the g-code is ready.

4.2.3 Preparing the printer

The printer has to be prepared for being able to print. The solder paste is stored in the fridge and can harm, when being used often. Therefore several safety measurements are taken.

1. Place the printer in a well ventilated area.
2. Get the solder paste out of the fridge, stored in a container that can be touched with bare hands.
3. Open the container with bare hands.
4. Put on protection gloves and glasses.
5. Get out the solder paste, screw on the nozzle and click off the cap.
6. Place the solder paste in the holder.
7. Use a control program for the printer and manually extrude some solder paste.
8. Wipe the nozzle.
9. Keep the protection on.

4.2.4 Printing solder paste in a 3D print

As everything is prepared to start the print, it is time to send the g-code to the 3D printer. As mentioned before a control program is used, instead of printing from an SD card. Make sure the thermoplastic extruder is in extruding mode, as explained in chapter 4.1. The followed steps need to be taken during the printing.

1. Send the g-code to the printer.
2. Wait until the printer has paused.
3. Manually move the thermoplastic extruder up to the resting position.
4. Move the extrusion head, nozzle of the solder paste, to the starting point.
5. Restart the print.

4.2.5 Pick and place components

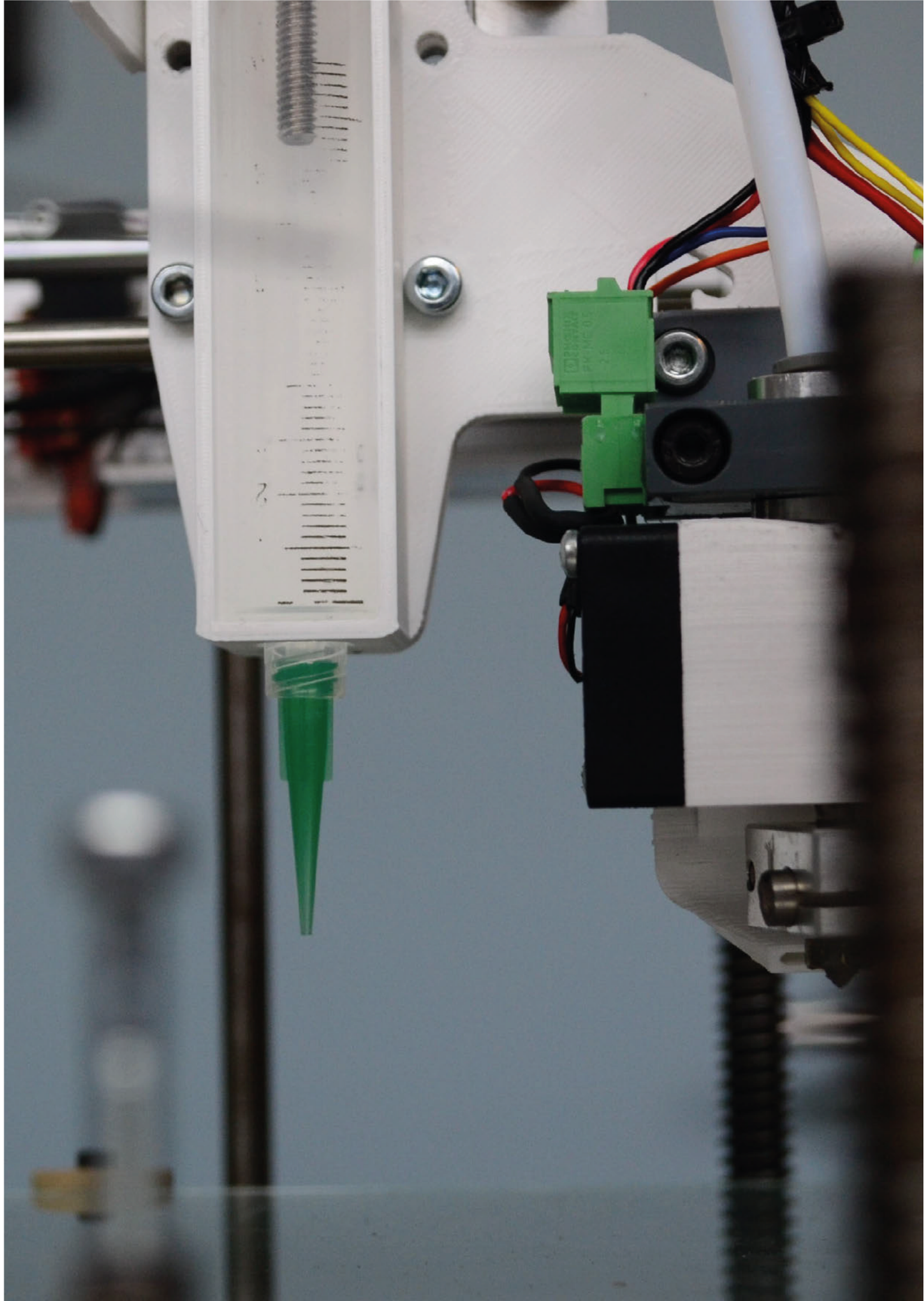
When the print is finished, and the solder paste has been added, the electrical components can be placed in the print. Be aware that the components have to withstand heat, do not add batteries or other components that are not suitable for this. These can be added after curing.

1. Handle the print only with gloves and glasses on.
2. Place the electrical components in the spots created in the model.
3. Make sure the components are secured.

4.2.6 Curing the 3D print

The print is now ready to go into the oven. The following steps are a guide for curing the solder paste.

1. Place the 3D print in the oven.
2. Turn the oven on.
3. Set the temperature at ***142 [°C]***.
4. Wait until the temperature is reached, approximately 15 minutes.
5. Set a timer of ten minutes, when the temperature has been reached.
6. After ten minutes, open the door of the oven or take out the print and let it cool down.
7. After half an hour the print is ready to use.
8. The print can now be handled without safety precautions.



4.3 Design and print guidelines

This chapter describes the guidelines for designing and printing electronics. For instance it describes the used tolerances for printing solder paste. The general guidelines for 3D printing are left out, these are considered to be known. [31]

4.3.1 Design guidelines

- The electrical components have to be picked and placed after the 3D print is finished.

- Check if the components can withstand the heat, if not these have to be soldered afterwards.

- The traces for the solder paste always have to be closed from the sides, in the vertical plane.

- The electrical circuit has to be printed and cured in the horizontal plane, see Figure 4.11.

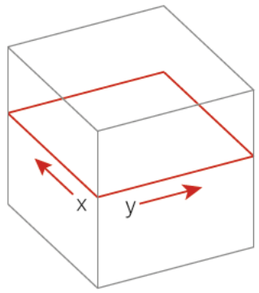


Figure 4.11: Horizontal plane.

- The electrical circuit can only be designed in 2D.

- Keep ***2.5 [mm]*** between two traces, see Figure 4.12.

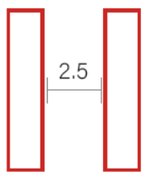


Figure 4.12: Distance between two traces, topview.

4.3.2 Print guidelines

- Using the trace cross section with the predefined printing settings for solder paste, print at least 2 layers of solder paste.

- The solder paste shrinkes after being cured, if the solder paste has to be at a certain level, the solder paste can be printed over the cured trace and cured again.

- Lower the nozzle of the solder paste in the 3D printed trace.

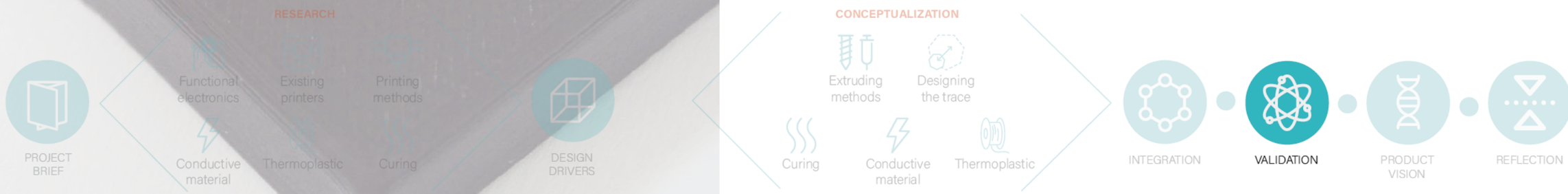
- Using a ***0.8 [mm]*** nozzle, keep ***0.6 [mm]*** from the ends of the trace, see Figure 4.13.



Figure 4.13: Distance from the center of the nozzle to the side of the trace, topview.

5 Validation

This chapter tackles the combination of the tracks of curing solder paste, printing solder paste and the right thermoplastic filament. A perfect way to bring them together is to design a demonstrator.



5.1 Method of validation

The designed extruder has certain capabilities. This chapter describes how these capabilities can be shown. What can the 3D printer that prints electronics produce?

It needs to be proved that the designed 3D printer can print integrated functional electronics. A perfect way to do this is by designing a demonstrator. The demonstrator will contain an electric circuit, electric components and a battery.
Designing the demonstrator will give insights in how to use the predescribed design guidelines.
The process described in Chapter 4 will be followed. The start is to design the demonstrator in a 3D CAD program, the usual way to design prototypes made to be 3D printed. The challenges faced during the continuation of the process are described in this chapter.

5.2 Demonstrator possibilities

A demonstrator is a good way to proof the concept design. The demonstrator will show what is possible with this cost-effective and simple method of 3D printing electronics. It will give new opportunities that were not possible before.

The demonstrator will show what is possible with 3D printed electronics. To be able to show this, it is important to further investigate the possibilities. The demonstrator will give insight in how to use the printer and to show its capacities.

Existing electrical 3D printers already printed different kind of demonstrators, like a gaming dice and several designs of a coil for 3D wireless power transfer, printed with the Voxel8. [14] [32]
Flex sensors and capacitive buttons were created using 3D printed carbon filament. [33]

The above designs printed by the Voxel8 are more complex and will cost more time to design. Moreover, the designed extruder is not yet capable of 3D printing electronics, but can only print 2D electronics. A new and simpler design needs to be investigated, which will easily prove the concept. The printed sensors using carbon filament come closer to a simple design. In those designs components still had to be soldered to the created circuit. For this proof of concept it is desired to create a product that can work without using extra technology to make the circuit work.

To start, the demonstrator needs to contain electronic components, it needs to be powered and it needs to show something, like a movement or a light.
The demonstrator should contain the following parts:

- A battery
- Electronic components

The following design guidelines need to be taken into account:

- The circuit should be designed in 2D.
- The components need to be picked and placed by hand.

Above these design guidelines, the guidelines described in Chapter 4.3 are followed too.

The demonstrator will be the first 3D printed electrical design, printed in this project. Therefore it is good to start with a simple but effective design. There are several possibilities; like a pressure sensor, a capacitive button or a flashlight.
It is chosen to print a flashlight, this demonstrator is feasible and contains one battery and two electrical components, an LED and a resistor.

5.3 Design of the demonstrator

This chapter shows the process of designing the demonstrator. It comes with certain challenges, for instance designing the circuit in 2D.

The following simple design of the flash light is made to give an indication of what is possible with 3D electrical printing.

5.2.1 Basic design

The main components are:

- Coin button CR2032 of $3.2\ [V]$
- Red LED
- Resistor of $180\ [\Omega]$

Figure 5.1 shows a picture of the electrical diagram.
The first design of the demonstrator can be seen in Figure 5.2. The solder paste is done manually and the design contains a battery holder.

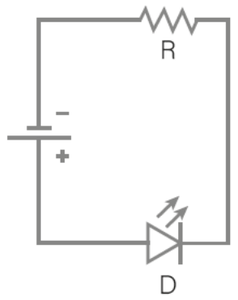


Figure 5.1: Circuit of the first design.

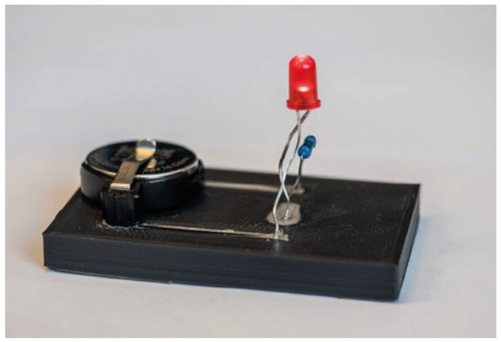


Figure 5.2: First design.

The next iterations are to find a way to design the demonstrator without the battery holder and by adding a switch.

5.2.2 Iteration 1

Ruling out the battery holder is difficult, the coin cell has a plus and minus side in 3D. Therefore smart thinking is needed. The first idea was to print two components that can click on top of each other, as can be seen in Figure 5.3
This design could have worked, however the solder paste is shrinking and therefore does not touch the battery.

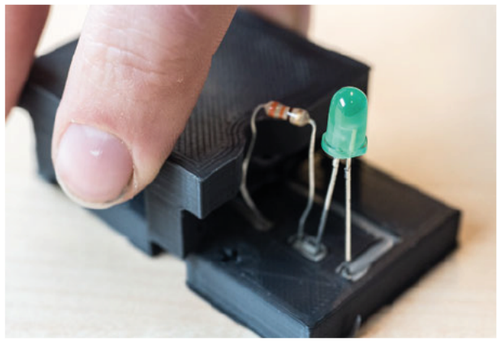


Figure 5.3: Iteration 1.

5.3.1 Iteration 2 and final design

The second idea was to add a switch that connects to the circuit and can be pushed onto the battery. This means that the battery only has one contact side with the solder paste.
It is important that the battery touches the solder paste. This can be done by filling and curing the trace multiple times.
For this final design it is important that the electrical components are more integrated than the previous designs. Therefore small placements for the LED and resistor are designed, this shows the capabilities of a 3D printer. Using a 3D printer anything can be designed, any form, therefore it gives a lot of freedom and design possibilities.
The final design is presented in Figure 5.4 and Figure 5.5.
The corresponding electrical circuit is shown in Figure 5.6, containing a battery, an LED, a resistor and a switch.

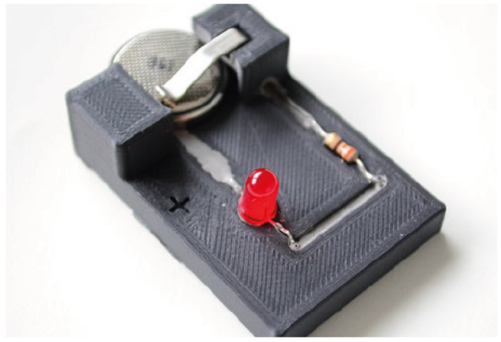


Figure 5.4: Final design.

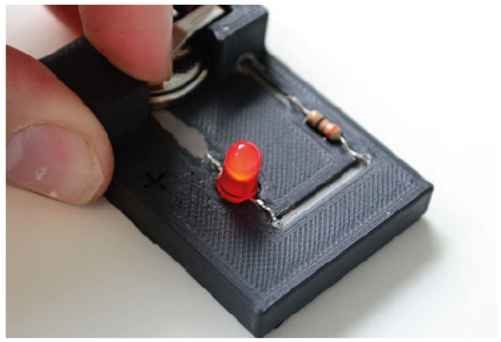


Figure 5.5: Final design, LED on.

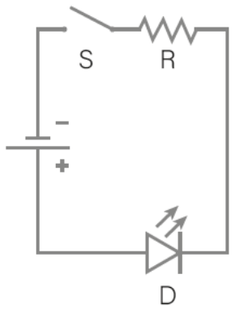


Figure 5.6: Final circuit design.

5.4 The capabilities of the 3D printer

The demonstrator shows clearly what the capabilities of the 3D printer are. In this chapter there will be zoomed into these specific capabilities. What does the demonstrator proof and what will be possible too?

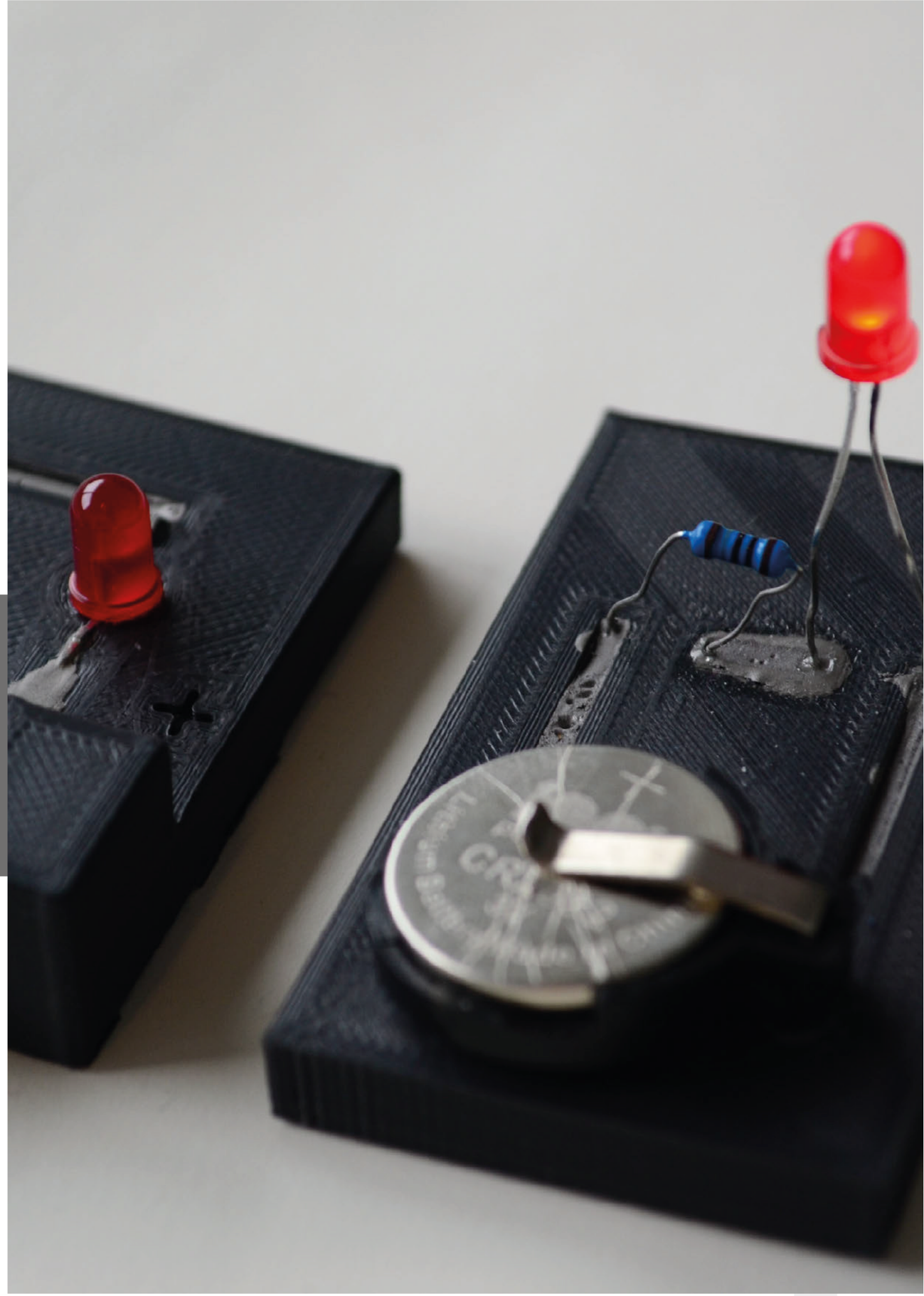
The previous chapter described the iterations to come to a design of a demonstrator. The working demonstrator shows that the 3D printer is capable of printing functional electronics.

The 3D printer can print with a dual core of a thermoplastic extruder and a solder paste extruder. The final set of materials proved to be working.

After printing the solder paste, the printer can switch back to printing thermoplastic material. For printing this demonstrator it was not needed to switch back and forth, however for printing the electric circuit in 3D this can be the case.
Another possibility , when printing the circuit in 2D, is to print multiple layers of electric circuits. This would result in multiple extruder switches. The demonstrator showed that switching from thermoplastic extruder to the solder paste extruder and switching back to the thermoplastic extruder is possible. This process can be elaborated with multiple switches, making it possible to print multiple layers of an electric circuit.
This enhances the freedom of design.

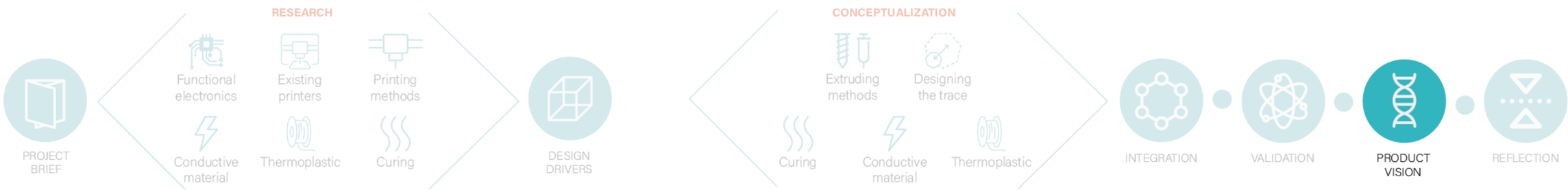
The used electric components, the LED and the resistor can withstand the heat in the oven.
The components are not damaged and still work.
Picking and placing the components manually is however more difficult. It makes it easier when the components are ready to go, these components had long wires and the wires had to be bend. Picking and placing components is left out of the scope, however it can be done easier by using another tool on the 3D printer that can pick and place the components. Moreover, using components that are designed to be picked and placed will make the process easier too.

Conclusion
The designed extruder on the Herman printer is capable of 3D printing functional electronics. The electric circuit is printed with solder paste that has a low resistivity. The working printed circuit creates a finished prototype. 3D printing electronics comes with challenges, however it gives the designer a lot of freedom in shape and design.

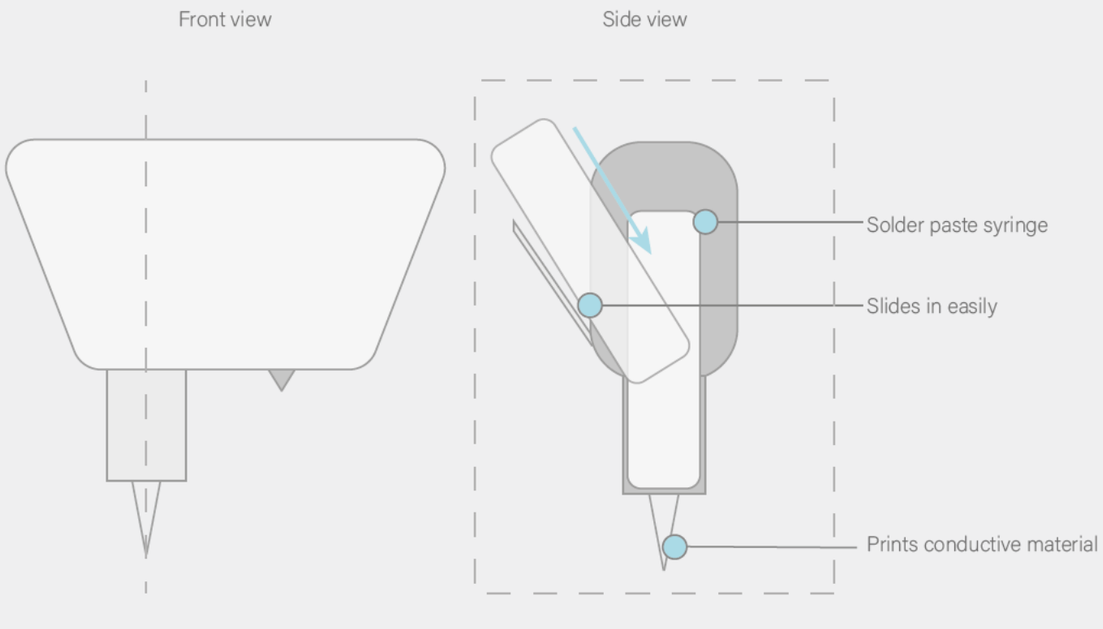


6 Product vision

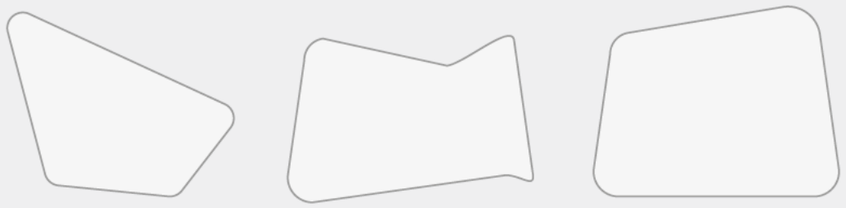
This chapter shows the product vision, the future of the designed proof of concept.



The 3D printer that prints integrated electronics

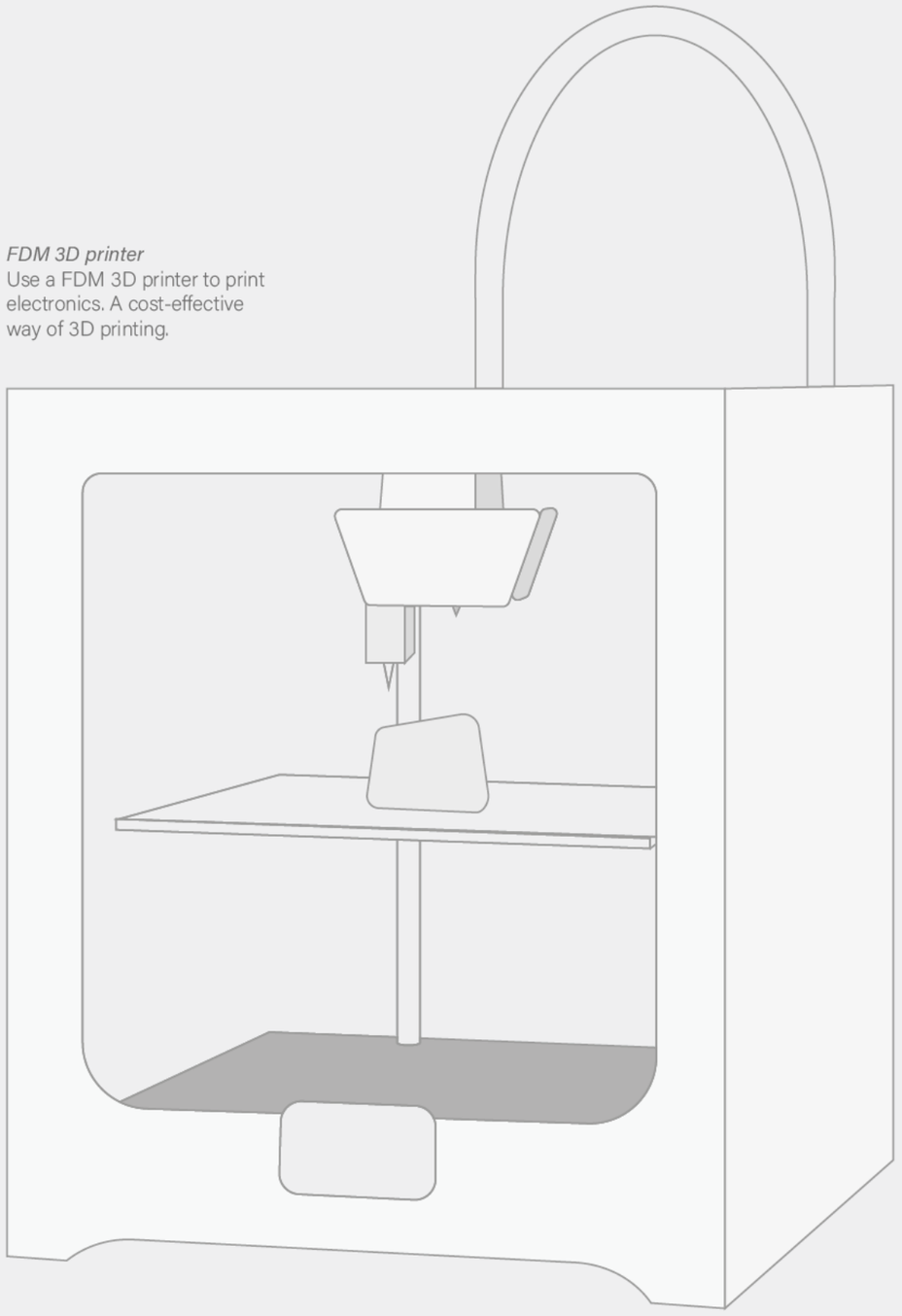


- Print conductive traces through the 3D print
- Design functional electronics in any shape.
- Print low cost prototypes in one go.
- No need to wait for a PCB, print on demand.



Freedom of shape
Using the 3D print technique, it gives a lot of freedom in form and shape. Printing electronics can be printed in any form or shape.

FDM 3D printer
Use a FDM 3D printer to print electronics. A cost-effective way of 3D printing.



7 Project reflection

This chapter describes the evaluation and conclusion of the designed extruder. It also describes the recommendations and a reflection on the conducted project.



7.1 Evaluation

In this chapter the achievements of this project will be evaluated, including the design rules (Chapter 2.4). According to these rules, it can be said if the goal has been reached and what still has to be researched. This will lead to the conclusion and recommendations.

The goal of this project is:

Building a cost-effective, compact and simple 3D printer that can print electronics for technical integration of prototypes.

During the project research it became clear that a proof of concept would be developed rather than a design of a 3D printer.
The proof of concept is shown in Chapter 4. Chapter 5 shows the validation of the proof of concept. Here it can be seen that the concept of 2D printing electronics in a cost-effective, compact and simple way has been proofed.
Of course more work can be done. For example the developed extruder for printing solder paste can be further tested. Moreover, the developed trace intersection can be reviewed.
This evaluation is setup according to the design rules and design drivers set during the research of this project.

7.1.1 Design rules

A first assessment is conducted by comparing the design rules to what has been achieved. The design rules are an extension of the project goal and are proposed as wishes for the project. Therefore hard requirements are not made, but the design rules can give an indication if the goal has been reached. The design rules are shown in Table 7.1.
How to read the indications of the rules:

✓ The rule has been satisfied.
◈ The rule has been partly satisfied.
× The rule has not been satisfied.

It can be seen that most rules are accomplished.
The demonstrator proved that the extruder is capable of printing integrated passive electronics in 2D. The step for printing 3D still has to be made.

The duration of the print shows some difficulties because a pause is needed to switch manually from the thermoplastic extruder to the solder paste extruder, a second pause is needed to switch back. This adds approximately 10 minutes to the print, compared to the original printing time. Moreover, it requires extra time from the user during the print.
The solder paste extruder prints at a speed of $150\ [mm/min]$, which is slow for a thermoplastic extruder. It must been said that in the design of the flashlight, not much solder paste had to be printed. This reduces the printing time. Concluding, printing solder paste increases the printing time and maintenance during the print but not to an extend that would double the printing time.

The resistivity of the designed trace has been measured over a meter, resulting in a resistivity of $2.0\ [\Omega*m]$, which does not satisfy the design rule. However, the used measurement tool is not as precise. Therefore it is wanted to measure the resistivity with a better tool.

The extruder is still in a proof of concept phase, therefore the design, including the used printer, does not have a straight forward system. With some further iterations, this system can be optimised and used as extrusion method.

Making a cost-effective system for printing electronics, using a conductive material and thermoplastic material that is widely available the printing system is very accesible.

Solder paste needs to be handled with care. The solder paste has a safety restricition, when being used more often. Placing the conductive material is easy and straight forward. The solder paste does not have to be touched, only the tube.

Group		#	Description
General	✓	1.1	The printer should be able to print integrated passive electronics.
	✓	1.2	The extruder is designed to be combined with an extruder that can print at least one thermoplastic.
	✓	1.3	The solder paste extruder is a start for a 3D FDM printer that can print electronics.
Performance	✓	2.1	The printer should be able to at least 2D print integrated electronics and be the start of a design venture seeking to explore the 3D printing of integrated electronics.
	◈	2.2	Printing a prototype with integrated electronics should not add too much time to the original printing time, when only printing thermoplastics.
	×	2.3	The printed conductive material should have a resistivity of less than $0.2\ [\Omega*m]$.
Costs	✓	3.1	The material expenses for $100\ [g]$ of conductive material should lay between $€10$ and $€100$.
	✓	3.2	The material expenses for $100\ [g]$ of thermoplastic material should lay between $€1$ and $€10$.
	✓	3.3	The retail price of the designed extruder should lay between $€50$ and $€200$.
Simplicity	×	4.1	The printer has a straight forward system.
	✓	4.2	The printer is accessible for everyone.
	✓	4.3	The printing materials should be readily available.
Use	✓	5.1	The printer should be safe to use.
	✓	5.2	Placing the conductive material should be easy and straight forward.

Table 7.1: The list of design rules.

7.1.2 Design drivers

To achieve the proof of concept, first a research has been conducted, guided by the main research question:

What is needed to make a cost-effective extruder printing integrated electronics?

This question was answered in Chapter 2.9 with the design drivers. They were used to setup the next phase, ideas and concept development. which lead to the design and construction of the extruder to print 3D electronics.

Each design driver is evaluated and it is assessed if it has been achieved.

Curing solder paste and the effects on thermoplastic

✓ *The solder paste should be cured so it can behave as a conductive material.*

A combination of the following materials and methods result in a cured solder paste in a 3D print, which can be used to design an electrical circuit.

Solder paste
A solder paste with a low melting temperature has been found. This makes sure that a low cost and widely available thermoplastic material can be used. The solder paste that has been found comes with safety regulations, but the least harmful solder paste has been chosen.

Thermoplastic material
The thermoplastic material that has been found can withstand the curing temperatures of the solder paste. The 3D print does not deform.

Shape of the trace
The cross section of the shape of the trace has been found. It gives a good performance and can be used to build an electric circuit.

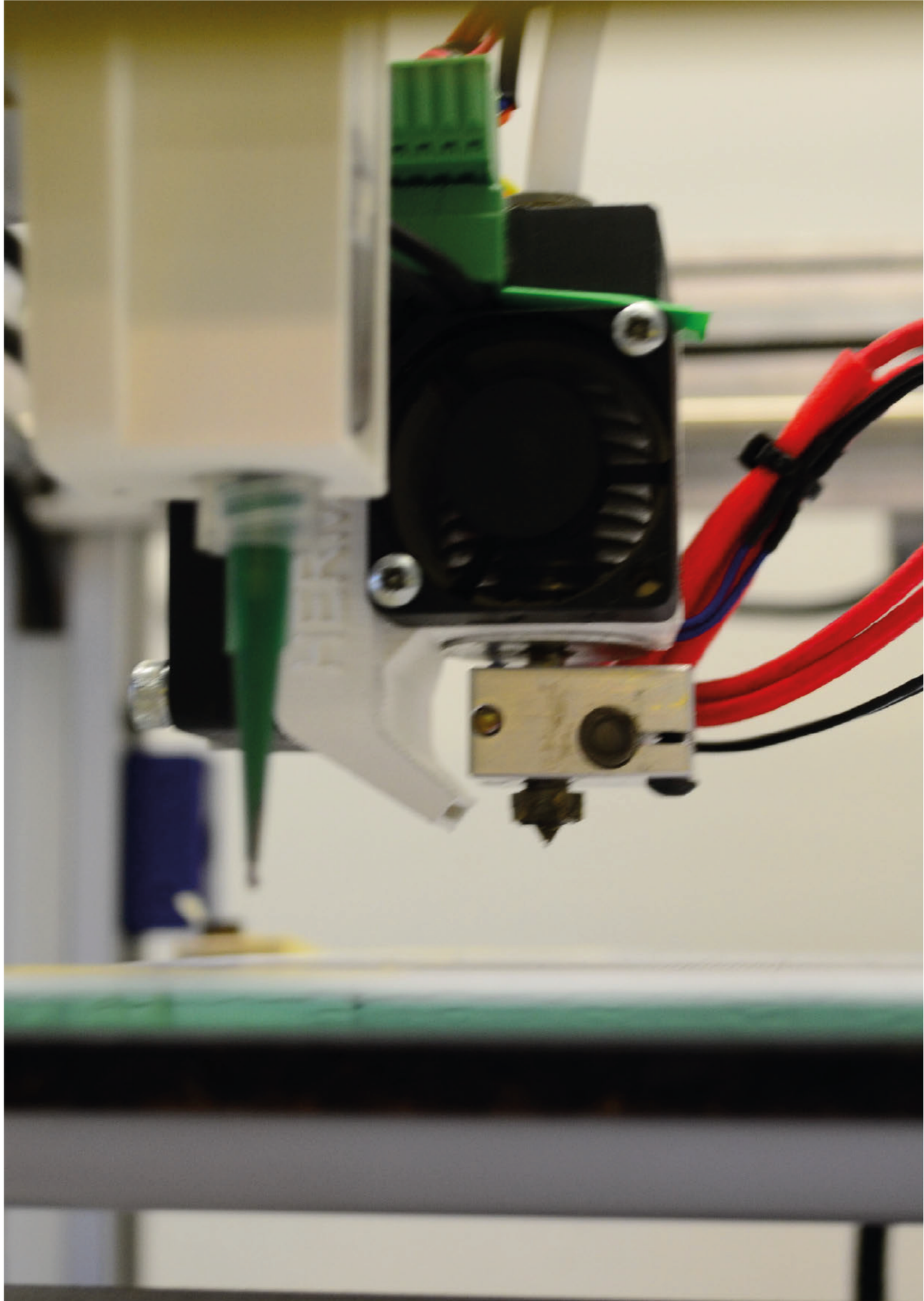
Temperature of curing
A reflow method with set times and temperatures has been found that works best for the combination of the used solder paste and thermoplastic material. It can be added that the fast reflow diagram has been used to create a slow reflow diagram.

Methods of curing
One method has been proved to work effectively with the used materials and reflow diagram. The method itself is considered left out of the scope and is therefore not taken into the considerations of being cost-effective, simple and compact.

Extruding solder paste

✓ *The extrusion method should be cost-effective and simple.*

The chosen method to extrude the solder paste on a 3D print system is the simplest and low cost method that has been explored.



7.2 Conclusion

This chapter describes the general conclusion of this project. It summarizes what has been achieved and how it has been achieved. The level of quality will be discussed and as well as which design aspects can still be improved.

In this project, there has been worked towards a proof of concept of a 3D printer to print electronics. The proof of concept shows that cost-effective, compact and simple 3D printing of electronics is possible. As described in the evaluation the proof of concept was only achieved for 2D printing electronics. The work done in this project is however very positive and brings us many steps closer to the printing of electronics in 3D.

7.2.1 Big picture

Looking at a broader picture the proved way of printing had not been done before. The existing printers used different techniques, which lead to different prices and quality of the produced products. The more advanced and professional printing methods are not shared neither accesible. Having the goal to make the printing method accessible gives more users and designers the tools to develop the concept further, which will boost the technology. This first step towards cost-effective, compact and simple 3D printing of electronics has been very important.

7.2.2 Details

In Chapter 7.1.2 it can be seen that following the guidelines through this project succesfully lead to the proof of concept. The identified design drivers helped designing the ideas and concepts through the several experiments.
The project was conducted following an experiential approach. Even if it could also have lead to missing indications of a working behaviour, it lead to the success of this project.
One interesting limitation of the project is that the design guidelines were studied one after the other. One can therefore wonder if the results would have been different following another order.
For instance the designed shape of the trace results in a rather big and deep cross section of the trace. The question is if all the results from the experiment will lead to the same outcome if they are conducted in a different order of time.
In the case of the designed trace, the slow reflow method could have a more leading consequence over the shape of the trace. So if this was found earlier it could have been that the trace shape might have been different.
To conclude, the approach lead to the very useful quick development of a proof of concept by giving the ability to iterate each parameters. However, certain parameters could have been approached in a different manner leading to slightly different results.

With the demonstrator, the quality of the printed product is not high. This corresponds to the quality requirement set at the beginning of the project. With the designed extruder prototypes can be made. However the produced quality can be increased, when the proven method will be developed further to a point where designers are able to use it in their daily approach.

7.2.3 Final thoughts

The proven concept can be developed further in many directions. Work has been done with a very viscous material, which can be replaced by any other viscous material that was previously assessed as not suitable for 3D printing.

The solder paste can also be replaced by silver ink to print more high end prototypes with. The Voxel8 also proved that the silver ink is more suitable for printing 3D.

This proven concept can also give a boost to the development of solder pastes, given the fact that the used conductive material is not originally designed to be 3D printed. A conductive paste better suited for 3D printing could be developed, one that can be used to print in 3D, one that is less harmful, one that does not have to be cured or can be cured at room temperature. Concluding, this proven concept can already be used for many applications regardless of a recommended optimisation.

7.3 Recommendations

This chapter describes the way forward to improve the designed concept. Next to this, recommendations are also made for follow up experiments and additions to the project. Design aspects and further research aspects are recommended.

7.3.1 Local heating to cure solder paste

A local heating source to cure solder paste would enhance the process of printing electronics and could be added on the 3D printer, instead of a process where the sample has to be taken off the printer and needs postproccessing. Local heating can also be the step from 2D to 3D printing with solder paste. For instance, if a laser is used to cure, it can be attached to the head of the printer. After printing solder paste the laser could cure the trace.
It is recommended to look into local curing options and research if they can be adapted to work. Although it will push forward the design of the printer, this addition to the extruder head will decrease the build volume even more.

7.3.2 Safety regulations

Solder paste is a material that is toxic before being cured. The chosen solder paste can be harmful when being used more often. Although it is always important to make sure the user is protected from the material.
Research has to be done to develop the concept further into keeping it as safe as possible to use the solder paste. At least working with the paste, gloves and protection glasses have to be worn. The printer has to be used in a well ventilated area.

Feeding the material and storage

Most solder pastes have to be refrigerated for a longer shelf life. Only during printing the material has to be used at room temperature. Therefore it should be easy to take the container with material off and on. Right now the material comes in a syringe. This syringe is placed in the extruder bracket.
The concept has to be developed further to make it as easy and straightforward as possible using the syringe. Placing it in the refrigerator and placing it at the printer.

7.3.3 Buildvolume

Right now the extruding head has two extruders, the thermoplastic extruder and the solder paste extruder. This already has a big influence on the build volume, as presented in Chapter 4.1. It was recommended to add a tool for local curing as well. This will make the head even bigger, resulting in an even smaller build volume.
To solve this problem the extruder head can be designed to have the most volume of the extruder head going under the construction of the 3D printer, as can be seen in Figure 7.1.

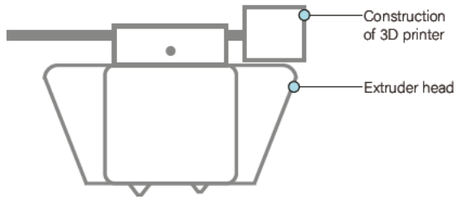


Figure 7.1: Design recommendation.

Another solution can be to use a tool changer, the extruder head will carry just one tool that is needed at that time. The other tools are placed on the back of the 3D printer. The head or tool switch picks up the tool it needs. After use it can place the tool back and pick up another tool.
This gives a lot of freedom in adding extra tools and extruders. E3D has designed such a system, called the ToolChanger. [34] Examples are given in Figure 7.2 and Figure 7.3.

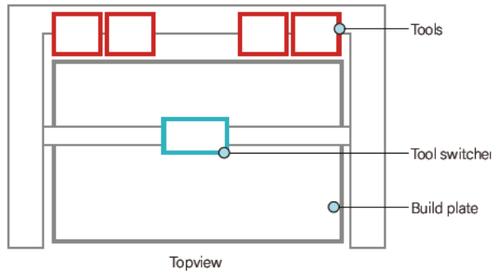


Figure 7.2: Topview of the toolchanger.

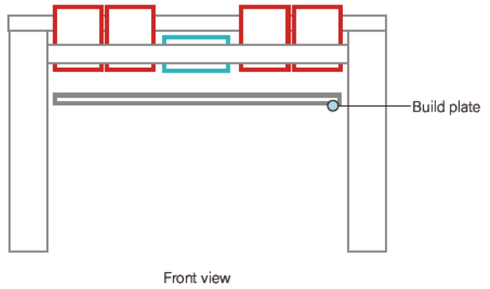


Figure 7.3: Front view of the toolchanger.

7.3.4 Extruding methods

The settings of the chosen extruding method are not yet optimal. In the experimental phase the research area was highlighted. It is recommended to further optimise the printing settings, doing experiments with the settings in the found research area, shown in Figure 7.4.

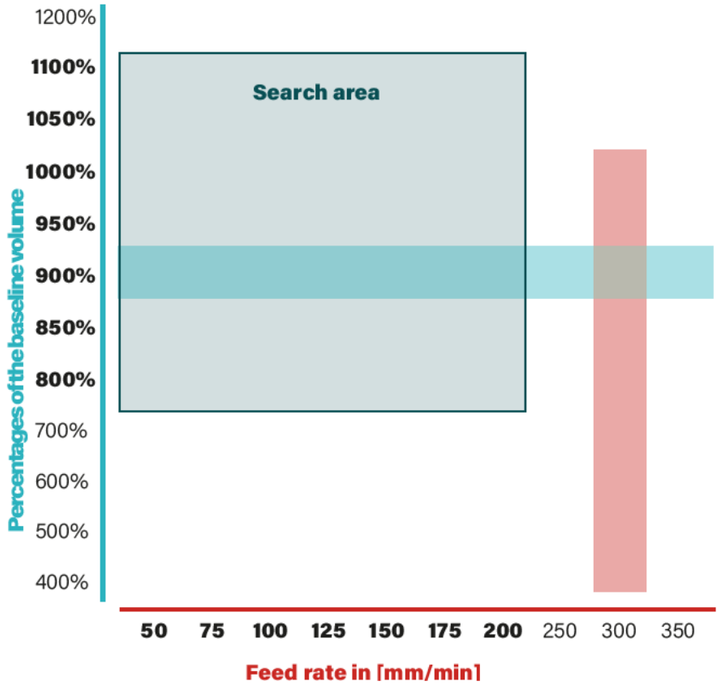


Figure 7.4: Search area to finetune the settings of the extruder.

7.4 Reflection

In this final chapter, I will look back on the conducted project and research. I reflect on the process and the experience. What did it bring me and what did I learn about myself?

First, I would like to reflect the moment I dove into my graduation project. I had the idea that graduation was an impossible project to complete. This thought was of course not a reasonable thought, as I know that an amazing lot of students already went through this path.

As at this point of writing, almost the end of this project, I do not have this thought anymore, the thought influenced my view on my work in the project. I put a lot of pressure on myself, also believing that I was not capable of doing it, next that the work I did was ever good enough.

This was actually in big contrast of with what I now think and the feedbacks that I received from my supervisors. Because of their positive feedback, I was able to give myself the space to look from another side onto the project.

To put it in perspective this thought was not there all the time, but it fed my insecurity. If I had let this thought grow bigger, I probably would not have been able to graduate. Logical reasoning and being able to look at my project from another point of view gave me the strength and motivation to continue the project.

Looking at the process I went through, I can now say that it fits the classical design process. The start is always very fuzzy, which makes you swimming around in a very big pool. This also resulted in experiments that I conducted that did not even appear in this written thesis. However, these experiments will gave guidance in where to go. A hands-on approach was my goal from the beginning. I already had experienced that this gives satisfaction, also when you will never look back at this prototype or experience. It gives a feeling in which direction you have to swim.

At the moment where the project became clearer, I knew better which steps had to be taken to come to a result. Taking these steps is a process on its own. During those experiments it can be almost heartbreaking and enduring when a result is not happening, although you know it should somehow work. At those points, I really did not like it that I was doing this project on my own. It was very hard to reason what the next step should be when the previous experiment did not work.
It helped me a lot that I became more talkative about the experiments that I did, so other people could look at it with me and give advice and their thoughts about the problem.

This was always easier with my friend and co-student in IPD, Jordan, I discussed a lot of problems with him. He always gave me advise and hope to conduct the next experiment.

This project was somehow also a bit lonely, just because you have to carry the project on your own, which is in contrast when you are conducting a project in a group, where you have the community feeling of all working towards one goal. I think I do not like to miss out of that community feeling.

What I learned was that it is very important to document all your experiments in a constructive way. In the beginning of my project I was pretty consious about this fact and I also did more documentation then. At the point that the experiments were being conducted more and more, I lost the urge to write everything down.
When writing this thesis, definitely Chapter 3, I had to go over my notes and combine the right samples to the right g-codes and experiments. This was almost detective work and it would have been way easier if I had done better documentation.

What I found out conducting this project on my own, is that in a group I am really good at keeping the overview, knowing what has to be done. In this project, I sometimes lost this overview and was sucked in into the details and working on one part of my project, forgetting about the other parts. Later during the project I was more conscious about this fact, so I also learned to sometimes take the time to be satisfied with what I achieved in one part of the project and being able to switch to another part to develop that to the same level.

Writing this report gives a lot of structure back to my project, or the other way around the report pushed me to create a structure for my project. To be able to tell why I took this path. At the point of taking certain steps it is very different from taking a step back and seeing the overview.

There are also a lot of things that I liked during this project. I can say that I also liked conducting this project. I can say I developed a lot to be able to create the proof of concept. Developing and creating, being hands on really fits me. This is also the reason that I chose Integrated Product Design as my masters.

I am intrigued by material behaviours, production methods and machining. I get extremely happy when I have turned something and it perfectly fits in another designed part. That is the moment that your thoughts at front are coming together in a design. These things have pushed my motivation to work on the proof of the concept until a satisfying result.

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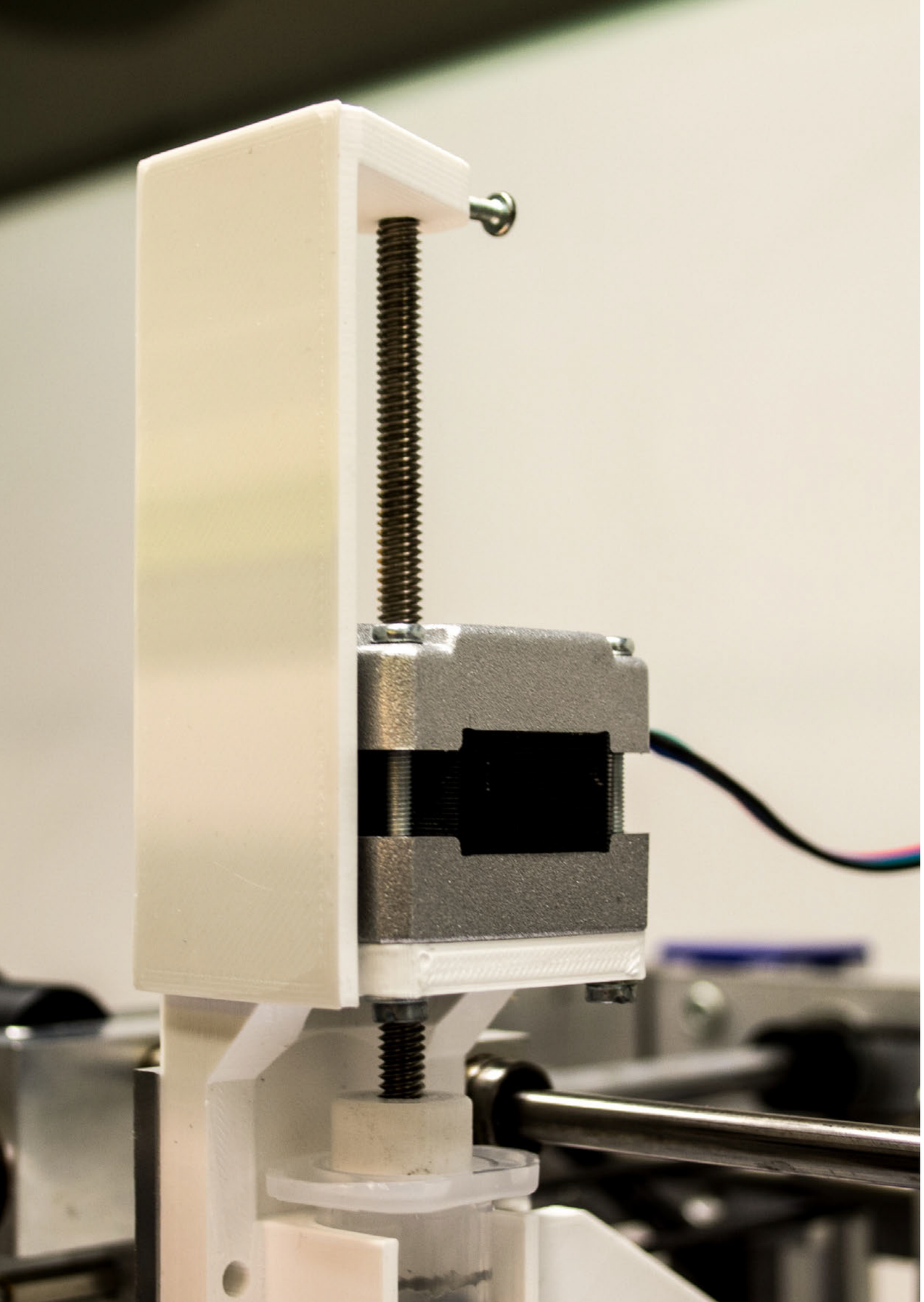
[30] B. Redwood, F. Schoffer and B. Garret, "Layer adhesion," in The 3D Printing Handbook, Amsterdam, Coers & Roest, 2018, pp. 30-31.

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Appendix

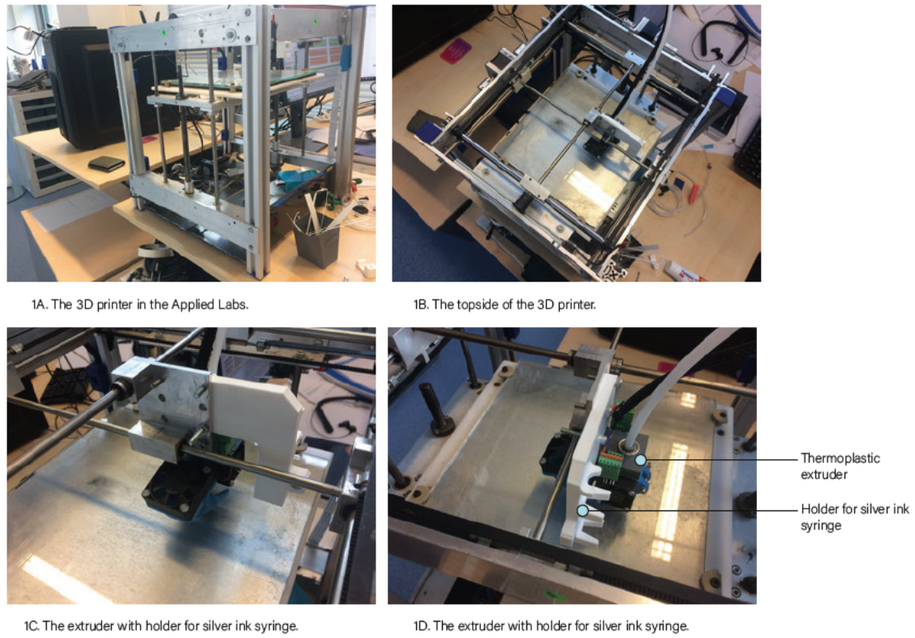
Appendix A: The Project Brief

A.1 The introduction

Structural electronics is the next generation of electronics manufacturing technology, and 3D printing of functional electronic circuitries across freeform shaped architectures are innovations in structural electronics. 3D printed electronics brings the following new opportunities to designers: 1) With 3D printed electronics the freedom of the designer is enabled to combine aesthetics and functions together in the design; 2) It gives the opportunity to miniaturize the design; 3) The design and manufacturing process of mechatronic products will be accelerated; and 4) It will boost the efficiency of producing customized/personalized and mechatronic/ electronic products, e.g. hospital equipment, parts of airplanes etc. Meanwhile it also posts challenges on the sustainability in the product design and manufacturing process. (Song et al., 2017)

In 3D printed electronics, printing conductive materials is a key. It is not yet possible to print pure copper or silver at a low temperature. However, it is possible to print with silver ink, either by inkjet or FDM. Currently, there are two types of FDM printers that are able to print silver ink: Voxel8 and Aerosol Jet. The Voxel8 is not on the market anymore. The Aerosol Jet is meant for the professional market., and the initial investment is rather high (>150K euro). In this project the 3D print method will be FDM (Fused Deposition Modeling), because FDM printers are more common for low cost custom thermoplastic parts and prototypes. (Varotsis, 2019)

Currently, a 3D electronics printer is prototyped in the Applied Labs of Industrial Design Engineering, it uses the same principle for printing silver ink as the Voxel8. The prototyped printer is very primitive and it is not working now. See Figure A.1, 1A and 1B for the current state of the prototyped printer in the Applied Labs. Besides, its working envelope is also limited by the added extra head. Figures 1C and 1D show the added extra head for printing silver ink. This limits the build size massively. See Figure A.2, 2A for the effective build size without extra head, and 2B for the build size with extra head.



1A. The 3D printer in the Applied Labs.

1B. The topside of the 3D printer.

1C. The extruder with holder for silver ink syringe.

1D. The extruder with holder for silver ink syringe.

Figure A.1: State of the current Hermann printer.

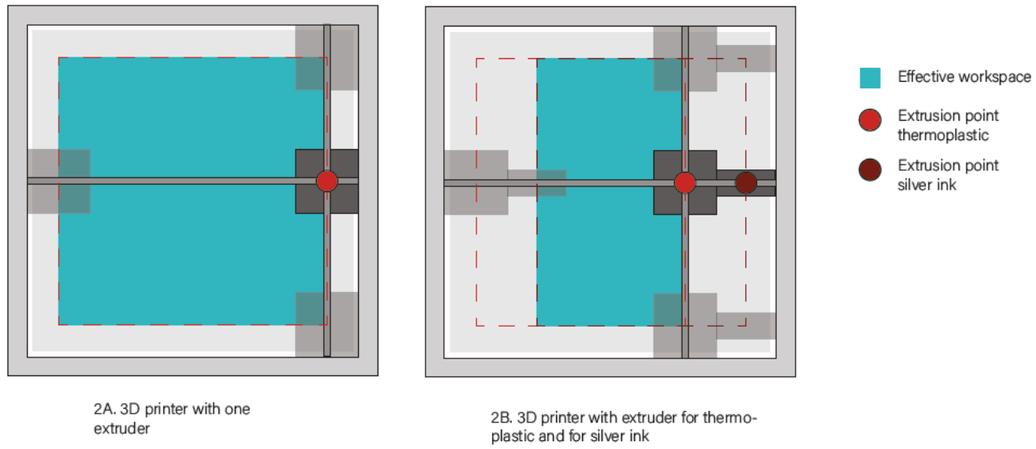
A.2 Problem definition

On the market are several electronics printers available. Most of these printers are inkjet printers meant for the professional market. In this project a prototype of an FDM electronics printer for the industry will be developed. Few FDM printers focus on prototyping products with relative large scale using 3D printed electronics. For a designer in the industry, a 3D electronics printer should have an “optimal” build size and overall size for different kinds of prototyping and building tasks.

In this project an FDM electronics printer will be designed and prototyped. In the design of the printer, the desired prototyping scale, the mechanical structure of the printer, the design of the extruder(s) will be investigated first. Another innovation of this project is that multiple extruder options, especially silver ink extruder, will be explored. Based on the literature review, to our knowledge, there is not a printer that combines all the functionalities for designers in the market. The large scale electronics printer will be designed and prototyped within the Center of Design for Agile Manufacturing.Assignment

Design and build an extrusion head and a large size 3D FDM printer system to enable printing of standard materials in combination with conductive materials.

The lean approach will be used in the project with 3 iterations. In the first iteration (2-3 weeks), we will focus on the design specification. Currently, the build size of printers is never evaluated for usability nor technology. Desktop printers have a build size that range from ***10x10x10 [cm]*** to ***50x50x50 [cm]*** within a price class of ***€200*** to ***€3000***. A bigger build volume will start at ***100x100x100 [cm]*** and start at a price of ***€20.000***. (E. van Munster, 3D printing expert at MTB3D, personal communication, 25th of Sep. 2019). Therefore, a critical look at the “optimal” build size, which fits the wish of the user, the available technologies, and the affordability of the user, is essential.



2A. 3D printer with one extruder

2B. 3D printer with extruder for thermo-plastic and for silver ink

Figure A.2: Effective build size.

In the second iteration (10 weeks), we will focus on designing the printer where different parts of the printers, e.g., the mechanical structure, the driving unit, the silver extruder will be explored. It is worth mentioning that we will use existing prototypes and off-the-shelf solutions as much as possible to accelerate the development.

In the third iteration (5 weeks), different parts of the design will be integrated as a 3D printed electronics printer, and the functionalities will be tested as well. The final deliverable will be a working 3D electronics printer with at least two extruders, a thermoplastic extruder and a silver ink extruder.

A.3 Approach

Due to circumstances I do not graduate full time. I planned to have on average 36 hours per week. So per week I will work 4,5 days. I planned the regular holidays free to stay in the same rhythm as the last years.

In the Research phase the most important requirements of the printer will be set. In the ideas and concept phase every part of the project will be further explored and prototypes will be made.
In the design phase all comes together in one design, this design will be prototyped and made.
Having the final prototype it is further tested and validated to see what the next steps are.
For every phase prototypes will be made to be able to quickly evaluate every part of the printer.

A.4 Motivation and personal ambitions

This project enables me to tackle a hard technical problem. I will improve the view on 3D printers and their future. Targeting the industry with 3D electronic printers creates a big challenge. 3D electronic printers exist, however not on this market. To make a 3D printer that fit the industry requires an FDM printer that will be working quite differently than regular desktop 3D printers.

To be able to successfully create the working prototype I have to develop it in a fast way. Rapid prototyping is a suitable approach. Rapid prototyping works as follows: by making small prototypes of first ideas, these prototypes can be tested. In this way ideas can be evaluated quickly and development will go fast. I have never used this approach in my studies before. Therefore this will be my big learning goal.

Next to this goal it is a challenge to build a 3D print system and the silver ink extruder. The following things will be checked off:
- Mechanical structure of the printer
- Working with existing software for 3D printers
- Mechanical structure of the extruder
- Mechanical structure of the feeder
- Working with different and new materials to print with

Song, Y., Boekraad, R. A., Roussos, L., Kooijman, A., Wang, C. C. L., & Geraedts, J. M. P. (2017). 3D Printed Electronics: Opportunities and Challenges from Case Studies. IDETC/CIE 2017.

Varotsis, A. B. (2019). Introduction to FDM 3D printing. Retrieved September 19, 2019, from https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing

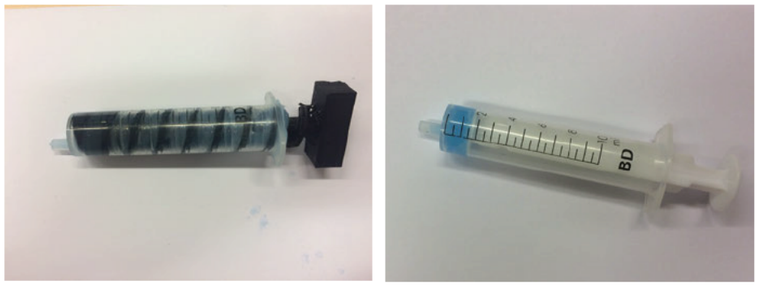
Appendix B: Voxel8 and Silver ink

The quality of the silver ink traces tested by the Voxel8 differ significantly. With the Voxel8 it is hard to print in real 3D directions. (Papers)
Printing silver in one go will increase the quality of the trace.
FDM printing is based on building layers horizontally and going up one layer when all the layers are done. Therefore now it is only possible to print a successful horizontal silver ink trace.

Appendix C: Extruding material

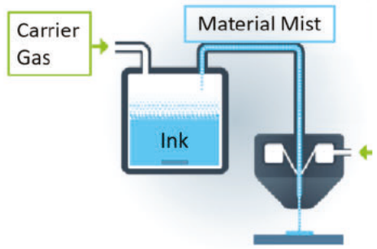
Two tests are done by hand. First the spiral is created to see if it is an option to use this method for pushing out the silver ink. This can be compared to using the plunger; which is also tested by hand.

	Trace size	Complexity	Influences build size of printer
Spiral	4 mm (manual tested with a 2 mm nozzle)	Low	Low
Plunger	5 mm (manual tested with a 2 mm nozzle)	Low	Low
Pneumatic pump	0.200 mm	Medium	High
Aerosol jet	0.020 mm	High	High

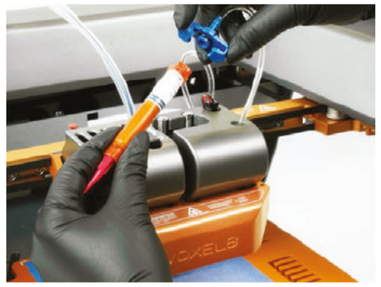


A. Extruder spiral

B. Plunger

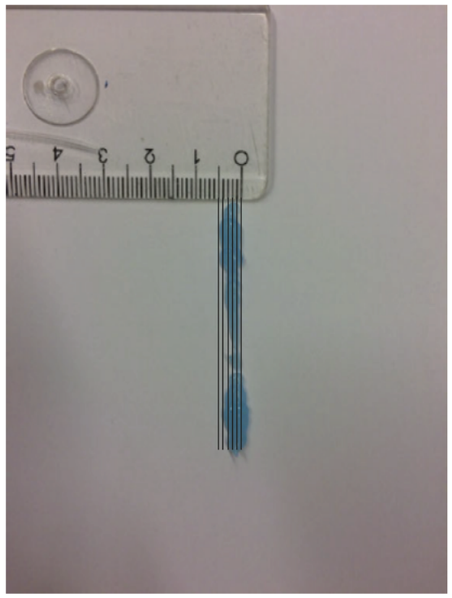


C. Aerosol Jet

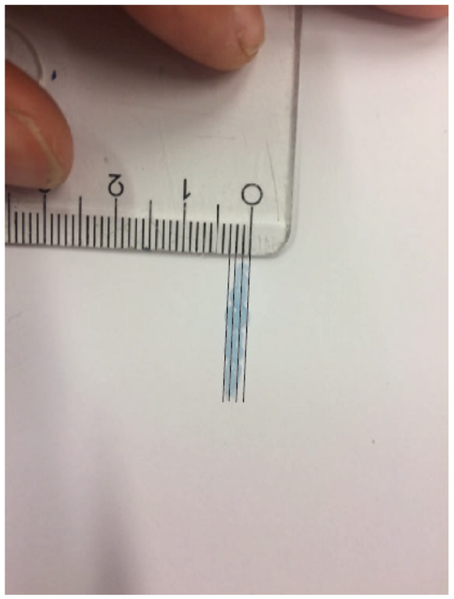


D. Pneumatic pump

Figure C.1: Pictures of the four different methods.



A. Trace of the plunger



B. Trace of the spiral

Figure C.2: Results.

Figure C.2 shows the results of using the plunger and spiral by hand. The used material is toothpaste.

Appendix D: Curing methods

The following curing methods have not been taken into account in the project, however are used in industrial processes to cure solder paste on PCB's.

Induction
An expensive oven is needed to use induction for curing the solder paste. They use this at a university in the United States, however is not present in the Applied Labs at the TU Delft.

Infra-red
Infra-red ovens can be used to cure solder paste as well.

Microwave
Microwave curing of solder pastes is used in the industry. It is a good opportunity as it will not heat up the plastic surroundings. However, this method implies the additional requirement for the microwave to precisely set the temperature. This is only possible on specific microwaves and not the usually commerically available for food consumption.

Appendix E: Test with ABS

To test if the oven is an option, the start test is done by printing a small ABS print with a 2 mm trace gap for the solder paste. This part is put in the oven and wires are attached to be able to measure resistance.
The oven is gradually heated up to 190 °C, at this point the ABS part is permanently deformed. During the test it was not possible to measure the resistance outside of the oven. Therefore a second test is set up to see when the trace becomes conductive. Six of the same prints are printed and solder paste is put in the print. Every different print is heated up to a different temperature. Starting from 120 °C to 200 °C. With this test the ABS can be measured after coming out of the oven and see whether there was a physical deformation. Next to the resistance of the trace can be measured with a multi meter.
Test results:

Sample	Temperature [°C]			
Conductivity		Steady?		Deformation
4	100	No	-	-
5	110	No	-	-
6	120	No	-	-
4	120	No	-	-
5	130	No	-	Yes
6	140	Yes	No	Yes
1	150	Yes	No	Yes
2	155	Yes	No	Yes
3	160	Yes	No	Yes

Conclusion:
It can be seen that before the trace becomes conductive the material already starts deforming.

Appendix F: Viscosity test

7.4.1 The viscosity test 1

As previous tests have shown that the printed line is not continuous in thickness, it has to be troubleshooted. It could be that the screw does not work with too viscous materials. Therefore there is chosen to see how other materials behave. However first there is a test to see on which scale solder paste can be placed. This test is done as following (materials in order of low viscosity to high viscosity):

Material

- Honey
- Ketchup
- Mustard
- Sour Cream
- Peanut Butter
- Solder paste Sn42Bi57,6Ag0,4 (room temperature)
- Solder paste Sn42Bi57,6Ag0,4 (out of the fridge)

B-D Plastipak 10 mL syringe with concentric tip

Setup

Seven syringes filled with 2 mL of the above materials are placed in a shelf. The second step is that the syringes are being pushed down at the same moment with another shelf. This is all filmed, on the film it can be seen how fast the material is coming out and how fast the material is flowing afterwards.

Test

This test will give a scale of the viscosity of the different materials. Where the solder paste can be placed in between. The follow up test is to see whether the screw is able to extrude the materials in the print.

Results

The experiment was filmed a still out of this movie is presented in Figure F.2. The peanut butter is considered out of the experiment as it might had to big particles to go through the nozzle. In the picture it can be seen that the honey has stopped, and the rest of the materials is still being pushed out.
The material that first came out was honey, second was the ketchup, but third was the sour cream. The fourth material that came out was mosterd, followed by the solder paste on room temperature and the solder paste just out of the fridge.

Conclusion

Based on the results of the materials are ranked from low viscosity to a high viscosity. Peanut butter is considered out of the experiment.
The following order is based on the experiment, rating from low to a high viscosity:

- Honey
- Ketchup
- Sour Cream
- Mustard
- Solder paste Sn42Bi57,6Ag0,4 (room temperature)
- Solder paste Sn42Bi57,6Ag0,4 (out of the fridge)

It is considered that mustard has the highest viscosity, close to the solder paste.

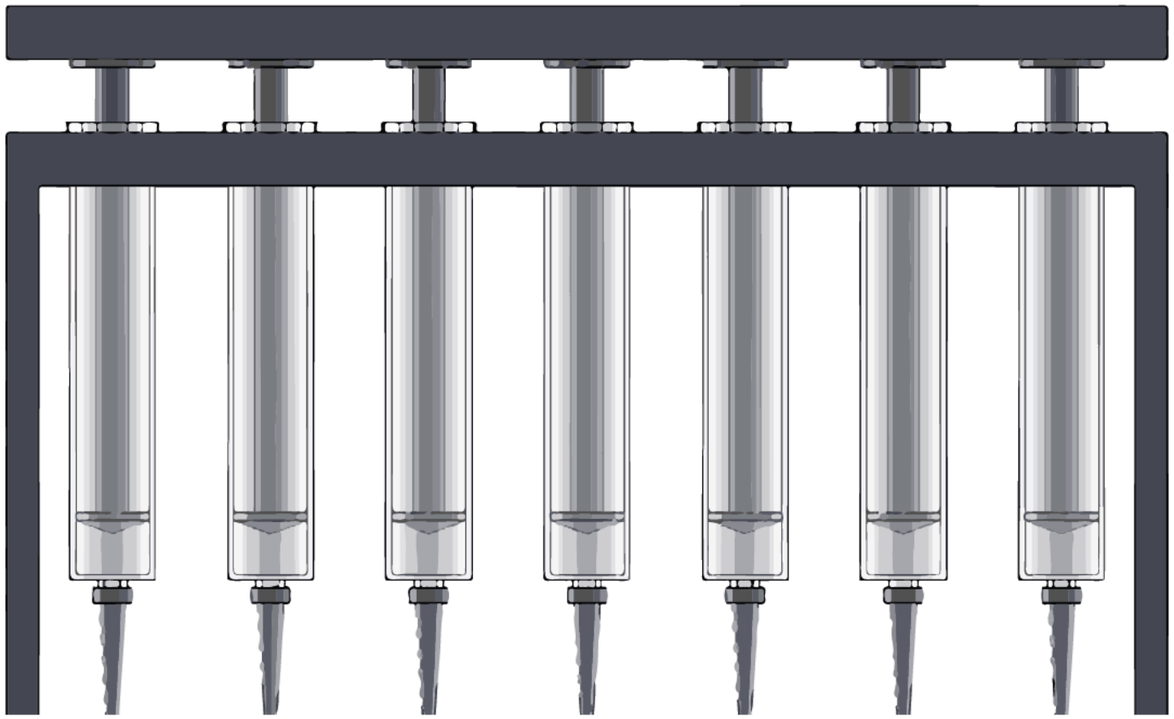


Figure F.1: Setup of the viscosity test

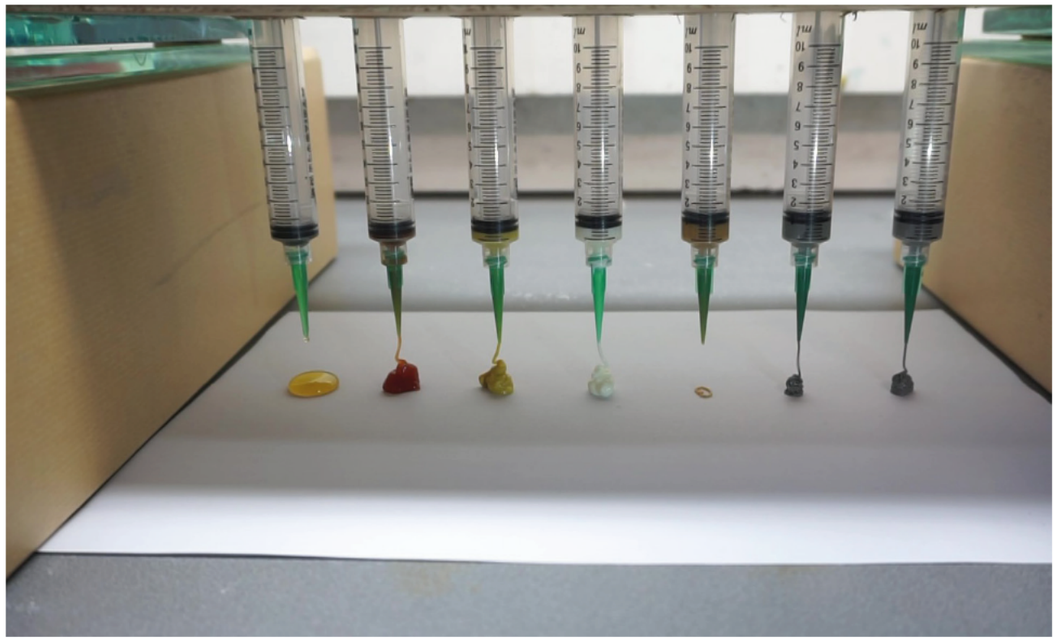


Figure F.2: Results.

Appendix G: G-codes screw

G.1 G-code 1

```
G21 ; set units to millimeters
M107
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle

G90 ; use absolute coordinates
G92 E0
M82 ; use absolute distances for extrusion
G1 F1800.000 E-1.00000
G92 E0
G1 Z0.400 F7800.000
G1 X51.412 Y94.058 F7800.000
G1 E1.00000 F1800.000
G1 X53.574 Y93.236 E1.09627 F600.000
G1 X54.850 Y93.114 E1.14962
G1 X145.150 Y93.114 E4.90859
G1 X147.428 Y93.511 E5.00486
G1 X149.438 Y94.656 E5.10113 F600.000
G1 X150.942 Y96.412 E5.19740
G1 X151.764 Y98.574 E5.29367
G1 X151.886 Y99.850 E5.34702
G1 X151.886 Y100.150 E5.35951
G1 X151.489 Y102.428 E5.45578
G1 X150.344 Y104.438 E5.55205
G1 X148.588 Y105.942 E5.64832
G1 X146.426 Y106.764 E5.74459
G1 X145.150 Y106.886 E5.79794
G1 X54.850 Y106.886 E9.55691
G1 X52.572 Y106.489 E9.65318
G1 X50.562 Y105.344 E9.74945
G1 X49.058 Y103.588 E9.84572
G1 X48.236 Y101.426 E9.94200
G1 X48.114 Y100.150 E9.99534
G1 X48.114 Y99.850 E10.00783
G1 X48.511 Y97.572 E10.10410
G1 X49.656 Y95.562 E10.20037
G1 X51.355 Y94.106 E10.29352
M106 S255
G1 F1800.000 E9.29352

M107
M104 S0 ; turn off temperature
G28 X0  ; home X axis
M84     ; disable motors
```

G.2 G-code 2

```
M107
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle

; Filament gcode

G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0
G1 E-1.00000 F1800.00000
G92 E0
G1 Z0.400 F7800.000
G1 X145.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X145.000 Y50.000 E191.87324
G1 E190.87324 F1800.00000
G92 E0
G1 X135.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X135.000 Y50.000 E191.85898
G1 E190.85898 F1800.00000
G92 E0
G1 X125.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X125.000 Y50.000 E191.85898
G1 E190.85898 F1800.00000
G92 E0
G1 X115.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X115.000 Y50.000 E191.86253
G1 E190.86253 F1800.00000
G92 E0
G1 X105.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X105.000 Y50.000 E191.87681
G1 E190.87681 F1800.00000
G92 E0
G1 X95.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X95.000 Y50.000 E191.86965
G1 E190.86965 F1800.00000
G92 E0
G1 X85.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X85.000 Y50.000 E191.86965
G1 E190.86965 F1800.00000
G92 E0
G1 X75.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X75.000 Y50.000 E191.86965
G1 E190.86965 F1800.00000
G92 E0
G1 X65.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X65.000 Y50.000 E191.86965
G1 E190.86965 F1800.00000
G92 E0
G1 X55.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X55.000 Y50.000 E191.86965
G1 E190.86965 F1800.00000
G92 E0
; Filament-specific end gcode
;END gcode for filament

M104 S0 ; turn off temperature
G28 X0  ; home X axis
M84     ; disable motors

M140 S0 ; set bed temperature
```

G.3 G-code 3

```
M107
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle
M900 K75 ; Set K factor for extruder
; Filament gcode

G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0
G1 E-1.00000 F1800.00000
G92 E0
G1 Z0.400 F7800.000
G1 X145.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X145.000 Y50.000 E382.74647
G1 E381.74647 F1800.00000
G92 E0
G1 X135.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X135.000 Y50.000 E382.71795
G1 E381.71795 F1800.00000
G92 E0
G1 X125.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X125.000 Y50.000 E382.71795
G1 E381.71795 F1800.00000
G92 E0
G1 X115.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X115.000 Y50.000 E382.72506
G1 E381.72506 F1800.00000
G92 E0
G1 X105.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X105.000 Y50.000 E382.75361
G1 E381.75361 F1800.00000
G92 E0
G1 X95.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X95.000 Y50.000 E382.73930
G1 E381.73930 F1800.00000
G92 E0
G1 X85.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X85.000 Y50.000 E382.73930
G1 E381.73930 F1800.00000
G92 E0
G1 X75.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
```

```
G1 F60
G1 X75.000 Y50.000 E382.73930
G1 E381.73930 F1800.00000
G92 E0
G1 X65.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X65.000 Y50.000 E382.73930
G1 E381.73930 F1800.00000
G92 E0
G1 X55.000 Y150.000 F7800.000
G1 E1.00000 F1800.00000
G1 F60
G1 X55.000 Y50.000 E382.73930
G1 E381.73930 F1800.00000
G92 E0
; Filament-specific end gcode
;END gcode for filament

M104 S0 ; turn off temperature
G28 X0  ; home X axis
M84     ; disable motors

M140 S0 ; set bed temperature
```

G.4 G-code 4

```
M107
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle
M900 K75 ; Set K factor for extruder
; Filament gcode

G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0
G1 E-0.20000 F600.00000
G92 E0
G1 Z0.400 F7800.000
G1 X145.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X145.000 Y50.000 E381.94647
G1 E381.74647 F600.00000
G92 E0
G1 X135.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X135.000 Y50.000 E381.91795
G1 E381.71795 F600.00000
G92 E0
G1 X125.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X125.000 Y50.000 E381.91795
G1 E381.71795 F600.00000
G92 E0
G1 X115.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X115.000 Y50.000 E381.92506
G1 E381.72506 F600.00000
G92 E0
G1 X105.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X105.000 Y50.000 E381.95361
G1 E381.75361 F600.00000
G92 E0
G1 X95.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X95.000 Y50.000 E381.93930
G1 E381.73930 F600.00000
G92 E0
G1 X85.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X85.000 Y50.000 E381.93930
G1 E381.73930 F600.00000
G92 E0
G1 X75.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X75.000 Y50.000 E381.93930
G1 E381.73930 F600.00000
G92 E0
G1 X65.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X65.000 Y50.000 E381.93930
G1 E381.73930 F600.00000
G92 E0
G1 X55.000 Y150.000 F7800.000
G1 E0.20000 F600.00000
G1 F60
G1 X55.000 Y50.000 E381.93930
G1 E381.73930 F600.00000
G92 E0
; Filament-specific end gcode
;END gcode for filament

M104 S0 ; turn off temperature
G28 X0  ; home X axis
M84     ; disable motors

M140 S0 ; set bed temperature
```

G.5 G-code 5

```
M107
G28 ; home all axes with heated bed
G21 ; set units to millimeters
M204 P500 ; set acceleration
G90 ; use absolute coordinates
M83 ; use relative distances for extrusion
G92 E0 ; reset extruder distance
G1 X100 Y100 F6000 ; move to start
G1 Z0.3 F0 ; move to layer height
;
; prime nozzle
;
G1 X51 Y62.5 F6000 ; move to start
G1 X51 Y137.5 E4010.7046 F60 ; print line
G1 X63 Y137.5 F6000 ; move to start
G1 X63 Y62.5 E4010.7046 F60 ; print line
G1 E-1 F1800 ; retract
;
; start the Test pattern
;
G4 P2000 ; Pause (dwell) for 2 seconds
G1 X61 Y62.5 F6000 ; move to start
M900 K0 ; set K-factor
M117 K0 ;
G1 E1 F1800 ; un-retract
G1 X81 Y62.5 E1069.5212 F0 ; print line
G1 X121 Y62.5 E2139.0424 F60 ; print line
G1 X141 Y62.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y67.5 F6000 ; move to start
M900 K0.2 ; set K-factor
M117 K0.2 ;
G1 E1 F1800 ; un-retract
G1 X81 Y67.5 E1069.5212 F0 ; print line
G1 X121 Y67.5 E2139.0424 F60 ; print line
G1 X141 Y67.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y72.5 F6000 ; move to start
M900 K0.4 ; set K-factor
M117 K0.4 ;
G1 E1 F1800 ; un-retract
G1 X81 Y72.5 E1069.5212 F0 ; print line
G1 X121 Y72.5 E2139.0424 F60 ; print line
G1 X141 Y72.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y77.5 F6000 ; move to start
M900 K0.6 ; set K-factor
M117 K0.6 ;
G1 E1 F1800 ; un-retract
G1 X81 Y77.5 E1069.5212 F0 ; print line
G1 X121 Y77.5 E2139.0424 F60 ; print line
G1 X141 Y77.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y82.5 F6000 ; move to start
M900 K0.8 ; set K-factor
M117 K0.8 ;
G1 E1 F1800 ; un-retract
G1 X81 Y82.5 E1069.5212 F0 ; print line
G1 X121 Y82.5 E2139.0424 F60 ; print line
G1 X141 Y82.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y87.5 F6000 ; move to start
M900 K1 ; set K-factor
M117 K1 ;
G1 E1 F1800 ; un-retract
G1 X81 Y87.5 E1069.5212 F0 ; print line
G1 X121 Y87.5 E2139.0424 F60 ; print line
G1 X141 Y87.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y92.5 F6000 ; move to start
M900 K1.2 ; set K-factor
M117 K1.2 ;
G1 E1 F1800 ; un-retract
G1 X81 Y92.5 E1069.5212 F0 ; print line
G1 X121 Y92.5 E2139.0424 F60 ; print line
G1 X141 Y92.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y97.5 F6000 ; move to start
M900 K1.4 ; set K-factor
```

```
M117 K1.4 ;
G1 E1 F1800 ; un-retract
G1 X81 Y97.5 E1069.5212 F0 ; print line
G1 X121 Y97.5 E2139.0424 F60 ; print line
G1 X141 Y97.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y102.5 F6000 ; move to start
M900 K1.6 ; set K-factor
M117 K1.6 ;
G1 E1 F1800 ; un-retract
G1 X81 Y102.5 E1069.5212 F0 ; print line
G1 X121 Y102.5 E2139.0424 F60 ; print line
G1 X141 Y102.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y107.5 F6000 ; move to start
M900 K1.8 ; set K-factor
M117 K1.8 ;
G1 E1 F1800 ; un-retract
G1 X81 Y107.5 E1069.5212 F0 ; print line
G1 X121 Y107.5 E2139.0424 F60 ; print line
G1 X141 Y107.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y112.5 F6000 ; move to start
M900 K2 ; set K-factor
M117 K2 ;
G1 E1 F1800 ; un-retract
G1 X81 Y112.5 E1069.5212 F0 ; print line
G1 X121 Y112.5 E2139.0424 F60 ; print line
G1 X141 Y112.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X61 Y117.5 F6000 ; move to start
;
; mark the test area for reference
M117 K0 ;
M900 K0 ; set K-factor 0
G1 X81 Y117.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X81 Y137.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 X121 Y117.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X121 Y137.5 E1069.5212 F0 ; print line
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
;
; print K-values
;
G1 X143 Y60.5 F6000 ; move to start
G1 Z0.3 F0 ; zHop
G1 E1 F1800 ; un-retract
G1 X145 Y60.5 E106.9521 F0 ; 0
G1 X145 Y62.5 E106.9521 F0 ; 0
G1 X145 Y64.5 E106.9521 F0 ; 0
G1 X143 Y64.5 E106.9521 F0 ; 0
G1 X143 Y62.5 E106.9521 F0 ; 0
G1 X143 Y60.5 E106.9521 F0 ; 0
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
G1 X143 Y70.5 F6000 ; move to start
G1 Z0.3 F0 ; zHop
G1 E1 F1800 ; un-retract
G1 X145 Y70.5 E106.9521 F0 ; 0
G1 X145 Y72.5 E106.9521 F0 ; 0
G1 X145 Y74.5 E106.9521 F0 ; 0
G1 X143 Y74.5 E106.9521 F0 ; 0
G1 X143 Y72.5 E106.9521 F0 ; 0
G1 X143 Y70.5 E106.9521 F0 ; 0
G1 E-1 F1800 ; retract
G1 X146 Y70.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X146 Y70.9 E21.3904 F0 ; dot
G1 E-1 F1800 ; retract
G1 X147 Y70.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X147 Y72.5 F6000 ; move to start
G1 X147 Y74.5 F6000 ; move to start
G1 X147 Y72.5 E106.9521 F0 ; 4
G1 X149 Y72.5 E106.9521 F0 ; 4
G1 X149 Y74.5 F6000 ; move to start
G1 X149 Y72.5 E106.9521 F0 ; 4
G1 X149 Y70.5 E106.9521 F0 ; 4
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
G1 X143 Y80.5 F6000 ; move to start
G1 Z0.3 F0 ; zHop
G1 E1 F1800 ; un-retract
G1 X145 Y80.5 E106.9521 F0 ; 0
G1 X145 Y82.5 E106.9521 F0 ; 0
G1 X145 Y84.5 E106.9521 F0 ; 0
G1 X143 Y84.5 E106.9521 F0 ; 0
G1 X143 Y82.5 E106.9521 F0 ; 0
G1 X143 Y80.5 E106.9521 F0 ; 0
G1 E-1 F1800 ; retract
G1 X146 Y80.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X146 Y80.9 E21.3904 F0 ; dot
G1 E-1 F1800 ; retract
G1 X147 Y80.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X147 Y82.5 F6000 ; move to start
G1 X149 Y82.5 E106.9521 F0 ; 8
G1 X149 Y80.5 E106.9521 F0 ; 8
G1 X147 Y80.5 E106.9521 F0 ; 8
G1 X147 Y82.5 E106.9521 F0 ; 8
G1 X147 Y84.5 E106.9521 F0 ; 8
G1 X149 Y84.5 E106.9521 F0 ; 8
G1 X149 Y82.5 E106.9521 F0 ; 8
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
G1 X143 Y90.5 F6000 ; move to start
G1 Z0.3 F0 ; zHop
G1 E1 F1800 ; un-retract
G1 X143 Y92.5 E106.9521 F0 ; 1
G1 X143 Y94.5 E106.9521 F0 ; 1
G1 E-1 F1800 ; retract
G1 X144 Y90.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X144 Y90.9 E21.3904 F0 ; dot
G1 E-1 F1800 ; retract
G1 X145 Y90.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X145 Y92.5 F6000 ; move to start
G1 X145 Y94.5 F6000 ; move to start
G1 X147 Y94.5 E106.9521 F0 ; 2
G1 X147 Y92.5 E106.9521 F0 ; 2
G1 X145 Y92.5 E106.9521 F0 ; 2
G1 X145 Y90.5 E106.9521 F0 ; 2
G1 X147 Y90.5 E106.9521 F0 ; 2
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
G1 X143 Y100.5 F6000 ; move to start
G1 Z0.3 F0 ; zHop
G1 E1 F1800 ; un-retract
G1 X143 Y102.5 E106.9521 F0 ; 1
G1 X143 Y104.5 E106.9521 F0 ; 1
G1 E-1 F1800 ; retract
G1 X144 Y100.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X144 Y100.9 E21.3904 F0 ; dot
G1 E-1 F1800 ; retract
G1 X145 Y100.5 F6000 ; move to start
G1 E1 F1800 ; un-retract
G1 X145 Y102.5 F6000 ; move to start
G1 X147 Y102.5 E106.9521 F0 ; 6
G1 X147 Y100.5 E106.9521 F0 ; 6
G1 X145 Y100.5 E106.9521 F0 ; 6
G1 X145 Y102.5 E106.9521 F0 ; 6
G1 X145 Y104.5 E106.9521 F0 ; 6
G1 X147 Y104.5 E106.9521 F0 ; 6
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
G1 X143 Y110.5 F6000 ; move to start
G1 Z0.3 F0 ; zHop
G1 E1 F1800 ; un-retract
G1 X143 Y112.5 F6000 ; move to start
G1 X143 Y114.5 F6000 ; move to start
G1 X145 Y114.5 E106.9521 F0 ; 2
G1 X145 Y112.5 E106.9521 F0 ; 2
G1 X143 Y112.5 E106.9521 F0 ; 2
G1 X143 Y110.5 E106.9521 F0 ; 2
G1 X145 Y110.5 E106.9521 F0 ; 2
G1 E-1 F1800 ; retract
G1 Z0.4 F0 ; zHop
;
; finish
;
M104 S0 ; turn off hotend
M140 S0 ; turn off bed
G1 Z30 X200 Y200 F6000 ; move away from the print
M84 ; disable motors
M502 ; resets parameters from ROM
M501 ; resets parameters from EEPROM
;
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G.6 G-code 6

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M107
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle

; Filament gcode

G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0
G1 E-0.20000 F600.00000
G92 E0
G1 Z0.400 F7800.000
G1 X185.000 Y23.000 F7800.000
G1 E0.20000 F600.00000
G1 F120
G1 X16.000 Y23.000 E393.61298
G1 X15.896 Y23.021 E393.85916
G1 F120
G1 X15.689 Y23.064 E394.39772
G1 F120
G1 X15.586 Y23.086 E394.69010
G1 X15.543 Y23.293 E395.27485
G1 F120
G1 X15.500 Y23.500 E395.81341
G1 F120
G1 X15.500 Y33.500 E419.09229
G1 X15.521 Y33.604 E419.33846
G1 F120
G1 X15.564 Y33.811 E419.87702
G1 F120
G1 X15.586 Y33.914 E420.16940
G1 X15.793 Y33.957 E420.75416
G1 F120
G1 X16.000 Y34.000 E421.29271
G1 F120
G1 X184.000 Y34.000 E812.37781
G1 X184.104 Y34.021 E812.62399
G1 F120
G1 X184.311 Y34.064 E813.16254
G1 F120
G1 X184.414 Y34.086 E813.45492
G1 X184.457 Y34.293 E814.03968
G1 F120
G1 X184.500 Y34.500 E814.57824
G1 F120
G1 X184.500 Y44.500 E837.85711
G1 X184.479 Y44.604 E838.10329
G1 F120
G1 X184.436 Y44.811 E838.64185
G1 F120
G1 X184.414 Y44.914 E838.93423
G1 X184.207 Y44.957 E839.51899
G1 F120
G1 X184.000 Y45.000 E840.05754
G1 F120
G1 X16.000 Y45.000 E1231.14264
G1 X15.896 Y45.021 E1231.38882
G1 F120
G1 X15.689 Y45.064 E1231.92737
G1 F120
G1 X15.586 Y45.086 E1232.21975
G1 X15.543 Y45.293 E1232.80451
G1 F120
G1 X15.500 Y45.500 E1233.34307
G1 F120
G1 X15.500 Y55.500 E1256.62196
G1 X15.521 Y55.604 E1256.86813
G1 F120
G1 X15.564 Y55.811 E1257.40668
G1 F120
G1 X15.586 Y55.914 E1257.69906
G1 X15.793 Y55.957 E1258.28382
G1 F120
G1 X16.000 Y56.000 E1258.82237
G1 F120
G1 X184.000 Y56.000 E1649.90406
G1 X184.104 Y56.021 E1650.15023
G1 F120
G1 X184.311 Y56.064 E1650.68879
G1 F120
G1 X184.414 Y56.086 E1650.98117
G1 X184.457 Y56.293 E1651.56592
G1 F120
G1 X184.500 Y56.500 E1652.10446
G1 F120
G1 X184.500 Y66.500 E1675.38334
G1 X184.479 Y66.604 E1675.62951
G1 F120
G1 X184.436 Y66.811 E1676.16807
G1 F120
G1 X184.414 Y66.914 E1676.46045
G1 X184.207 Y66.957 E1677.04521
G1 F120
G1 X184.000 Y67.000 E1677.58377
G1 F120
G1 X16.000 Y67.000 E2068.66887
G1 X15.896 Y67.021 E2068.91504
G1 F120
G1 X15.689 Y67.064 E2069.45360
G1 F120
G1 X15.586 Y67.086 E2069.74598
G1 X15.543 Y67.293 E2070.33074
G1 F120
G1 X15.500 Y67.500 E2070.86929
G1 F120
G1 X15.500 Y77.500 E2094.14819
G1 X15.521 Y77.604 E2094.39436
G1 F120
G1 X15.564 Y77.811 E2094.93291
G1 F120
G1 X15.586 Y77.914 E2095.22528
G1 X15.793 Y77.957 E2095.81004
G1 F120
G1 X16.000 Y78.000 E2096.34860
G1 F120
G1 X184.000 Y78.000 E2487.43028
G1 X184.104 Y78.021 E2487.67646
G1 F120
G1 X184.311 Y78.064 E2488.21501
G1 F120
G1 X184.414 Y78.086 E2488.50739
G1 X184.457 Y78.293 E2489.09214
G1 F120
G1 X184.500 Y78.500 E2489.63069
G1 F120
G1 X184.500 Y88.500 E2512.90956
G1 X184.479 Y88.604 E2513.15574
G1 F120
G1 X184.436 Y88.811 E2513.69430
G1 F120
G1 X184.414 Y88.914 E2513.98668
G1 X184.207 Y88.957 E2514.57144
G1 F120
G1 X184.000 Y89.000 E2515.10999
G1 F120
G1 X16.000 Y89.000 E2906.19509
G1 X15.896 Y89.021 E2906.44127
G1 F120
G1 X15.689 Y89.064 E2906.97982
G1 F120
G1 X15.586 Y89.086 E2907.27220
G1 X15.543 Y89.293 E2907.85696
G1 F120
G1 X15.500 Y89.500 E2908.39552
G1 F120
G1 X15.500 Y99.500 E2931.67439
G1 X15.521 Y99.604 E2931.92057
G1 F120
G1 X15.564 Y99.811 E2932.45912
G1 F120
G1 X15.586 Y99.914 E2932.75150
G1 X15.793 Y99.957 E2933.33626
G1 F120
G1 X16.000 Y100.000 E2933.87482
G1 F120
G1 X184.000 Y100.000 E3324.95992
G1 X184.104 Y100.021 E3325.20609
G1 F120
G1 X184.311 Y100.064 E3325.74465
G1 F120
G1 X184.414 Y100.086 E3326.03703
G1 X184.457 Y100.293 E3326.62179
G1 F120
G1 X184.500 Y100.500 E3327.16035
G1 F120
G1 X184.500 Y110.500 E3350.43922
G1 X184.479 Y110.604 E3350.68540
G1 F120
G1 X184.436 Y110.811 E3351.22395
G1 F120
G1 X184.414 Y110.914 E3351.51633
G1 X184.207 Y110.957 E3352.10109
G1 F120
G1 X184.000 Y111.000 E3352.63965
G1 F120
G1 X16.000 Y111.000 E3743.72475
G1 X15.896 Y111.021 E3743.97092
G1 F120
G1 X15.689 Y111.064 E3744.50948
G1 F120
G1 X15.586 Y111.086 E3744.80186
G1 X15.543 Y111.293 E3745.38662
G1 F120
G1 X15.500 Y111.500 E3745.92517
G1 F120
G1 X15.500 Y121.500 E3769.20405
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G1 X15.521 Y121.604 E3769.45022
G1 F120
G1 X15.564 Y121.811 E3769.98878
G1 F120
G1 X15.586 Y121.914 E3770.28116
G1 X15.793 Y121.957 E3770.86592
G1 F120
G1 X16.000 Y122.000 E3771.40448
G1 F120
G1 X184.000 Y122.000 E4162.48957
G1 X184.104 Y122.021 E4162.73575
G1 F120
G1 X184.311 Y122.064 E4163.27431
G1 F120
G1 X184.414 Y122.086 E4163.56669
G1 X184.457 Y122.293 E4164.15145
G1 F120
G1 X184.500 Y122.500 E4164.69000
G1 F120
G1 X184.500 Y132.500 E4187.96888
G1 X184.479 Y132.604 E4188.21505
G1 F120
G1 X184.436 Y132.811 E4188.75361
G1 F120
G1 X184.414 Y132.914 E4189.04599
G1 X184.207 Y132.957 E4189.63075
G1 F120
G1 X184.000 Y133.000 E4190.16931
G1 F120
G1 X16.000 Y133.000 E4581.25440
G1 X15.896 Y133.021 E4581.50058
G1 F120
G1 X15.689 Y133.064 E4582.03914
G1 F120
G1 X15.586 Y133.086 E4582.33152
G1 X15.543 Y133.293 E4582.91627
G1 F120
G1 X15.500 Y133.500 E4583.45483
G1 F120
G1 X15.500 Y143.500 E4606.73371
G1 X15.521 Y143.604 E4606.97988
G1 F120
G1 X15.564 Y143.811 E4607.51844
G1 F120
G1 X15.586 Y143.914 E4607.81082
G1 X15.793 Y143.957 E4608.39558
G1 F120
G1 X16.000 Y144.000 E4608.93413
G1 F120
G1 X184.000 Y144.000 E5000.01923
G1 X184.104 Y144.021 E5000.26541
G1 F120
G1 X184.311 Y144.064 E5000.80396
G1 F120
G1 X184.414 Y144.086 E5001.09634
G1 X184.457 Y144.293 E5001.68110
G1 F120
G1 X184.500 Y144.500 E5002.21966
G1 F120
G1 X184.500 Y154.500 E5025.49854
G1 X184.479 Y154.604 E5025.74471
G1 F120
G1 X184.436 Y154.811 E5026.28327
G1 F120
G1 X184.414 Y154.914 E5026.57565
G1 X184.207 Y154.957 E5027.16041
G1 F120
G1 X184.000 Y155.000 E5027.69896
G1 F120
G1 X16.000 Y155.000 E5418.78406
G1 X15.896 Y155.021 E5419.03024
G1 F120
G1 X15.689 Y155.064 E5419.56879
G1 F120
G1 X15.586 Y155.086 E5419.86117
G1 X15.543 Y155.293 E5420.44593
G1 F120
G1 X15.500 Y155.500 E5420.98449
G1 F120
G1 X15.500 Y165.500 E5444.26336
G1 X15.521 Y165.604 E5444.50954
G1 F120
G1 X15.564 Y165.811 E5445.04809
G1 F120
G1 X15.586 Y165.914 E5445.34048
G1 X15.793 Y165.957 E5445.92523
G1 F120
G1 X16.000 Y166.000 E5446.46379
G1 F120
G1 X184.000 Y166.000 E5837.54889
G1 X184.104 Y166.021 E5837.79506
G1 F120
G1 X184.311 Y166.064 E5838.33362
G1 F120
G1 X184.414 Y166.086 E5838.62600
G1 X184.457 Y166.293 E5839.21076
G1 F120
G1 X184.500 Y166.500 E5839.74932
G1 F120
G1 X184.500 Y176.500 E5863.02819
G1 X184.479 Y176.604 E5863.27437
G1 F120
G1 X184.436 Y176.811 E5863.81292
G1 F120
G1 X184.414 Y176.914 E5864.10531
G1 X184.207 Y176.957 E5864.69007
G1 F120
G1 X184.000 Y177.000 E5865.22862
G1 F120
G1 X15.000 Y177.000 E6258.64161
G1 E6258.44161 F600.00000
G92 E0
; Filament-specific end gcode
;END gcode for filament

M104 S0 ; turn off temperature
G28 X0  ; home X axis
M84     ; disable motors

M140 S0 ; set bed temperature
```

G.7 G-code 7

```
G90
M82
M106 S0
M104 S0 T0
G28 ; home all axes
G92 E0
G1 E-1.0000 F1800
G1 Z0.180 F1002
; process Process1
; layer 1, Z = 0.180
T0
; tool H0.200 W0.400
; outer perimeter
G1 X15.200 Y22.700 F4800
G1 E0.0000 F540
G92 E0
G1 X184.800 Y22.700 E11.2818 F300
G1 X184.800 Y34.300 E12.0535
G1 X15.800 Y34.300 E23.2954
G1 X15.800 Y44.700 E23.9872
G1 X184.800 Y44.700 E35.2291
G1 X184.800 Y56.300 E36.0008
G1 X15.800 Y56.300 E47.2427
G1 X15.800 Y66.700 E47.9345
G1 X184.800 Y66.700 E59.1764
G1 X184.800 Y78.300 E59.9481
G1 X15.800 Y78.300 E71.1900
G1 X15.800 Y88.700 E71.8818
G1 X184.800 Y88.700 E83.1237
G1 X184.800 Y100.300 E83.8954
G1 X15.800 Y100.300 E95.1373
G1 X15.800 Y110.700 E95.8291
G1 X184.800 Y110.700 E107.0710
G1 X184.800 Y122.300 E107.8427
G1 X15.800 Y122.300 E119.0846
G1 X15.800 Y132.700 E119.7764
G1 X184.800 Y132.700 E131.0183
G1 X184.800 Y144.300 E131.7900
G1 X15.800 Y144.300 E143.0319
G1 X15.800 Y154.700 E143.7237
G1 X184.800 Y154.700 E154.9656
G1 X184.800 Y166.300 E155.7373
G1 X15.800 Y166.300 E166.9792
G1 X15.800 Y176.700 E167.6710
G1 X184.800 Y176.700 E178.9129
G1 X184.800 Y177.300 E178.9528
G1 X15.200 Y177.300 E190.2347
G1 X15.200 Y165.700 E191.0063
G1 X184.200 Y165.700 E202.2482
G1 X184.200 Y155.300 E202.9400
G1 X15.200 Y155.300 E214.1820
G1 X15.200 Y143.700 E214.9536
G1 X184.200 Y143.700 E226.1955
G1 X184.200 Y133.300 E226.8873
G1 X15.200 Y133.300 E238.1293
G1 X15.200 Y121.700 E238.9009
G1 X184.200 Y121.700 E250.1428
G1 X184.200 Y111.300 E250.8346
G1 X15.200 Y111.300 E262.0766
G1 X15.200 Y99.700 E262.8482
G1 X184.200 Y99.700 E274.0901
G1 X184.200 Y89.300 E274.7819
G1 X15.200 Y89.300 E286.0239
G1 X15.200 Y77.700 E286.7955
G1 X184.200 Y77.700 E298.0374
G1 X184.200 Y67.300 E298.7292
```

G1 X15.200 Y67.300 E309.9712
G1 X15.200 Y55.700 E310.7428
G1 X184.200 Y55.700 E321.9847
G1 X184.200 Y45.300 E322.6765
G1 X15.200 Y45.300 E333.9185
G1 X15.200 Y33.700 E334.6901
G1 X184.200 Y33.700 E345.9320
G1 X184.200 Y23.300 E346.6238
G1 X15.200 Y23.300 E357.8657
G1 X15.200 Y22.700 E357.9057
G92 E0
G1 E-1.0000 F1800
; layer 2, Z = 0.380
M106 S255
G1 X15.200 Y22.700 F4800
G1 Z0.380 F1002
G1 E0.0000 F1800
G92 E0
G1 X184.800 Y22.700 E11.2818 F600
G1 X184.800 Y34.300 E12.0535
G1 X15.800 Y34.300 E23.2954
G1 X15.800 Y44.700 E23.9872
G1 X184.800 Y44.700 E35.2291
G1 X184.800 Y56.300 E36.0008
G1 X15.800 Y56.300 E47.2427
G1 X15.800 Y66.700 E47.9345
G1 X184.800 Y66.700 E59.1764
G1 X184.800 Y78.300 E59.9481
G1 X15.800 Y78.300 E71.1900
G1 X15.800 Y88.700 E71.8818
G1 X184.800 Y88.700 E83.1237
G1 X184.800 Y100.300 E83.8954
G1 X15.800 Y100.300 E95.1373
G1 X15.800 Y110.700 E95.8291
G1 X184.800 Y110.700 E107.0710
G1 X184.800 Y122.300 E107.8427
G1 X15.800 Y122.300 E119.0846
G1 X15.800 Y132.700 E119.7764
G1 X184.800 Y132.700 E131.0183
G1 X184.800 Y144.300 E131.7900
G1 X15.800 Y144.300 E143.0319
G1 X15.800 Y154.700 E143.7237
G1 X184.800 Y154.700 E154.9656
G1 X184.800 Y166.300 E155.7373
G1 X15.800 Y166.300 E166.9792
G1 X15.800 Y176.700 E167.6710
G1 X184.800 Y176.700 E178.9129
G1 X184.800 Y177.300 E178.9528
G1 X15.200 Y177.300 E190.2347
G1 X15.200 Y165.700 E191.0063
G1 X184.200 Y165.700 E202.2482
G1 X184.200 Y155.300 E202.9400
G1 X15.200 Y155.300 E214.1820
G1 X15.200 Y143.700 E214.9536
G1 X184.200 Y143.700 E226.1955
G1 X184.200 Y133.300 E226.8873
G1 X15.200 Y133.300 E238.1293
G1 X15.200 Y121.700 E238.9009
G1 X184.200 Y121.700 E250.1428
G1 X184.200 Y111.300 E250.8346
G1 X15.200 Y111.300 E262.0766
G1 X15.200 Y99.700 E262.8482
G1 X184.200 Y99.700 E274.0901
G1 X184.200 Y89.300 E274.7819
G1 X15.200 Y89.300 E286.0239
G1 X15.200 Y77.700 E286.7955
G1 X184.200 Y77.700 E298.0374
G1 X184.200 Y67.300 E298.7292
G1 X15.200 Y67.300 E309.9712
G1 X15.200 Y55.700 E310.7428
G1 X184.200 Y55.700 E321.9847
G1 X184.200 Y45.300 E322.6765
G1 X15.200 Y45.300 E333.9185
G1 X15.200 Y33.700 E334.6901
G1 X184.200 Y33.700 E345.9320
G1 X184.200 Y23.300 E346.6238
G1 X15.200 Y23.300 E357.8657
G1 X15.200 Y22.700 E357.9057
G92 E0
G1 E-1.0000 F1800
; layer end
M104 S0 ; turn off extruder
M140 S0 ; turn off bed
M84 ; disable motors

Appendix H: G-codes plunger

H.1 G-code 1 Volume 100% to 500%

```
G90
M82
M106 S0
M140 S20
M104 S25 T0
M109 S25 T0
G21                 ;metric values
G90                 ;absolute positioning
M82                 ;set extruder to absolute
mode
M107                ;start with the fan off
G28 X0 Y0           ;move X/Y to min
endstops
G28 Z0              ;move Z to min endstops
G92 E0              ;reset extruder
G92 E0
;G1 E-1.0000 F200
G1 Z0.400 F600
; print line 1
; layer 1, Z = 0.200
T1
; tool H0.200 W0.400
; outer perimeter
G1 X37.309 Y26.218 F6000
G1 Z0.1 F600
G1 E0.1 F200
G92 E0
G1 X37.329 Y26.218 E0.0000 F300
G1 X37.329 Y125.818 E0.2672
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 2
; layer 2, Z = 0.200
G1 X43.709 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X43.729 Y26.218 E0.0000 F300
G1 X43.729 Y125.818 E0.5344
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 3
; layer 3, Z = 0.200
G1 X50.109 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X50.129 Y26.218 E0.0000 F300
G1 X50.129 Y125.818 E0.802
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 4
; layer 4, Z = 0.200
G1 X56.509 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X56.529 Y26.218 E0.0000 F300
G1 X56.529 Y125.818 E1.0689
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 5
; layer 5, Z = 0.200
G1 X62.909 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X62.929 Y26.218 E0.0000 F300
G1 X62.929 Y125.818 E1.336
G92 E0
G1 E-1.0000 F200

; layer end

M400                ;Run all code before continuing
M104 S0             ;extruder heater off
M140 S0             ;heated bed heater off
G91                 ;relative positioning
G1 E-1.0 F300       ;retract the filament a bit
before lifting the nozzle to release some of the
pressure
G1 Z+1.0 E-1.0  F1000.0
G90
G28 X0 Y0           ;move X/Y to min
endstops
M84                 ;Disable steppers
M107                ;Fan off
```

H.2 G-code 2 Volume 600% to 1000%

```
G90
M82
M106 S0
M140 S20
M104 S25 T0
M109 S25 T0
G21                 ;metric values
G90                 ;absolute positioning
M82                 ;set extruder to absolute
mode
M107                ;start with the fan off
G28 X0 Y0           ;move X/Y to min
endstops
G28 Z0              ;move Z to min endstops
G92 E0              ;reset extruder
G92 E0
;G1 E-1.0000 F200
G1 Z0.400 F600
; print line 6
; layer 1, Z = 0.200
T1
; tool H0.200 W0.400
; outer perimeter
G1 X37.309 Y26.218 F6000
G1 Z0.1 F600
G1 E0.1 F200
G92 E0
G1 X37.329 Y26.218 E0.0000 F300
G1 X37.329 Y125.818 E1.603
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 7
; layer 2, Z = 0.200
G1 X43.709 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X43.729 Y26.218 E0.0000 F300
G1 X43.729 Y125.818 E1.87
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 8
; layer 3, Z = 0.200
G1 X50.109 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X50.129 Y26.218 E0.0000 F300
G1 X50.129 Y125.818 E2.14
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 9
; layer 4, Z = 0.200
G1 X56.509 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X56.529 Y26.218 E0.0000 F300
G1 X56.529 Y125.818 E2.405
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; print line 10
; layer 5, Z = 0.200
G1 X62.909 Y26.218 F6000
G1 Z0.100 F600
G1 E0.1000 F200
G92 E0
G1 X62.929 Y26.218 E0.0000 F300
G1 X62.929 Y125.818 E2.67
G92 E0
G1 E-1.0000 F200
; layer end

M400                ;Run all code before continuing
M104 S0             ;extruder heater off
M140 S0             ;heated bed heater off
G91                 ;relative positioning
G1 E-1.0 F300       ;retract the filament a bit
before lifting the nozzle to release some of the
pressure
G1 Z+1.0 E-1.0  F1000.0
G90
G28 X0 Y0           ;move X/Y to min
endstops
M84                 ;Disable steppers
M107                ;Fan off
```


H.3 G-code 3 Feed rate 50 - 250

```
G90
M82
M106 S0
M140 S20
M104 S25 T1
M109 S25 T1
G21                 ;metric values
G90                 ;absolute positioning
M82                 ;set extruder to absolute
mode
M107                ;start with the fan off
G28 X0 Y0           ;move X/Y to min
endstops
G28 Z0              ;move Z to min endstops
G92 E0              ;reset extruder
G92 E0
G1 Z0.400 F600
; line 1 F200
; layer 1, Z = 0.200
T1
; tool H0.200 W0.400
; outer perimeter
G1 X37.309 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1 F200
G92 E0
G1 X37.329 Y26.218 E0.0000 F50
G1 X37.329 Y125.818 E2.672
G92 E0
G1 E-1 F200
G1 Z0.400 F600
; line 2 F400
; layer 2, Z = 0.200
G1 X43.709 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1 F200
G92 E0
G1 X43.729 Y26.218 E0.0000 F100
G1 X43.729 Y125.818 E2.672
G92 E0
G1 E-1 F200
G1 Z0.400 F600
; line 3 F600
; layer 3, Z = 0.200
G1 X50.109 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1000 F200
G92 E0
G1 X50.129 Y26.218 E0.0000 F150
G1 X50.129 Y125.818 E2.672
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; line 4 F800
; layer 4, Z = 0.200
G1 X56.509 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1000 F200
G92 E0
G1 X56.529 Y26.218 E0.0000 F200
G1 X56.529 Y125.818 E2.672
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; line 5 F1000
; layer 5, Z = 0.200
G1 X62.909 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1000 F200
G92 E0
G1 X62.929 Y26.218 E0.0000 F250
G1 X62.929 Y125.818 E2.672
G92 E0
G1 E-1.0000 F200
; layer end

M400                ;Run all code before continuing
M104 S0             ;extruder heater off
M140 S0             ;heated bed heater off
G91                 ;relative positioning
G1 E-1.0 F300       ;retract the filament a bit
before lifting the nozzle
 to release some of the pressure
G1 Z+1.0 E-1.0  F1000.0
G90
G28 X0 Y0           ;move X/Y to min
endstops
M84                 ;Disable steppers
M107                ;Fan off
```

H.4 G-code 4 Feed rate 300 - 500

```
G90
M82
M106 S0
M140 S20
M104 S25 T1
M109 S25 T1
G21                 ;metric values
G90                 ;absolute positioning
M82                 ;set extruder to absolute
mode
M107                ;start with the fan off
G28 X0 Y0           ;move X/Y to min
endstops
G28 Z0              ;move Z to min endstops
G92 E0              ;reset extruder
G92 E0
G1 Z0.400 F600
; line 1 F300
; layer 1, Z = 0.200
T1
; tool H0.200 W0.400
; outer perimeter
G1 X37.309 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1 F200
G92 E0
G1 X37.329 Y26.218 E0.0000 F300
G1 X37.329 Y125.818 E2.672
G92 E0
G1 E-1 F200
G1 Z0.400 F600
; line 2 F350
; layer 2, Z = 0.200
G1 X43.709 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1 F200
G92 E0
G1 X43.729 Y26.218 E0.0000 F350
G1 X43.729 Y125.818 E2.672
G92 E0
G1 E-1 F200
G1 Z0.400 F600
; line 3 F400
; layer 3, Z = 0.200
G1 X50.109 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1000 F200
G92 E0
G1 X50.129 Y26.218 E0.0000 F400
G1 X50.129 Y125.818 E2.672
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; line 4 F450
; layer 4, Z = 0.200
G1 X56.509 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1000 F200
G92 E0
G1 X56.529 Y26.218 E0.0000 F450
G1 X56.529 Y125.818 E2.672
G92 E0
G1 E-1.0000 F200
G1 Z0.400 F600
; line 5 F500
; layer 5, Z = 0.200
G1 X62.909 Y26.218 F6000
G1 Z0.200 F600
G1 E0.1000 F200
G92 E0
G1 X62.929 Y26.218 E0.0000 F500
G1 X62.929 Y125.818 E2.672
G92 E0
G1 E-1.0000 F200
; layer end
M400                ;Run all code before continuing
M104 S0             ;extruder heater off
M140 S0             ;heated bed heater off
G91                 ;relative positioning
G1 E-1.0 F300       ;retract the filament a bit
before lifting the nozzle
 to release some of the pressure
G1 Z+1.0 E-1.0  F1000.0
G90
G28 X0 Y0           ;move X/Y to min
endstops
M84                 ;Disable steppers
M107                ;Fan off
```


Appendix I: G-code

A g-code controls the motion of four motors, the X, Y and Z axes and the extruder motor. A g-code exists out of several commands, every line is a new command. Two lines can look like this:
G1 X37 Y26 E0.00 F600
G1 X37 Y126 E0.66
These two lines give the command: move linear from Y26 to Y126 at a speed of 600 mm/minute while extruding 0.66 mm.
G1 gives the command linear movement. The X, Y and Z values are specific positions in 3D. The E value is how much millimeters to extrude, which technically is a position too. The F is the feed rate or the speed that the extrusion head has to move. This is in units per minute, the units are set in the metric system or in the imperial system. In this project only the metric system is used, which means that the feed rate is in millimeters per minute.
[g-code tutorial]

G-code
To test how fast the screw has to turn and how fast the printer head can move a STL file with horizontal lines is sliced into a G-code. The printer settings have to be find out according to the printing speed and the feeding speed.
A G-code consists of several commands that control the printer. It controls the speed of the motors. How fast it is moving when not printing and how fast it is moving when printing and what the extruding speed is.

DESIGN FOR our future

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TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name
initials
student number
street & no.
zipcode & city
country
phone
email

[redacted]

Your master programme (only select the options that apply to you):

IDE master(s): ★ IPD | ○ DfI | ○ SPD

2nd non-IDE master: _____

individual programme: __ - __ - ____ (give date of approval)

honours programme: ○ Honours Programme Master

specialisation / annotation: ○ Medisign
○ Tech. in Sustainable Design
○ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Dr. Song, Yu (Wolf) — dept. / section: M&M

** mentor: Ir. Minnoye, A.L.M. — dept. / section: M&M

2nd mentor: _____

organisation: _____

city: _____ country: _____

comments (optional): Both chair and mentor belong to the same department. Therefore a division within the project is made. Wolf will focus on the silver ink extruder. While Sander will focus on the mechanical structure of the 3D printer.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

TU Delft

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Dr. Song, Yu (Wolf) date 2 - 10 - 2019 signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 33 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

List of electives obtained before the third semester without approval of the BoE

(V) YES all 1st year master courses passed

( ) NO missing 1st year master courses are:

name D. Hansler date 4 - 10 '19 signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: (V) APPROVED ( ) NOT APPROVED

Procedure: (V) APPROVED ( ) NOT APPROVED

- no (unknown) abbreviation in title: FDM can be replaced by 3D

comments

name Mv Magen date 15 - 10 - 19 signature

Initials & Name M Bon Student number 4350901

Title of Project Large scale FDM printer system

Design and prototype a large scale electronics FDM printer

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 02 - 10 - 2019

01 - 04 - 2020 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Structural electronics is the next generation of electronics manufacturing technology, and 3D printing of functional electronic circuitries across freeform shaped architectures are innovations in structural electronics. 3D printed electronics brings the following new opportunities to designers: 1) With 3D printed electronics the freedom of the designer is enabled to combine aesthetics and functions together in the design; 2) It gives the opportunity to miniaturize the design; 3) The design and manufacturing process of mechatronic products will be accelerated; and 4) It will boost the efficiency of producing customized/personalized and mechatronic/electronic products, e.g. hospital equipment, parts of airplanes etc. Meanwhile it also posts challenges on the sustainability in the product design and manufacturing process. (Song et al., 2017)

In 3D printed electronics, printing conductive materials is a key. It is not yet possible to print pure copper or silver at a low temperature. However, it is possible to print with silver ink, either by inkjet or FDM. Currently, there are two types of FDM printers that are able to print silver ink: Voxel8 and Aerosol Jet. The Voxel8 is not on the market anymore. The Aerosol Jet is meant for the professional market., and the initial investment is rather high (>150K euro). In this project the 3D print method will be FDM (Fused Deposition Modeling), because FDM printers are more common for low cost custom thermoplastic parts and prototypes. (Varotsis, 2019)

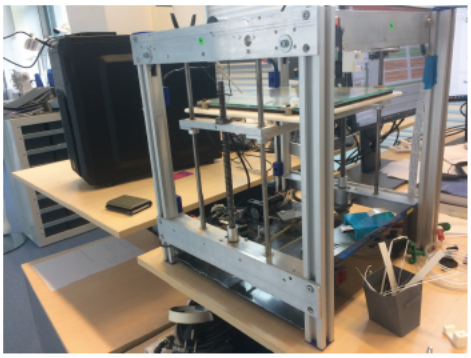
Currently, a 3D electronics printer is prototyped in the Applied Labs of Industrial Design Engineering, it uses the same principle for printing silver ink as the Voxel8. The prototyped printer is very primitive and it is not working now. See figure 1A and 1B for the current state of the prototyped printer in the Applied Labs. Besides, its working envelope is also limited by the added extra head. Figures 1C and 1D show the added extra head for printing silver ink. This limits the build size massively. See figure 2A for the effective build size without extra head, and figure 2B for the build size with extra head.

Song, Y., Boekraad, R. A., Roussos, L., Kooijman, A., Wang, C. C. L., & Geraedts, J. M. P. (2017). 3D Printed Electronics: Opportunities and Challenges from Case Studies. IDETC/CIE 2017.

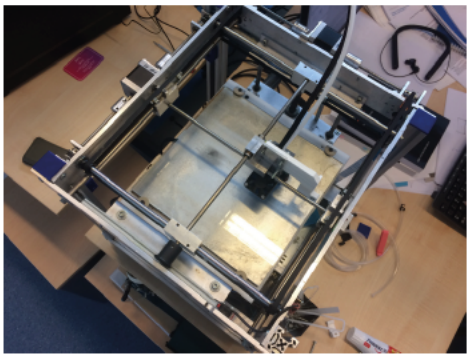
Varotsis, A. B. (2019). Introduction to FDM 3D printing. Retrieved September 19, 2019, from https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing

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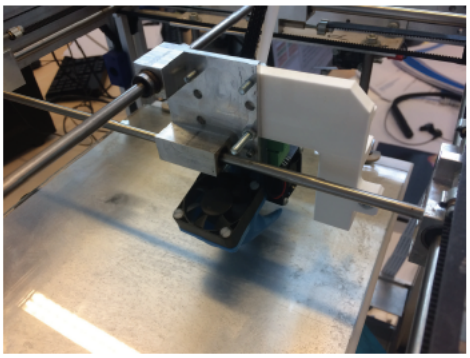
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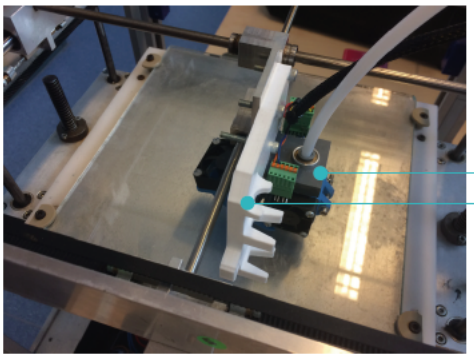
1A. The 3D printer in the Applied Labs.



1B. The topside of the 3D printer.

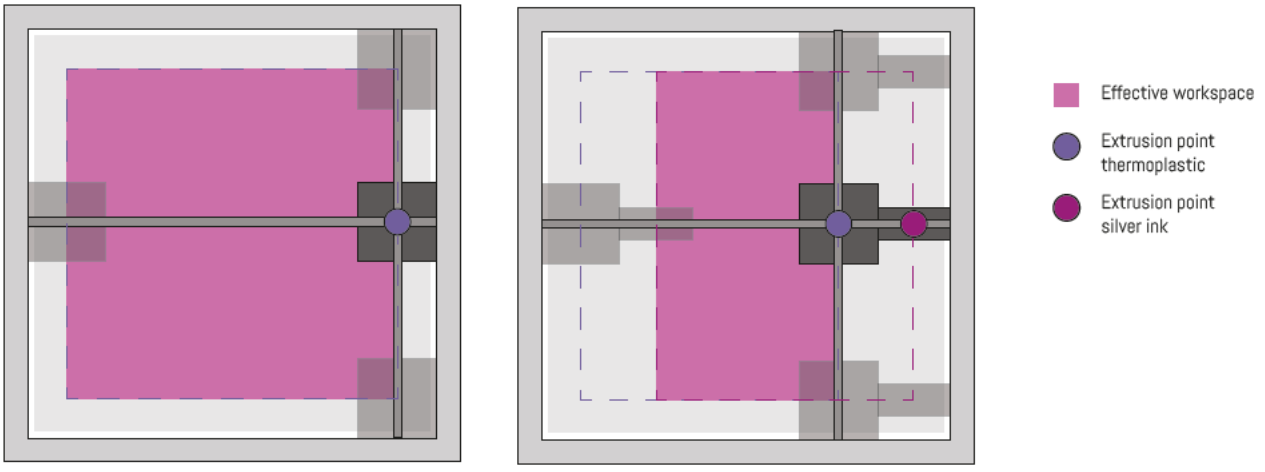


1C. The extruder with holder for silver ink syringe.



1D. The extruder with holder for silver ink syringe.

image / figure 1: Figure 1A to 1D. Pictures of the prototyped printer in the Applied Labs.



2A. 3D printer with one extruder

2B. 3D printer with extruder for thermoplastic and for silver ink

image / figure 2: Figure 2A and 2B. Top view of the 3D printer with and without silver ink extruder.

Initials & Name M Bon Student number 4350901

Title of Project Design and prototype a large scale electronics FDM printer

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

On the market are several electronics printers available. Most of these printers are inkjet printers meant for the professional market. In this project a prototype of an FDM electronics printer for the industry will be developed. Few FDM printers focus on prototyping products with relative large scale using 3D printed electronics. For a designer in the industry, a 3D electronics printer should have an "optimal" build size and overall size for different kinds of prototyping and building tasks.

In this project an FDM electronics printer will be designed and prototyped. In the design of the printer, the desired prototyping scale, the mechanical structure of the printer, the design of the extruder(s) will be investigated first. Another innovation of this project is that multiple extruder options, especially silver ink extruder, will be explored. Based on the literature review, to our knowledge, there is not a printer that combines all the functionalities for designers in the market. The large scale electronics printer will be designed and prototyped within the Center of Design for Agile Manufacturing.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Design and build an extrusion head and a large size 3D FDM printer system to enable printing of standard materials in combination with conductive materials.

The lean approach will be used in the project with 3 iterations. In the first iteration (~2-3 weeks), we will focus on the design specification. Currently, the build size of printers is never evaluated for usability nor technology. Desktop printers have a build size that range from 10x10x10 [cm] to 50x50x50 [cm] within a price class of €200 to €3000. A bigger build volume will start at 100x100x100 [cm] and start at a price of €20.000. (E. van Munster, 3D printing expert at MTB3D, personal communication, 25th of Sep. 2019). Therefore, a critical look at the "optimal" build size, which fits the wish of the user, the available technologies, and the affordability of the user, is essential.

In the second iteration (~10 weeks), we will focus on designing the printer where different parts of the printers, e.g., the mechanical structure, the driving unit, the silver extruder will be explored. It is worth mentioning that we will use existing prototypes and off-the-shelf solutions as much as possible to accelerate the development.

In the third iteration (~5 weeks), different parts of the design will be integrated as a 3D printed electronics printer, and the functionalities will be tested as well. The final deliverable will be a working 3D electronics printer with at least two extruders, a thermoplastic extruder and a silver ink extruder.

Initials & Name M Bon Student number 4350901

Title of Project Design and prototype a large scale electronics FDM printer

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 2 - 10 - 2019 1 - 4 - 2020 end date

				36 hours per week																								
Month	Sept			Oct					Nov				Dec				Jan				Feb			Mar				
Calender week	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12
Project week	0	0	0	1	2	3	4	5	6	7	8	9	10	11	12		13	14	15	16		17	18	19	20	21	22	
Projectbrief				KICKOFF																								
Research																												
Ideas & Concepts																												
Design														Midterr														
Prototyping																												
Validation																							GL		Report		Presentation	

Due to circumstances I do not graduate full time. I planned to have on average 36 hours per week. So per week I will work 4,5 days.
I planned the regular holidays free to stay in the same rhythm as the last years.

In the Research phase the most important requirements of the printer will be set. In the ideas and concept phase every part of the project will be further explored and prototypes will be made.
In the design phase all comes together in one design, this design will be prototyped and made.
Having the final prototype it is further tested and validated to see what the next steps are.
For every phase prototypes will be made to be able to quickly evaluate every part of the printer.

Initials & Name M Bon Student number 4350901

Title of Project Design and prototype a large scale electronics FDM printer

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

This project enables me to tackle a hard technical problem. I will improve the view on 3D printers and their future. Targeting the industry with 3D electronic printers creates a big challenge. 3D electronic printers exist, however not on this market. To make a 3D printer that fit the industry requires an FDM printer that will be working quite differently than regular desktop 3D printers.

To be able to successfully create the working prototype I have to develop it in a fast way. Rapid prototyping is a suitable approach. Rapid prototyping works as follows: by making small prototypes of first ideas, these prototypes can be tested. In this way ideas can be evaluated quickly and development will go fast. I have never used this approach in my studies before. Therefore this will be my big learning goal.

Next to this goal it is a challenge to build a 3D print system and the silver ink extruder. The following things will be checked off:
- Mechanical structure of the printer
- Working with existing software for 3D printers
- Mechanical structure of the extruder
- Mechanical structure of the feeder
- Working with different and new materials to print with

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Initials & Name M Bon Student number 4350901

Title of Project Design and prototype a large scale electronics FDM printer