Using solder paste in FDM based 3D printing of integrated electronics

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Master Thesis
MSc Integrated Product Design
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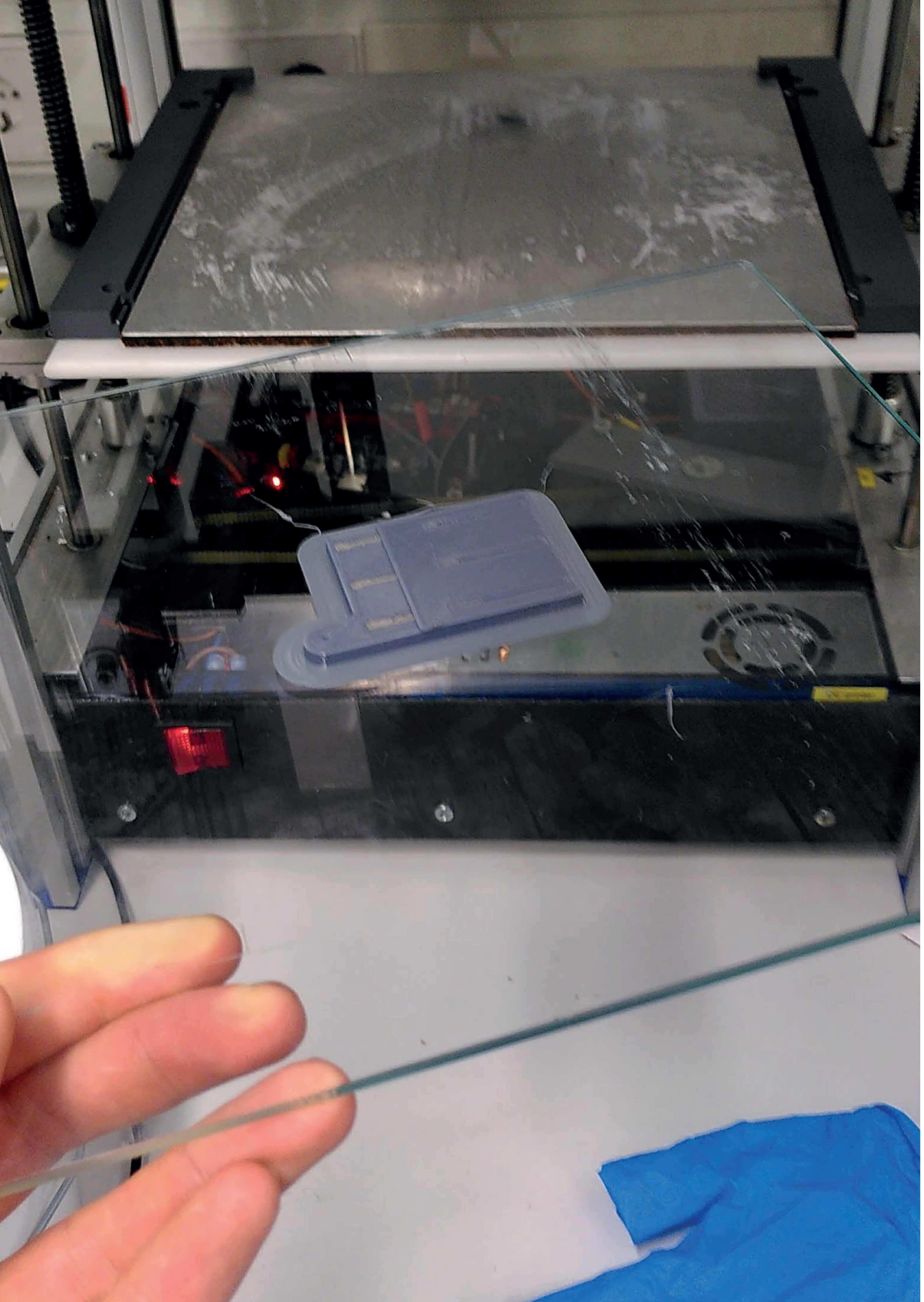

Preface

Before you lies the master thesis "Using solder paste in FDM based 3D printing of integrated electronics" which is written to complete the master program Integrated Product Design at the faculty of Industrial Design Engineering of the Delft University of Technology. The master thesis project was conducted from march to September of 2020.

I chose to research this topic for various reasons, first of which is the fact that 3D printing has been a hobby during the time I followed my masters. Secondly this project gave me the ability to combine the technical side of my bachelors in Mechanical Engineering with the design and product development side of my masters in Integrated Product Design.

This master thesis project was a continuation of another master thesis project from the same masters, M.Bon, who researched the combination of materials and the proof of concept of a usable combination. I will continue with developing a method for "3D printing" this combination of material and testing various characteristics of the method.

The thesis is written in two parts, part A being the script of the paper which has been submitted to HardwareX but has not been reviewed or published yet. Part B is the master thesis report including appendices at the end.

I would like to wish the readers of this master thesis good luck and may this project be continued in the future by another student to achieve a deeper understanding of the topic.

Kasper Eekhout
Delft, 03-09-2020

Part A

Manuscript of Paper

Using solder paste in FDM based 3D printing of integrated electronics

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Abstract

We present a design that uses solder paste as a conductive material in FDM 3D printing. Solder paste is chosen as a more affordable material than currently used conductive nano silver ink. Combining this material with FDM 3D printing makes it easy to use. The system utilizes an Ultimaker 3 for printing thermoplastic substrate material. Another printer, a RepRap 3D printing platform with a custom made solder paste extruder and hot air gun is used for printing and curing the solder paste. This system can be used to print traces with a cross section of 0.6mm height and 1.0mm width up to a resolution 2.54mm pitch. Components can be picked and placed by hand and connected to each other with the printer solder paste traces. The affordability and ease of use make it accessible for a greater audience. Improving the knowledge in designing for structural electronics.

1. Hardware in context

In the past decade, the development of 3D printing technology significantly accelerated the product development cycle. Recently, conductive materials were also introduced to 3D printing to create passive electronic circuits/components in 3D [1] [2] [3]. Integrating electronics circuits directly into structures generates new opportunities in product design as it offers designers more freedom in their designs; promotes miniaturization of design; accelerates the design and manufacturing process; improves the efficiency of producing customized/personalized mechatronic/electronic products and brings new opportunities of making the product design and manufacturing process more sustainable [4].

Manufacturers of 3D printers utilizes different techniques, e.g. inkjet printing, aerosol deposition, material extrusion and fused deposition modelling (FDM), to integrated electronics in 3D prints. A typical example of using inkjet printing for printed electronics is the Nano Dimension Dragonfly 3D electronics printer [5]. Another example is the Aerosol Jet 5X [6], which utilizes the aerosol deposition technique. Both printers are able to achieve high accuracy, e.g. Aerosol Jet 5X is able to reach an 0.01mm resolution, however they are expensive (>€150.000), the size of the machines are large (~1x2x2 m) and special training is needed to operate those printers.

Researchers and industries have tried to make 3D electronics printers more accessible to designers and makers. For instance, a more compact solution of inkjet printing is the Botfactory SV2 (~€18,000) [7] which utilizes low-resistivity conductive inks and dielectric insulating inks for printing up to 4 layers structured electronics. Material extrusion can be an affordable alternative of inkjet and aerosol techniques. Desktop sized printers such as the Voltera v-one [8], and Voxel8 [9] utilize this technique to deposit conductive silver paste. The Voltera is designed for creating (double-sided) PCB's whereas the Voxel8 has more 3D capacities as it is able to use 3D FDM thermoplastic printing as the substrate. These printers are more affordable (Voltera v-one ~€3500, Voxel8 ~€7000). Unfortunately, the Voxel8 was discontinued. Using the FDM technique to directly deposit conductive materials is another alternative for building prototypes with structured electronics where the eForge printer [10] is a typical example. The eForge is priced similarly to the Voxel8 at ~€7000.

The conductive material that these printers use can be categorized to two groups: the silver ink/paste and the conductive filament. Silver ink/paste has great conductive properties but lacks good mechanical properties and is rather expensive (~€4500/100ml [11]), which often leads to high running cost. The (mechanical and electronics) properties and prices vary among different conductive filaments. For instance, the Proto-pasta [12] is a blend of polymer and carbon black. It is affordable (~€90/kg) but lacks good conductive properties (300 Ωcm). Electrifi [13] has good conductive properties (0.006 Ωcm), but it is expensive (€2,000/kg).

In the design process, many prototypes are often made in different design iterations to verify different aspects of designs. Therefore, besides the functions of integrating electronics in 3D prints, the affordability, the running cost and the usability of the printers are also the keys of making prototyping of structural electronics accessible to a larger audience. In this paper, we present the prototype of an affordable, low-running cost and easy-to-operate 3D electronics printing system. Building on existing 3D FDM printing platforms, the key advantage of the proposed system is that the solder paste was introduced as an alternative of the silver ink. It is expected that based on the descriptions of the hardware and software, designers and makers are able to make this low-cost solution, and use it to accelerate their design/prototyping process of mechatronic/electronics products with low-running cost.

2. Hardware description

2.1 The system

The overall system consists of a combination of two 3D printers (see Fig.1). The first one is an Ultimaker 3 3D printer with 0.4mm nozzle. The function of this printer is to print the substrate, and no modification was conducted. The other one is a DIY RepRap [14] 3D printer with Marlin firmware [15]. Different from the original design, a solder paste extruder and a focused hot air gun (see Fig.2) were developed and installed on the DIY printer for depositing conductive materials and curing the deposited materials, respectively. A glass build plate, which holds the prototypes during the printing process, can be moved between printers. This setup with two printers is chosen for simplifying the system as an integrated system with a printing head, a solder paste extruder and a hot air gun will have less building volume.

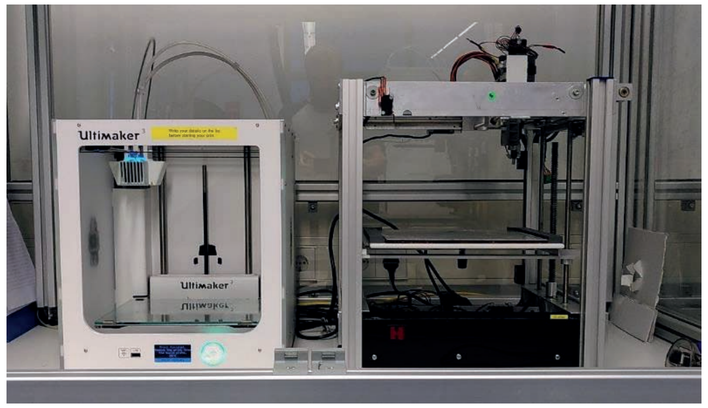

Figure 1: The Ultimaker 3 (left) for thermoplastic extrusion and the DIY printer (right) for solder paste extrusion and curing.

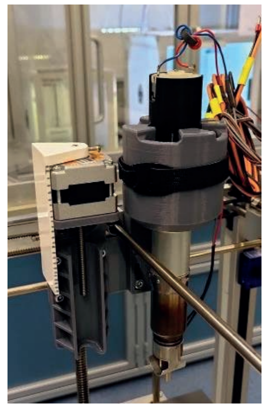

Figure 2: Closeup of the DIY printer printheads, the solder paste extruder (left) and hot air gun (right)

2.2 Solder paste extruder

The solder paste extruder is designed to directly fit the syringe of the solder paste. It is mounted vertically in a mounting bracket. Figure 3a illustrates the details of the extruder. The solder paste is pushed out by a stepper motor via a non-captive lead screw. Restricting the rotation of the lead screw with a brace enables the linear movement of the screw. The stepper motor has 200 steps per rotation and the leadscrew has a double thread with 1 mm pitch which results in 2 * 1mm translation per rotation, this special leadscrew was used due to availability another more standard leadscrew works as well. This pitch of the leadscrew results in a resolution of 0.01mm vertical translation per step. The cross-sectional area of the syringe is 188.7mm^2. Therefore, the minimal extrusion volume of is 1.9 mm^3.

2.3 Hot-air gun

The deposited solder paste is cured by a focused hot air flow from a hot air gun (see Fig.3b). The hot air gun is mounted vertically in the 3D printer and consists of a metal body housing a heating cartridge through which air flows from the fan on the top to the nozzle on the bottom. The temperature of the air is measured inside the barrel close to the nozzle with a thermistor. The temperature is controlled with a PID controller integrated in the motherboard of the 3D printer. The temperature can be controlled precisely within ± 1°C range when target temp is reached. The nozzle of the hot air gun is a square shape (4x4mm).

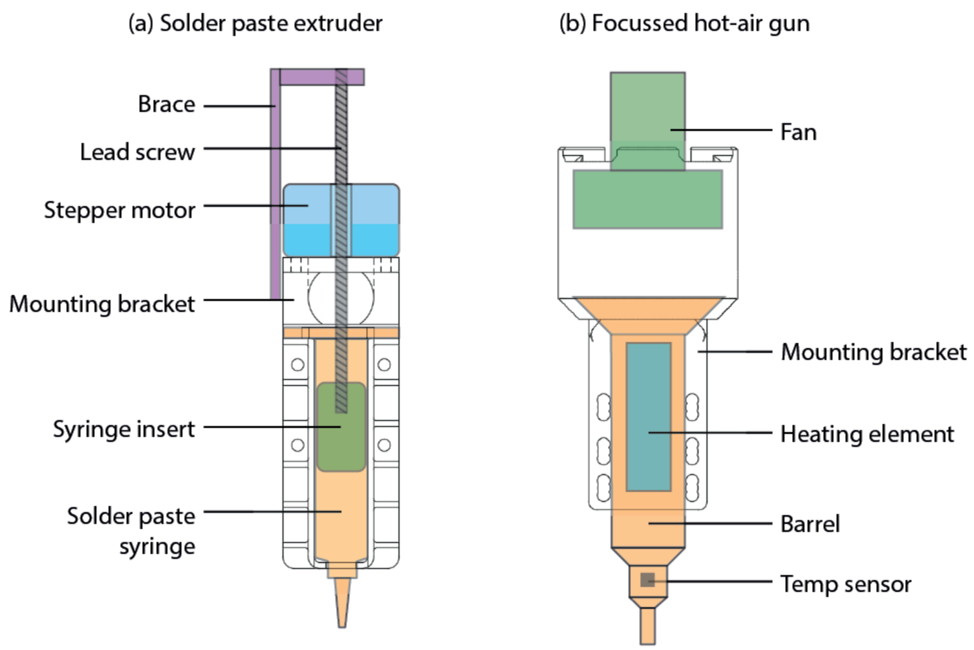

Figure 3: Schematic overview of the solder paste extruder (left), the hot-air gun (right) and the mounting plate (middle)

2.4 Materials

Two printers introduced in the previous section utilize two different materials for the substrate and the conductive trace.

2.1.1 Substrate material

The substrate material for 3D printing prototypes with integrated electronics can be PLA, PETG, ABS or PLA-HT. Table 1 presents the Tp (printing temperature), Tg (glass transition temperature) and Tm (melting temperature) of four types of substrates. In the curing process, the solder paste is heated to a temperature over 138°C. The thermoplastic substrate on which the solder paste is printed must withstand these temperatures without degrading and/or deforming. Generally, the higher the curing temperature over the Tg, the softer the material becomes which makes it more prone to deformation. The PLA is cheap and easy to print with making it the ideal choice for 3D printing quick prototypes. An alternative for regular PLA is PLA-HT [16] which is designed for annealing and because of this higher melting temperature but has the same ease of use while printing as regular PLA.

Table 1: Printing, glass transition and melting temperatures of thermoplastics.

	Tp	Tg	Tm
PLA	190 - 210 C	60 C	180 - 200 C
PETG	220 - 250 C	88 C	260 C
ABS	220 - 260 C	105 C	-
PLA-HT	220 - 240 C	70 C	190 - 220 C

2.1.2 Conductive material

Solder paste is used as the conductive material as it is up to 10 times cheaper (~€400/ 100ml) than conductive silver ink (~€4500/ 100ml). Solder paste can be dispensed similar to silver ink, however, an additional curing step, in which the solder paste is heated up to a specific temperature, is needed.

The solder paste chosen for this application is Sn42/Bi57.6/Ag0.4 solder paste (Chipquick SMDLTLFP10T5). This type of solder paste is chosen for its low melting point (138°C) this means the thermoplastic substrate does not have to be heated too much above its glass transition temperature (Tg). This solder paste is of the type 5 (T5) category with a minimum of 80% of the particles between 15 – 25 µm in diameter. Note: read the safety instruction before handling solder paste and wear the proper protection.

3. Design files

Solder paste extruder - Bracket	.stl file	.STEP file
Solder paste extruder - Brace	.stl file	.STEP file
Solder paste extruder – Syringe insert	.stl file	.STEP file
Hot air gun – Mounting bracket back	.stl file	.STEP file
Hot air gun – Mounting bracket front	.stl file	.STEP file
Mounting plate	.stl file	.STEP file
AC dimmer box	.stl file	.STEP file
AC dimmer lid	.stl file	.STEP file
Test sample 1 – Three lines	.stl file	.STEP file
Test sample 2 – Trace pitch	.stl file	.STEP file
Test sample 3 – Connecting components	.stl file	.STEP file
Test sample 4 – Overlapping traces	.stl file	.STEP file
Test sample 5 – Demonstrator - Base	.stl file	.STEP file
Test sample 5 – Demonstrator - Cover	.stl file	.STEP file
Test sample 1 – G code	.txt	.gcode
Test sample 2 – G code	.txt	.gcode
Test sample 3 – G code	.txt	.gcode
Test sample 4 – G code – layer 1	.txt	.gcode
Test sample 4 – G code – layer 2	.txt	.gcode
Test sample 5 – G code – layer 1	.txt	.gcode
Test sample 5 – G code – layer 2	.txt	.gcode
Firmware	.bin	

4. Bill of Materials

	Amount	Note
Electronics		
DIY RepRap 3D printer platform 12V	1x	Any 3-axis motion platform driven by stepper motors can work.
Bigtreetech SKR v1.3	1x	https://www.biqu.equipment/collections/skr-series/products/pre-sale-bigtreetech-skr-v1-3-smoothieboard-32-bit-open-source-arm-cpu-motherboard-support-uart-model-2004lcd-3d-printer-parts
Reichelt ACT 16HSL3404 Linear stepper motor, NEMA 16, 1.8°, 12 V, 100 mm	1x	https://www.reichelt.nl/linear-stepper-motor-nema-16-1-8-12-v-100-mm-act-16hsl3404-p260756.html?&trstct=pol_2&nbc=1
4 wire stepper motor cable	1x 1m	
Steinel 04019 HL STICK 350W	1x	https://www.conrad.nl/p/steinel-04019-hl-stick-heteluchtpistool-incl-accessoires-350-w-818872
AC dimmer module	1x	https://www.conrad.nl/p/velleman-k8064-dimmer-bouwpakket-230-vac-190955
10 kΩ resistor	1x	
10 µF 50V capacitor	1x	
100K thermistor	1x	
0.2 mm^2 flexible wire	6 m	For 12V components
1 mm^2 flexible wire	4 m	For 230V components
Various heat shrinks		
Various crimp bootlace ferrules		Optional (Stripped and tinned wire ends could work as well)
Various Dupont connectors		Optional (Stripped and tinned wire ends could work as well)
Terminal block	3 wide	
Hardware		
M5x20	6x	
M5 nut	4x	
M3x8	3x	
M3x5	3x	
M3 washer	2x	
Electrical tape	1 roll	
Cable ties	10x	
3D printed parts		
Solder paste extruder - Bracket	1x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
Solder paste extruder - Brace	1x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
Solder paste extruder – Syringe insert	2x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
Hot air gun – Mounting bracket back	1x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
Hot air gun – Mounting bracket front	1x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
Mounting plate	1x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
AC dimmer box	1x	Printed in PLA 0.2mm layer height 3 perimeters 25% infill and 3 top and bottom layers.
AC dimmer lid	1x	Printed in PLA, 0.2mm layer height 6 perimeters 25% infill and 0 top and bottom layers

5. Build Instructions

In this section, details of the solder paste extruder and the hot air gun will be explained. In addition, the connections between them and the rep-rap platform are illustrated as well.

5.1 Assembling solder paste extruder

The first step of constructing the solder paste extruder is to mount the stepper motor to the “Solder paste extruder – Bracket” using two M3x10 bolts and washers (see Fig.5.1). The next step is to insert the lead screw with the flat sided end pointing upwards (Fig.5.2). Insert the syringe insert in the solder paste syringe and put the syringe in the bracket (Fig.5.3 & Fig.5.4). The brace can now be connected to the flat sided end of the lead screw and secured with a M3x10 bolt (Fig.5.5 & Fig.5.6). To take out the syringe for storage when not in use follow steps 6 to 3 backwards.

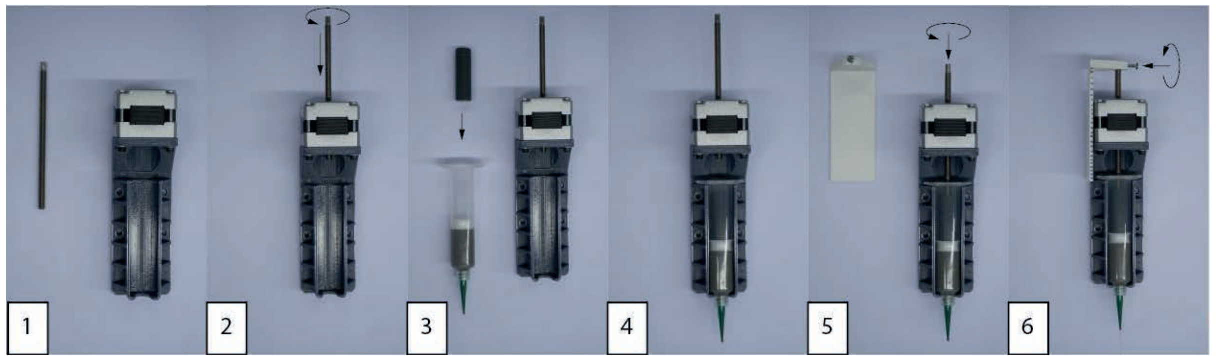

Figure 5: Step by step photos of assembling the solder paste extruder.

5.2 Assembling hot-air gun

The hot air gun is “assembled” in two steps. The first step is disassembling the Steinel hot-air gun to retrieve the barrel with the heating element and the radial fan. The wires connecting the heating element and the fan can be de-soldered from the internal PCB. Extra wires are soldered on to extend the wires of the components (heating element, fan and thermistor) to 1 meter to a female Dupont connector. Make sure the exposed wire at the solder joint is properly covered with a heat shrink. The second step is to assemble the hot air gun within 6 steps as illustrated in Figure 5: (1) Start with the “Hot-air gun - mounting bracket back”; (2) position the fan; (3) place the heating element barrel and fasten them with the M3x5 bolts; (4) secure the “Hot-air gun – mounting bracket front” and the rest with a Velcro strap; (5) Bend the end of thermistor and insert the thermistor into the barrel of the heating element, and (6) finally slide the nozzle in to secure it.

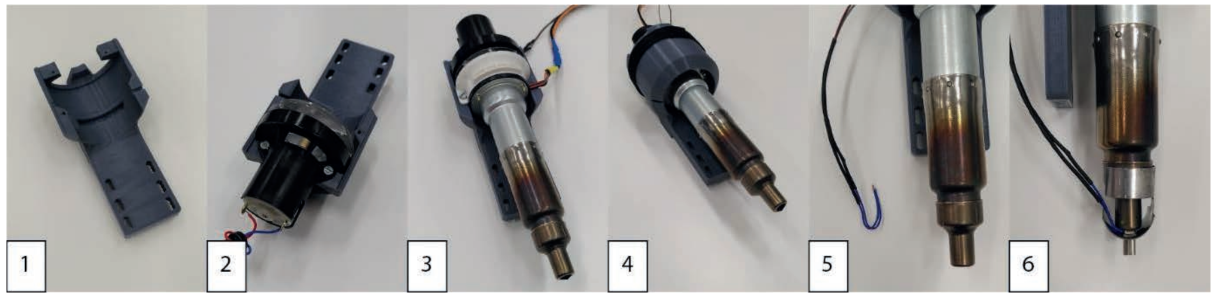

Figure 5: Step by step photos of assembling the hot air gun.

5.3 Assemble install printheads in the printer

Both the solder paste extruder and the hot air gun (see Fig.6.1) can be installed on the mounting plate using M5x20 screws and nuts (see Fig.6.2). The holes in the mounting plate match the fixture of the printing head of the 3D printer/ XYZ platform (see Fig.6.3 & Fig.6.4). For different printers/platforms, designs of the mounting plate might need to be adjusted slightly to make sure a good fixation.

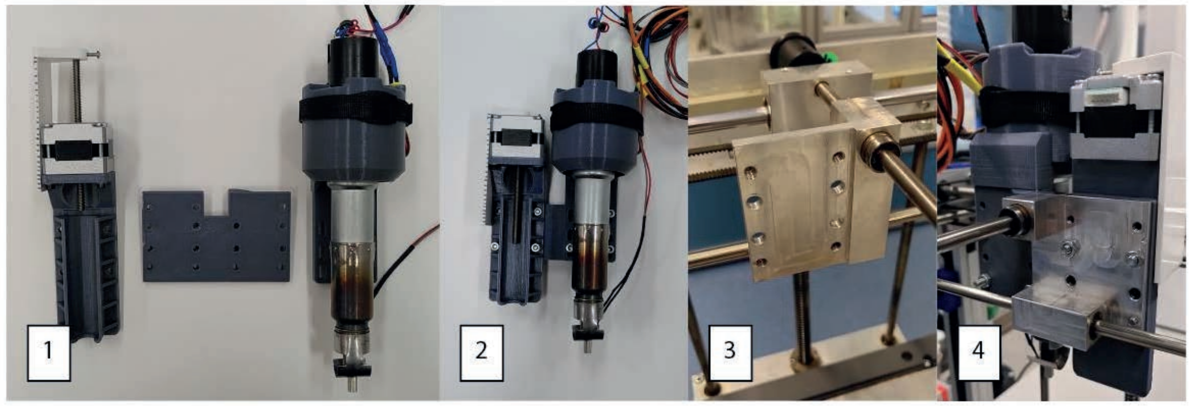

Figure 6: Step by step photos of assembling the solder paste extruder and hot-air gun.

5.4 Connect to printer platform

After the installations of the solder paste extruder and the hot air gun, both of them need to be connected to the controller in order to work properly. Layout of the motherboard of the rep-rap printer can be seen in Figure 7. First connect the X, Y and Z stepper motor to their respective pins. If the stepper motor moves in the reversed direction unplug the cable, turn it 180° and plug it back in. Place the stepper motor drivers on the stepper motor driver slots. Secondly connect the 12V input. Than connect the bed heater, note the +/- sides of the connection. Connect the thermistors. Then connect the endstops again note the +/- sides of the connection.

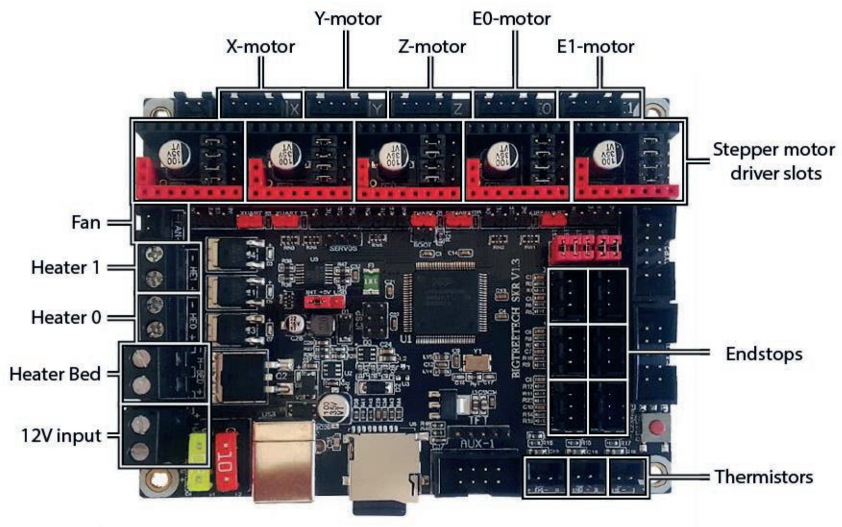

Figure 7: Overview of all the output ports of the 3D printer motherboard.

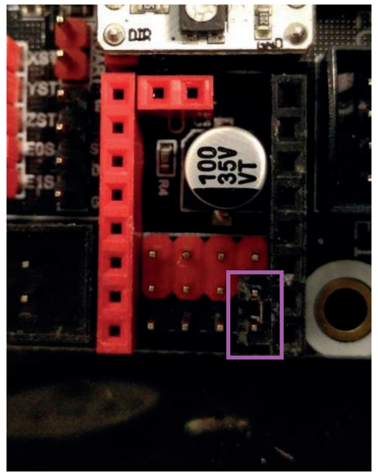

Figure 8: Placing 1 jumper to set E1-Motor stepper driver to half step mode

Figure 9: The AC dimmer module and its connections.

Now the custom parts are installed. Connect the solder paste extruder and the hot air gun to the motherboard following the list below and route the cables along the frame of the printer to the motherboard of the printer. Place the AC dimmer module in the 3D printed AC dimmer box and place it next to the 3D printer motherboard.

- The stepper motor from the solder paste extruder is connected to "E1-motor"
  - Set stepper driver to half step mode (see Fig.8) using a jumper pin.
  - Set V_{ref} of stepper motor driver to 160 mV
- The fan of the hot air gun is connected to the "CNC FAN" (note +/-)
- The thermistor is connected to the "E0-Thermistor"
- The heating element is connected to the "LOAD" on the AC dimmer module
- AC power is connected to the "AC POWER" on the AC dimmer module
- The low pass filter is connected to "ANALOG IN" on the AC dimmer module (note +/-) (see Fig.9)
- The "E0 Heater" is connected to low pass filter (see Fig.10).

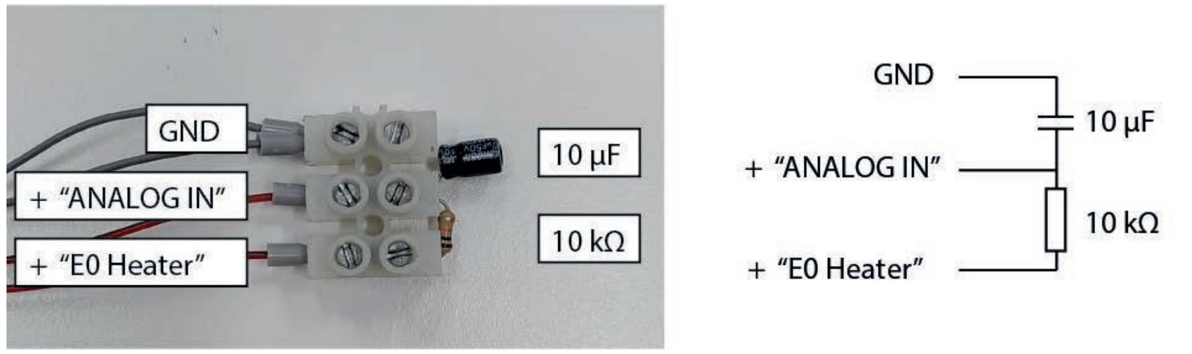

Figure 10: The low pass filter which is used to smooth the PWM signal from the motherboard to an analog DC signal..

5.5 Firmware

The firmware for the 3D printing platform configured for these printing heads is included in the design files. The firmware is Marlin Version 2.0 [15]. Some parameters have to be changed in the firmware.

Defining the board used and appropriate serial ports:

- #define SERIAL_PORT -1
- #define SERIAL_PORT_2 0
- #define MOTHERBOARD BOARD_BTT_SKR_V1_3

Using 2 extruders and defining the offset between them

- #define EXTRUDERS 2
- #define HOTEND_OFFSET_X { 0.0, -56 }
- #define HOTEND_OFFSET_Y { 0.0, -16.25 }

Defining temp sensor 0 for a 100K thermistor, and define temp sensor 1 as always being 25°C to prevent cold extrusion error.

- #define TEMP_SENSOR_0 1
- #define TEMP_SENSOR_1 998   //set to 998 for solder paste extruder

Define steps per mm of movement for each axis or extruder. E1 steps per mm are 100 in full step mode, but defined 200 here because stepper is in half step mode. All other stepper are in 1/16 step mode.

- #define DEFAULT_AXIS_STEPS_PER_UNIT   { 80, 80, 1006.28, 500, 200}

Also define the size of the build volume.

- #define X_BED_SIZE 200
- #define Y_BED_SIZE 200
- #define Z_MAX_POS 200

The firmware file can be copied to the micro SD card in the motherboard, the firmware boots automatically after powering off and on the motherboard. If another board is used follow the instructions from the manufacturer, The Marlin firmware can be configured for a lot of different boards and is very comprehensive.

6. Operating Instructions

Here the operating instructions are further explained with an example.

6.1 CAD design

The operation process starts with designing the plastic part with recessed channels in which the solder paste will be dispensed. The centerlines of the channel represent the circuit that being embedded in the 3D prints. The shape of the cross section is shown in Figure 11. The channel is 1mm wide to accommodate the 0.8mm nozzle of the solder paste extruder. The channel is 0.6mm deep to get good heating through the entire layer when curing.

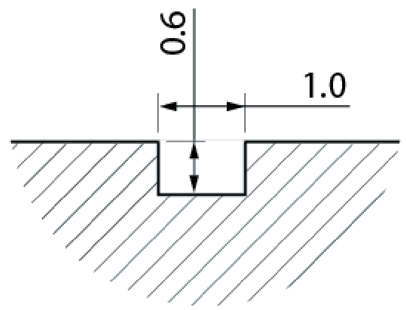

Figure 11: A schematic view of the cross section of the channel.

6.2 CAM design

The thermoplastic substrate is printed with the Ultimaker 3. The G-code for printing the substrate is prepared with Cura®. The DIY printer is controlled by Marlin firmware and the G-code for controlling the printing and curing of solder paste are self-made following the center lines of the trace. In the G-code, the position of the solder paste extruder and the hot air guns are controlled by the X, Y and Z coordinates.

6.2.1 FDM printing of substrate

The design is made in CAD software with recessed space for components and solder paste connections. The model is then sliced to create G-code which can be used by the 3D printer to create the part. Before starting the print, the printer must be paused between layers where components need to be inserted or where the build plate needs to be transferred to the second printer for printing and curing the solder paste. Pausing in G-code for Marlin firmware can be done by using command M25. The preview function in the slicing software can be used to find the exact layer number where the print needs to be paused, note that the Cura® preview start at layer 1 as the first layer whereas the G-code starts at layer 0 as the first layer. The Ultimaker pauses and resumes printing when the user presses resume printing on the Ultimaker control panel.

Figure 12: The channel recessed in the plastic part

6.2.2 Solder paste extrusion

The solder paste is extruded in the recessed channel in the plastic part (see Fig.12), because the solder paste shrinks during curing more solder paste needs to be extruded (see Fig.13 & Fig.14). Over-extruding is done by printing at a Z+0.2mm offset from the printed plastic part. Extruding the solder paste from the syringe requires the solder paste to be compressed before printing the line of solder paste (priming). The solder paste is compressed for 3mm (E3) after which the solder paste can be printed. When printing the solder paste extruder motor moves at E0.01mm per mm of trace length. After printing the solder paste extruder is retracted 3mm (E-3).

The motor of the solder paste extruder is controlled by the G-code in a similar fashion as the extruder motor in an FDM printer. The solder paste extruder is denoted by T1 (tool 1) and the input is the amount of mm moved by the lead screw, E1.2 would mean a 1.2mm movement downwards of the leadscrew. In the firmware the steps per mm are declared, which are 100 steps/mm.

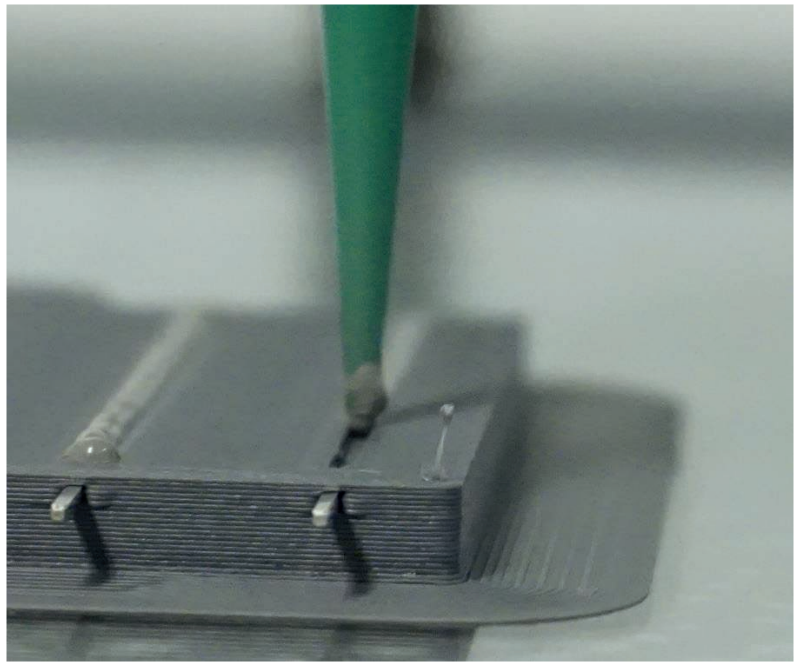

Figure 13: Solder paste being printed in the recessed channel. On the left the over extrusion of solder paste can be seen.

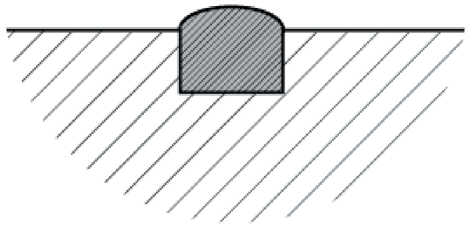

Figure 14: Schematic cross section of printed solder paste trace.

4.1.3 Solder paste curing

After the channel is filled with solder paste the solder paste is cured in two steps. The settings for both steps can be found in Table 2. The printer controls the fan speed and the temperature of the hot air gun. The fan speed is controlled by M106 Sxxx where the xxx value between 0 and 255, 0 being off and 255 being 100% on. The temperature of the hot air gun is controlled in the same fashion as the temperature of a hot end. The hot-air gun is denoted by T0 (tool 0). The temperature is set with M109 T0 Sxxx, where xxx is the temperature in °C. The M109 function waits for the temperature to be reached before continuing. Note that the fan must be turned on before the temperature is set. The temperature is measured at the exit of the hot air gun and needs airflow to register the temperature properly with a chance of overheating a damaging the system. The first step of curing

is done at a 10mm offset from the part to reflow the printed solder paste and create an evenly distributed solder paste trace, see figure 14. A 10mm offset is chosen so that a larger length of the channel is heated for even reflow of the solder paste. The second pass at 5 mm offset is done to fully cure the solder paste trace to make it conductive. After the second curing step the solder paste has shrunk as can be seen in figure 15 & 16.

Table 2: G code settings for both steps of the hot air curing process.

	Speed	Temperature	Height Offset
1st pass	F100	155C	Z+10
2nd pass	F30	155C	Z+5

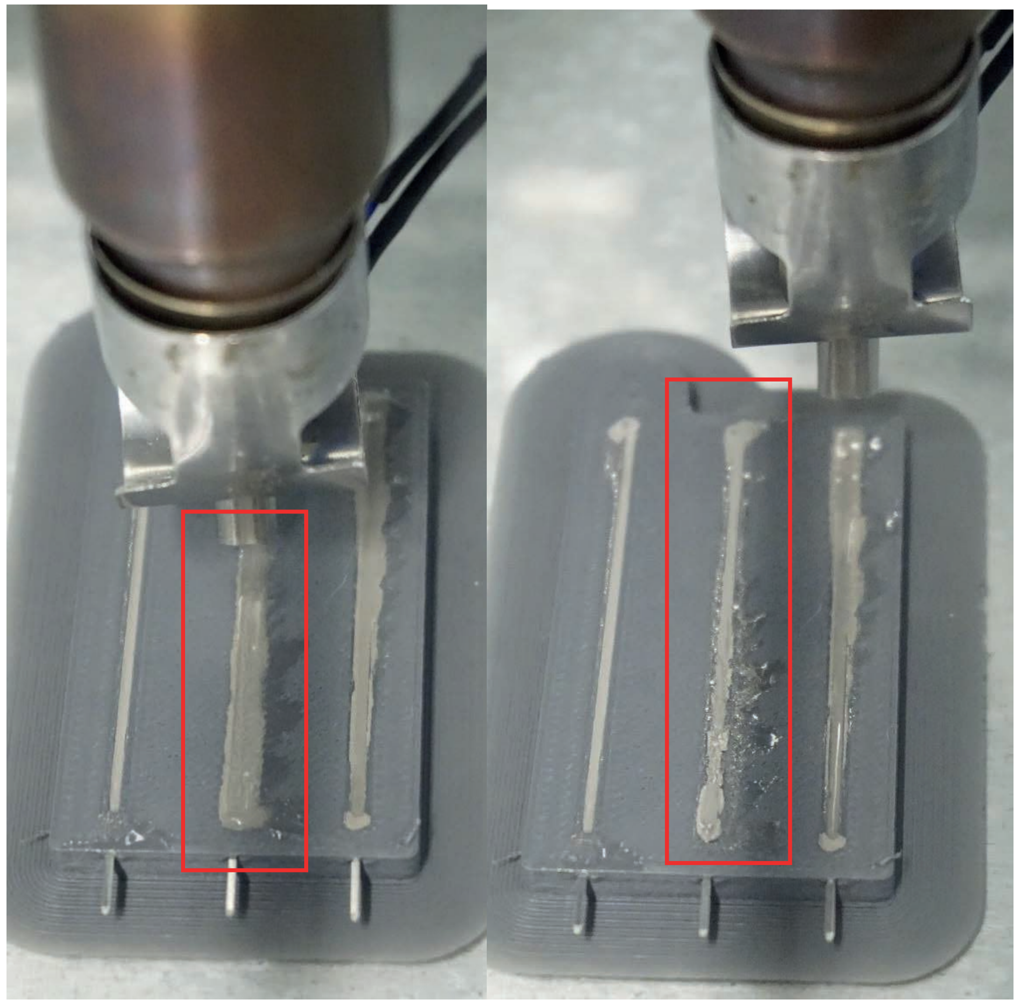

Figure 15: Marked with the red box (left) solder paste after the first curing step, (right) solder paste trace after the second curing step.

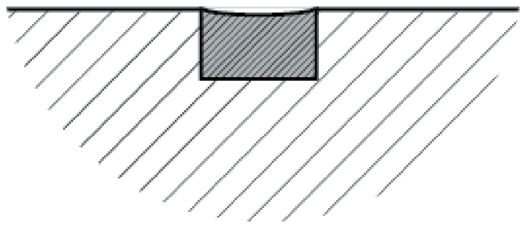

Figure 16: schematic cross section of cured solder paste trace

7. Validation and Characterization

To validate the function of the proposed design of the system first the process parameters of printing a simple straight conductive line are discussed. Secondly the resolution of the trace pitch is discussed. Thirdly the connecting of components is discussed. After which the stacking of multiple layers of solder paste is discussed. Lastly an integrated design is discussed showcasing all these design properties.

7.1 Conductivity of trace

The channel with the cured solder paste, and microscopic images of its surface and a cross section can be seen in Figure 17, the cured solder paste is not a solid metal trace but rather small metal balls tightly packed together. In Table 3 the resistivity of the printed trace is presented where the resistivity of the conductive filament (Proto-Pasta conductive filament) and the jumper wire with copper core are used as reference. The resistivity of the trace was measured over a 45mm trace, and the values for the conductive filament and the jumper wire are both from literature. It can be seen that the difference between the printed solder paste and the jumper wire of the same length differs with an order of magnitude in favour of the jumper wire. The conductive PLA filament has a resistance which is 5000 times greater than the printed solder paste which is outside of the useable range. In 3D printed electronics, a low resistivity or high conductivity of the trace is desirable, as a high resistance often result in high energy consumption and in the generation of heat. This is especially true for 3D prints, as the Tg of the PLA is lower than that of conventional plastics, e.g. PP, PTC.

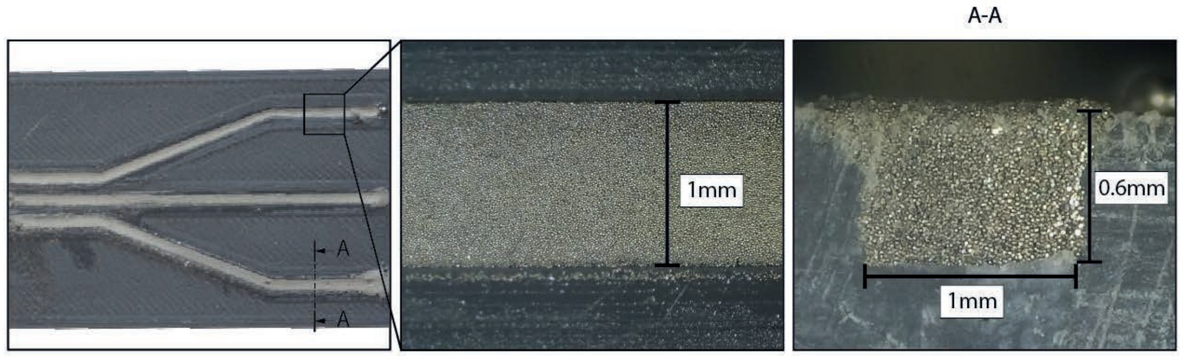

Figure 17: Overview of a sample with microscopic image of top of the solder paste trace and a microscopic image of the cross section of the solder paste trace. The microscopic images show the microstructure of the cured solder paste trace.

Table 3: properties of different conductive materials used in prototyping.

Type of conductive material	P (Ω.mm)	A (mm$^{2)}$	L (mm)	R (Ω)
Printed solder paste	6.7 $*10^{-3}$ - 6.7 $*10^{-2}$ (measured)	0.6	45	~0.5-5.0 (measured)
Jumper wire	1.68 $*10^{-5}$ (from literature)	0.14	45	5.4 $*10^{-3}$ (from literature)
Electrifi filament	6.0 $*10^{-2}$ (from literature [13])	0.6	45	4.5 (from literature)
Silver paste	3.0 $*10^{-4}$ (from literature)	0.6	45	2.25 $*10^{-2}$ (from literature)
Conductive PLA filament	3.0 $*10^{2}$ (from literature [12])	0.6	45	2.25 $*10^{4}$ (from literature)

7.2 Trace pitch

For the possible of using dual in-line package (DIP) integrated circuit (IC) in the design, a minimum pitch of 2.54mm between the solder paste traces is needed (see Fig.18). In the figure, 3 traces with 2.54mm in between were printed and cured without deforming the plastic between the channels.

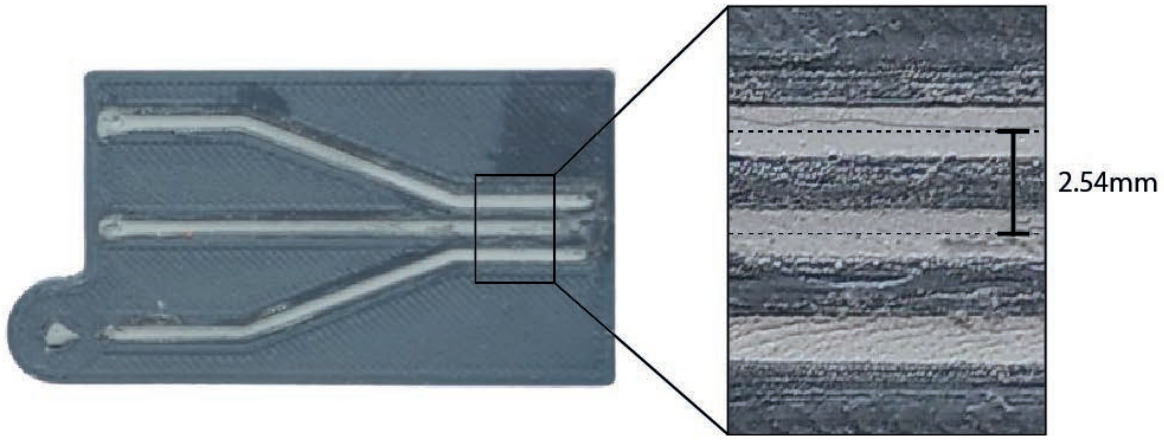

Figure 18: A sample with DIP pitch between lines, zoomed in image shows no information

7.3 Connecting components

The solder paste traces need to connect components with each other or connect to outside for powers, etc. Due to the nature of the 3D printing process, pick-n-place components placed in the prototype have to fully sit below the next printing layer for the 3D printer to continue printing over the component (Fig.19).

For connecting different trace with pins, we solve this problem by putting connection pins in recessed channels, then print the solder paste over it as in Figure 19. For those parts, curing over the pins is done at a slower speed because of the higher thermal conductivity of the pins. For instance, in the example presented in Figure 20, the curing speed over the solder paste where the pin in enclosed is reduced from F30 to F15.

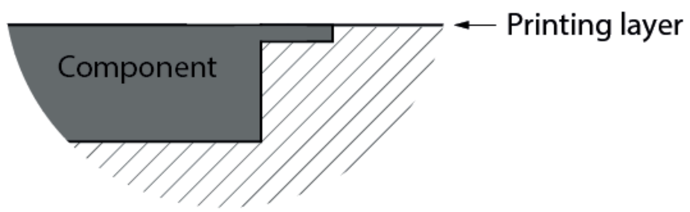

Figure 19: Schematic cross section of placing a component underneath the printing surface to avoid collisions with the printhead.

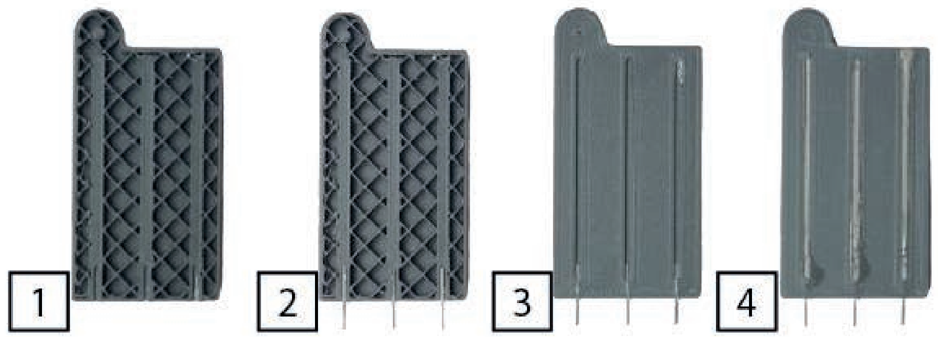

Figure 20: Four steps of printing over the lead of a component from left to right (1) print recessed channels for the lead to fit into. (2) insert leads into recessed channels (3) print recessed channel over the leads partly overlapping the lead and (4) print and cure solder paste in the channel creating a conductive interface between the lead and the solder paste trace.

7.4 Overlapping solder paste layers

To be able to create prototypes of designs in 3D it is important that conductive traces can be directed in every direction, connecting components in every part of the design. To achieve this, layers of solder paste need to be stacked to create traces in the vertical direction. For finding the needed overlap regions, an experiment is conducted that a sample with 3 different overlap lengths (2mm, 4mm and 6mm) were printed. Figure 21 presents that sample and the cross section view of overlapping lines which are conductive.

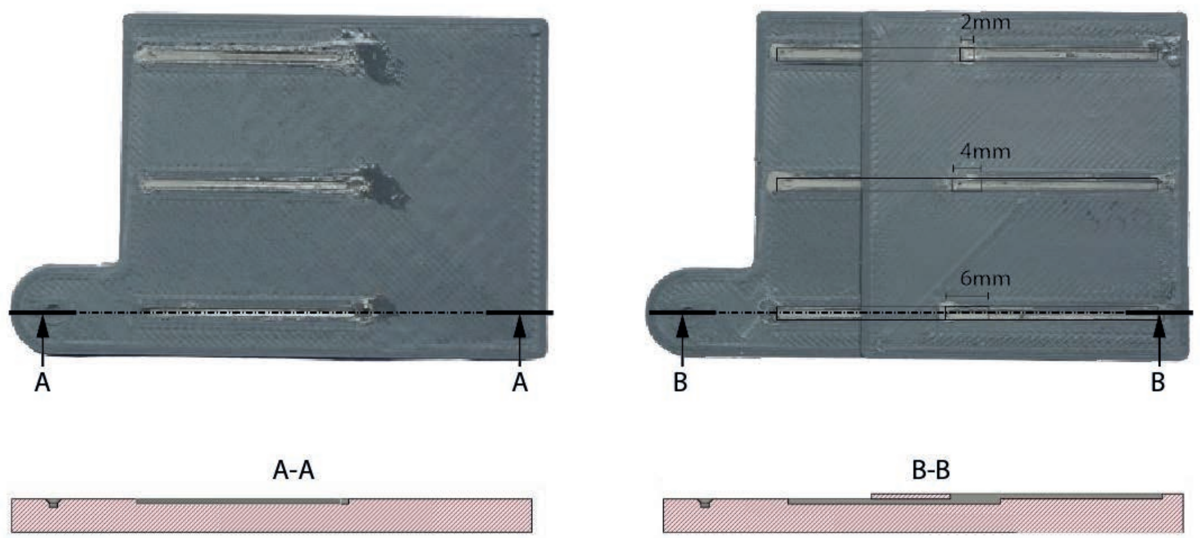

Figure 21: Sample with first solder paste layer(left) and thermoplastic and second layer of thermoplastic and solder paste printed over top (right).

8 Demonstrator

In this section, we presents a wireless computer mouse that is used as a dummy product to demonstrate the capabilities of the proposed printing system. The dummy mouse consists of a battery holder and a module with buttons and LED's which will be connected with each other with solder paste traces. The LED's will light up when the mouse buttons are pressed. An exploded view of the design can be seen in Figure 22.

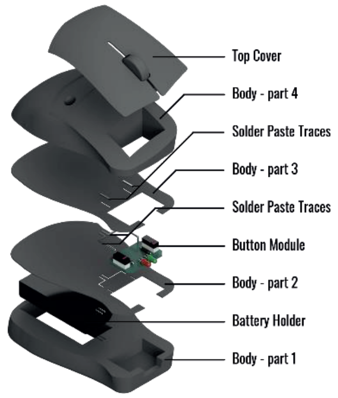

Figure 22: Exploded view of the dummy computer mouse used as demonstrator.

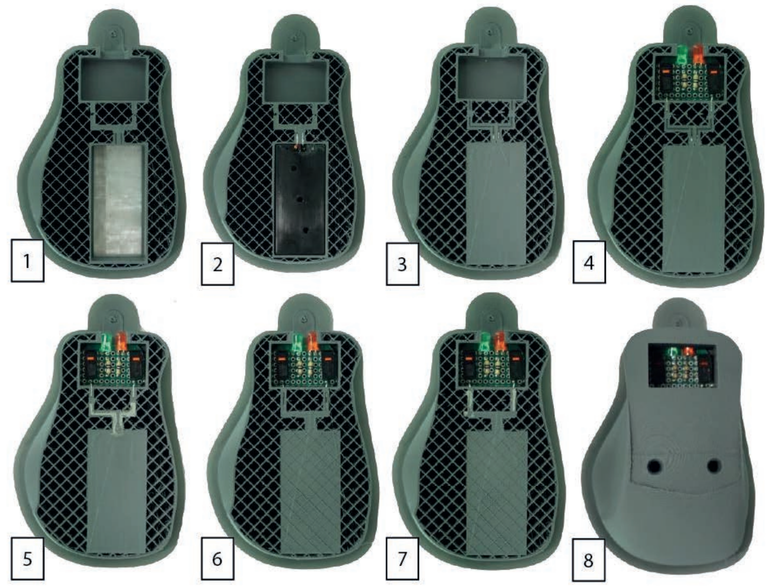

Figure 23: (1) The base is printed with room for the battery holder (2) The black battery holder is placed (3) A channel is printed over the leads of the battery holder room for the leads of the button module (4) The button module is placed (5) Solder paste is printed and cured in the channels (6) More layers of thermoplastic are printed with a channel connecting the leads of the button module and solder paste trace below (7) solder paste printed and cured in the channel (8) the remainder of the demonstrator is 3D printed.

The first step in printing the demonstrator is printing the base with a compartment for the battery (Fig.23.1), then the battery module is placed in (Fig.23.2). Several layers of plastic are printed where channels are created according to the circuit (Fig.23.3) and a compartment for the button module is created (Fig.23.4). The solder paste can now be printed and cured in the channels (Fig.23.5). The next step is printing new layers of thermoplastic over top with a recessed channel connecting the pins of the button module with the solder paste trace of the layer below (Fig.23.6). Another lay of solder paste is printed and cured in the channel (Fig.23.7) after which the remainder of the prototype can be printed on top (Fig.23.8). The top cover (Fig.24) of the demonstrator mouse is printed separately and placed on the base to create the completed demonstrator.

Figure 24: (left) The top cover printed separately and (right) placed onto the prototype.

9 Limitations

9.1 Surface artefacts from curing

As printing the substate and the solder paste were conducted in two different 3D printers, a glass building plate were used to transfer them between printing. During this transfer, slight surface artefacts maybe created due to mechanical positing error (see Fig.25). Structurally this has little effect but it has to be taken into account when a good surface finish is desired. Printing the thermoplastic and printing and curing solder paste in a single machine could eliminate these problems in the future because the build plate is no longer manually moved between printers.

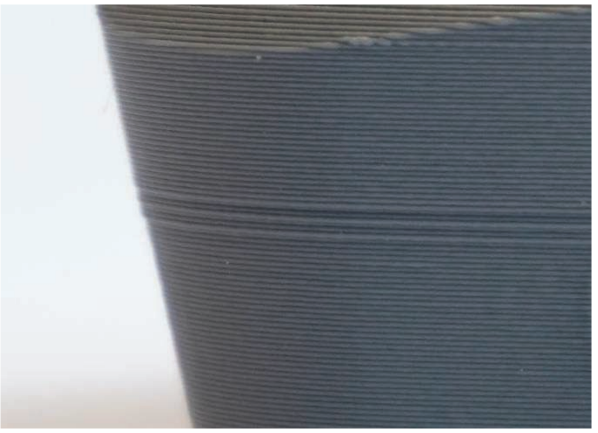

Figure 25: Surface artefacts can be seen between the top three layers and the rest of the bottom of the part.

9.2 Uneven extrusion of solder paste

The solder paste syringe is stored in a fridge before usage for keeping the homogeneous properties of the paste for a longer period of time. When the solder paste is heating up its viscosity decreases, which may influence its extrusion speed. A problem encountered in the test was that the heat from the heated bed of the printer would heat up the solder paste in the syringe during solder paste extrusion, resulting in more solder paste being extruded towards the end. Besides, small air bubbles in the solder paste may also create inconsistent trace as indicated in Figure 26. However, during the hot air curing, the trace is often smoothed due to the heat introduced by the hot air.

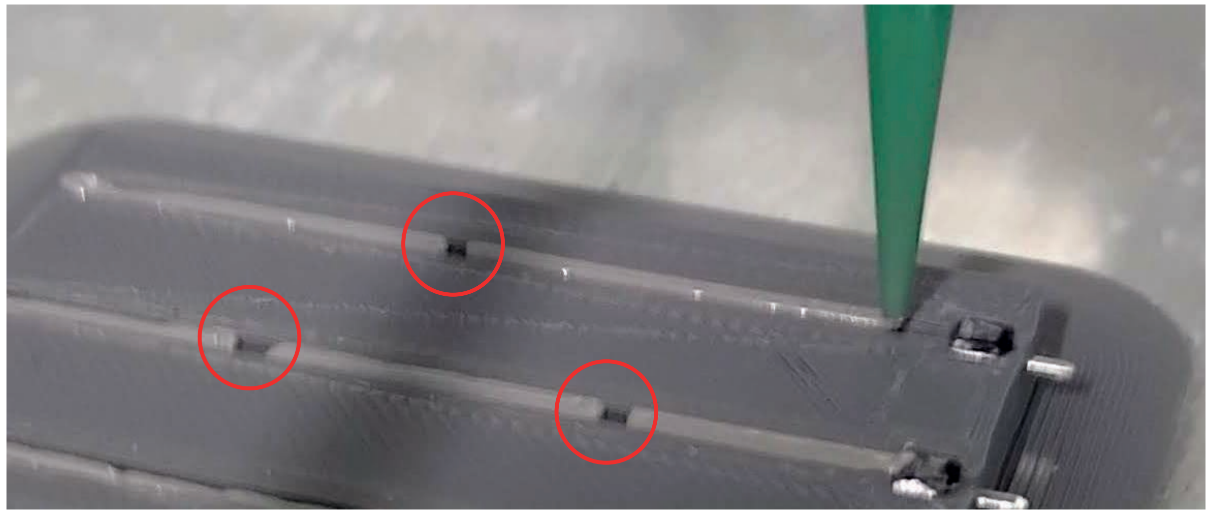

Figure 26: Breaks in the printed line of solder paste caused by air-bubbles.

10 Conclusions

In this paper, we proposed a 3D printing system that can utilize solder paste to print 3D structured electronics. Solder paste is an affordable alternative of the conductive silver paste. Experiments results indicates that the proposed system is able to print and cure solder paste with in 3D prints. The conductivity of the cured solder paste is less than that of the copper wires, but still well within the useable range for prototyping purposes. The resolution that can be achieved is 1mm wide traces with 1/10-inch (2.54mm) pitch. The combination of this method would make rapid prototyping of structural electronics more affordable and easier to use, therefore make it more accessible for a wider audience who can contribute to the further development of 3D printed prototypes with integrated electronics

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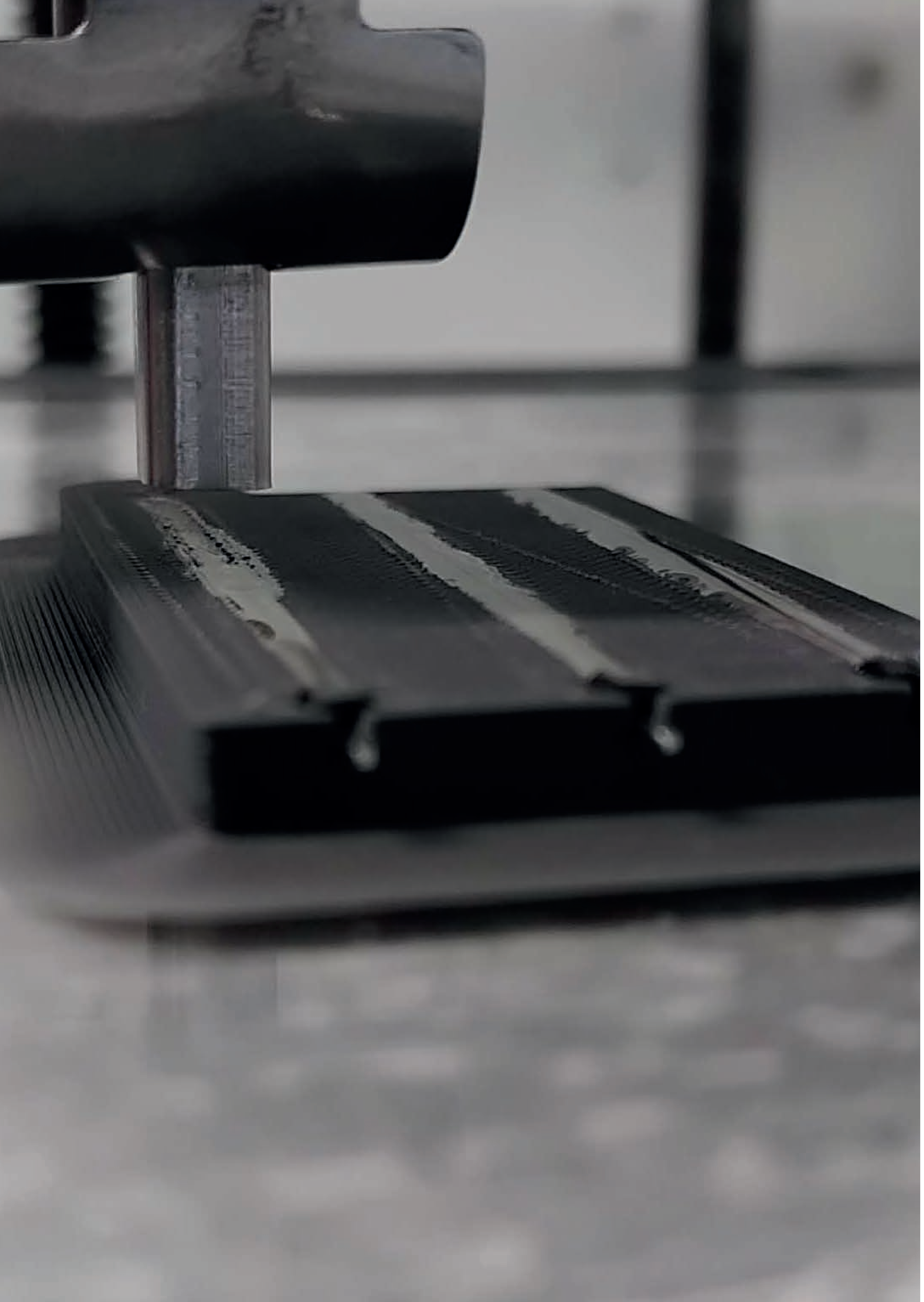
Part B

Master Thesis



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Without the help of others I could never have gotten as far as I did with this project and I here I would like express my thank to the people that helped me throughout the project.

First I would like to thank Milly Bon for working on a project I could continue with and for the help in getting me familiar with the project. Without you I would not have gone off to such a good start.

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And last but not least I would like to thanks my girlfriend Jonne Bremer who always tried to make my life easier in any way she could, so I could focus my time and energy on my graduation project, I hope to return the favor in the future.

Executive summary

Introduction
Starting this report 3D printing is explained and the state of the art in 3D printing structural electronics. From here the current state of the project is described after which the project goal is formed. The project goal for this project is as follows:

"Test and prototype on-site curing of solder paste on a 3D printed substrate to enable the 3D printing of structural electronics in prototypes using an FDM 3D printer"

After the project goal the vision for the future 3D printer is also discussed.

Research
Reflow soldering methods used in industry were researched and the most promising methods were chosen for the given use case of on-site curing of solder paste in a 3D printer. The most promising methods for on-site curing are a thermode, a diode laser and focused hot-air. Also the used materials (e.g. solder paste and thermoplastic substrate) are discussed in more detail.

Testing of methods
The three most promising methods were tried and tested to see which would be the most suitable method to continue with. Only the focused hot-air method produced usable results where the traces would be conductive.

Hot-air detailed testing
After determining that the focused hot-air method was most suitable method more detailed tests were done. Tests were conducted for printing overlapping traces as a first step in printing in the vertical direction. Trace pitch was tested for connecting DIP pitch components. As well as how pins can be connected to the solder paste traces. And lastly tests are done to quantify the conductivity of the printed and cured solder paste traces.

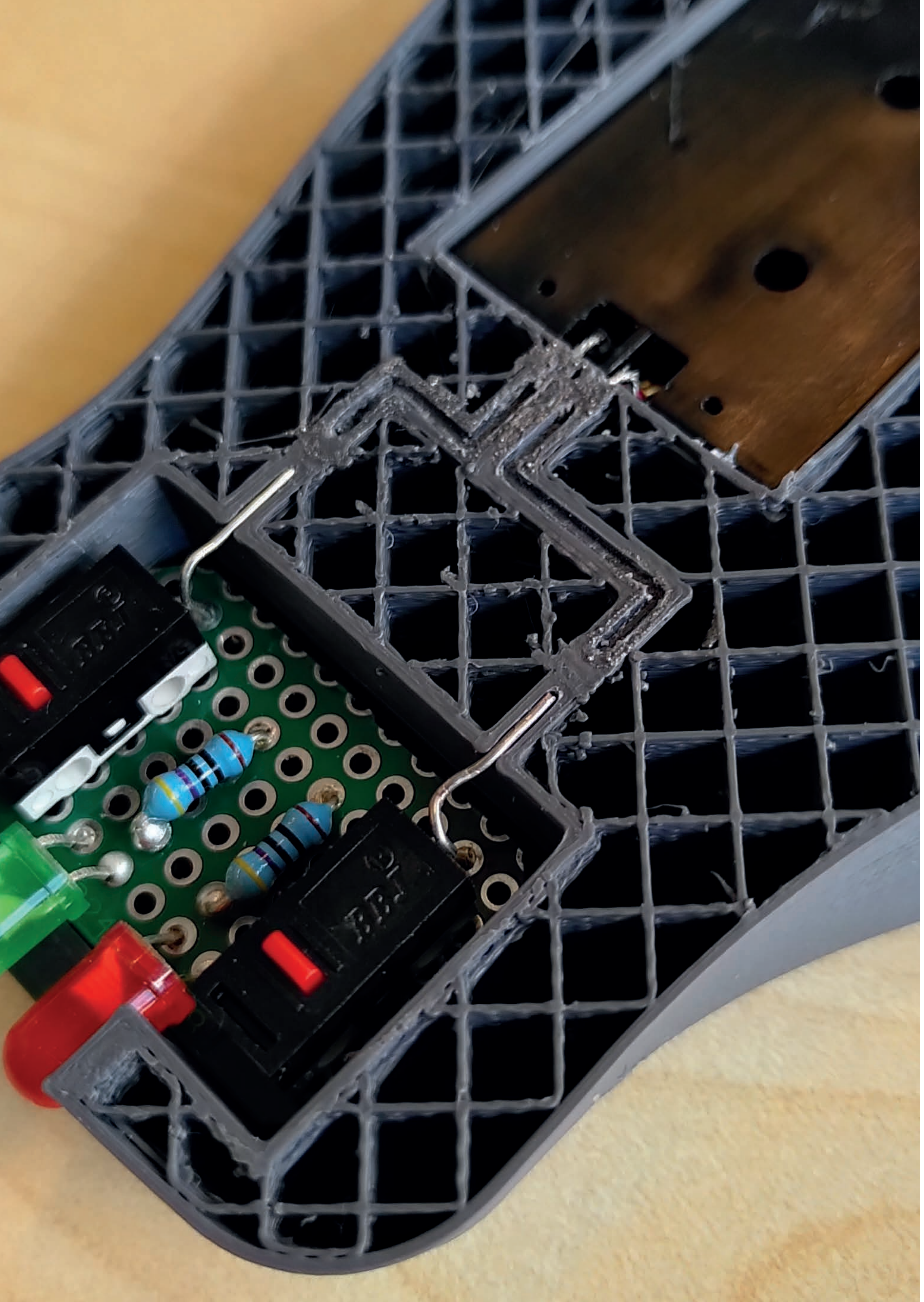
Architecture of the system
The system that was used for testing is described in detail. The system consists of a Ultimaker for printing the thermoplastic substrate and RepRap printing platform where the custom built solder paste extruder and focused hot-air gun are mounted in.

Design guidelines
To use the developed method for future research several design guidelines are described in this section. First the CAD is discussed with the dimensions of the trace and how components are to be placed in the design. After that the preparation of the Gcode for both printers is described.

Demonstrator
To demonstrate the abilities of the developed method a demonstrator product was designed and made. This demonstrator combines all the abilities that were tested separately in the hot-air detailed tasting chapter.

Conclusions
To finish this master thesis it is concluded that using this method of printing and curing as an alternative material in 3D printing prototypes of structural electronics is promising. It is easy to use and affordable with sufficient quality to be used for prototypes. However true 3D functionality has not been achieved yet.

Recommendations
In this master thesis a step forward has been made for using solder paste in 3D printing structural electronics. To improve this method more research is needed and possible steps for future research are discussed here. Creating consistent layers would open up the possibility of stacking multiple layers and open up the possibility of printing 3D structural electronics.



Glossary

FDM	-	Fused Deposition Modeling
SMD	-	Surface-Mount Device
SMT	-	Surface-Mount Technology
PCB	-	Printed Circuit Board
CAD	-	Computer Aided Design
PLA	-	Poly Lactic Acid, a type of polymer commonly used in FDM 3D printing
DIY	-	Do It Yourself
G code	-	The file format which is used by the 3D printer to make a 3D model
Hot-end	-	Thermoplastics extruder in a FDM 3D printer consisting of a heater cartridge heating block and the nozzle
CAM	-	Computer Aided Manufacturing
Ultimaker	-	Dutch company who design and manufacture desktop FDM 3D printers
Cura	-	Software which processes a 3D model to instructions the 3D printer can use to make the 3D model

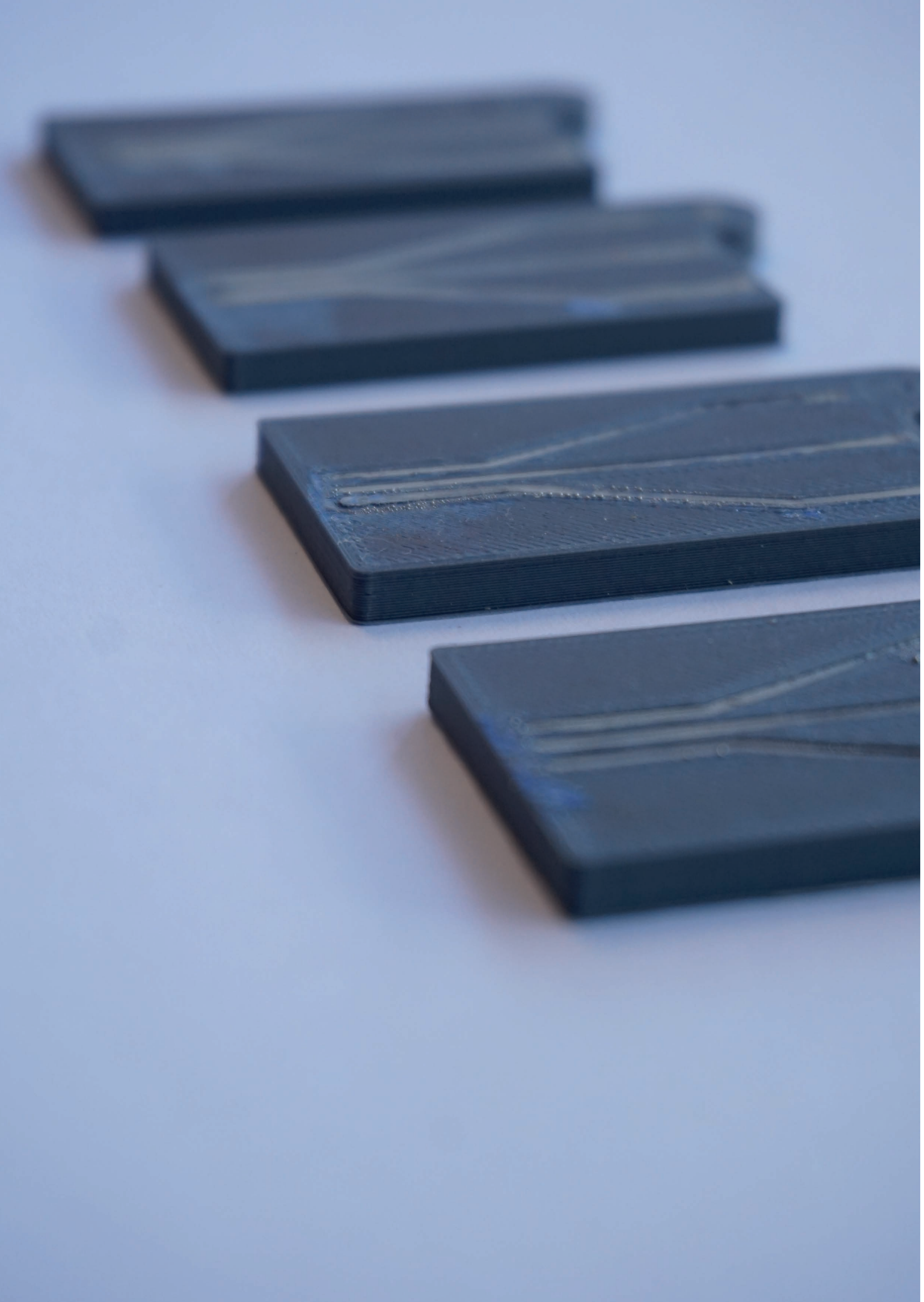


Table of contents

Preface . . . 1

Manuscript of Paper . . . 3

Acknowledgments. . . . 27

Executive summary . . . 29

Glossary . . . 31

Table of contents . . . 33

1 Introduction . . . 35
1.1 3D Printing . . . 36
1.2 State of the art . . . 37
1.3 Current state of the project . . . 41
1.4 Project brief . . . 45
1.5 Vision . . . 46

2 Research . . . 47
2.1 Approach . . . 48
2.2 Reflow soldering methods . . . 49
2.3 Solder paste. . . . 53
2.4 Target group . . . 54
2.5 Thermoplastic. . . . 55

3 Testing of methods. . . . 57
3.1 Test setup . . . 58
3.2 Thermode method . . . 59
3.3 Diode laser method. . . . 60
3.4 Hot air method . . . 61
3.5 Comparison of methods . . . 62

4 Architecture of the system . . . 63
4.1 System overview . . . 64
4.2 Thermoplastic extruder . . . 65
4.3 Pick and place . . . 65
4.4 Solder paste extruder . . . 66
4.5 Hot-air gun . . . 67

5 Hot-air curing detailed testing . . . 69
5.1 Integrated testing. . . . 70
5.2 Overlapping traces . . . 71
5.3 DIP trace pitch . . . 72
5.4 Connecting components . . . 73
5.5 Resistivity. . . . 74

6 Design guidelines . . . 75
6.1 CAD design of thermoplastic substrate. . . . 76
6.2 CAM design . . . 77

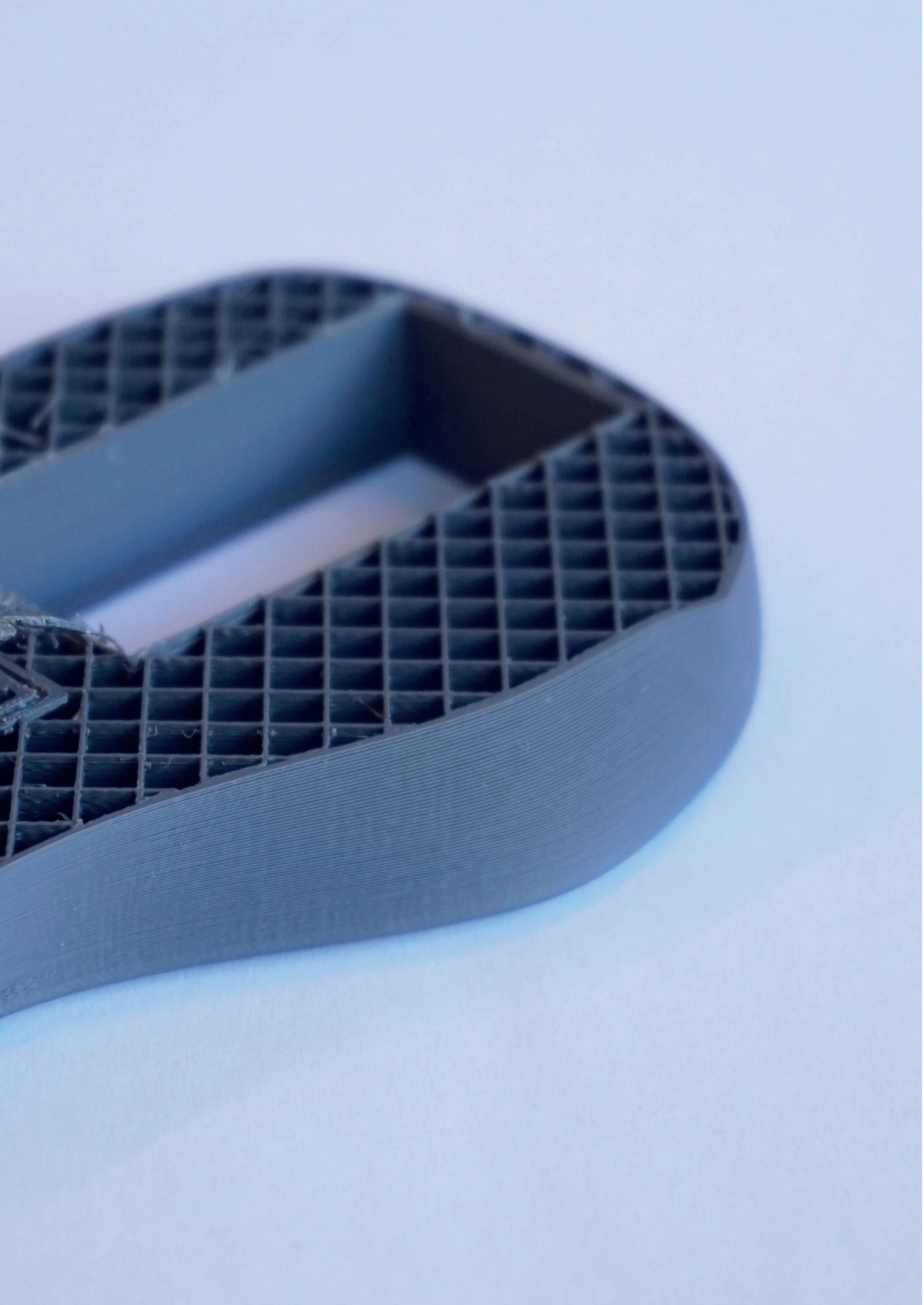
7 Demonstrator. . . . 79

8 Conclusions and recommendations . . . 83
8.1 The goal . . . 84
8.2 Conclusions. . . . 84
8.3 Recommendations . . . 85

9 Reflection . . . 87

References . . . 89

Appendices . . . 92
A Testing logbook. . . . 93
B Project brief. . . . 113



1 Introduction

First 3D printing in general is introduced after which the state of the art in the field of 3D printing is discussed. The current state of the project is described from which the project goal is formed. Lastly the envisioned printer is described.

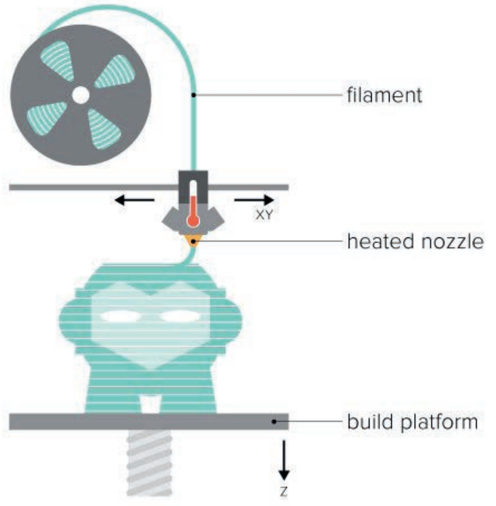


figure 1.1: Schematic overview of FDM 3D printing, photo: 3D Hubs

1.1 3D Printing

3D printing has been around for some time and is often used in prototyping and making products with low production volumes. There are different ways of 3D printing with different materials. The most well known method is FDM 3D printing. This method "prints" objects by laying different layers on top of each other. Each layer is "drawn"by pushing a thin plastic wire called filament through a hot nozzle which is located on a movable printing head. And by stacking these layers on top of each other a 3D object is formed (figure 1.1). Complex 3 dimensional objects can be made in the computer with the use of CAD software and are easily printed. This means prototypes can be modeled in the computer and are easily manufactured by the 3D printer.

Until not so long ago FDM printers used only thermoplastic filaments to create 3D objects. But since a couple of years 3D printing has expanded into the field of 3D printing passive and structural electronics [1]. The ability to print conductive materials is still under constant research and development and multiple handful of different printers are currently available.

1.2 State of the art

3D printing structural electronics has been a recent development in the field of 3D printing with a handful of 3D printers being commercially available at the moment. 3D printing is very useful for making one off designs, which means that they are very useful for making prototypes and high end one-off products. The electronics printers on the market differ in a lot of aspects, and can be categorized in industrial printers, educational/hobbyist printers, PCB printers and conductive filaments. The properties of all these printers/filaments are summarized in table 1.1.

Industrial 3D printers

The first two printers in table 1.1 are the Aerosol jet 5X [2] and the Nano dimension Dragonfly LDM [3] (see figure 1.2) which are large industrial grade machines and cost upwards of €100.000, these machines are made for high-end prototypes and end-use products. These printers are able to print multi material with thermoplastic and conductive nano silver ink using aerosol or material jetting technologies.

Desktop 3D printers

The third and fourth printer (Voxel8 [4], eForge [5]) (see figure 1.3) are professional 3D printers that fit on a desktop. They are able to print thermoplastic filament with the fused deposition modeling (FDM) method. The Voxel8 uses material extrusion to apply conductive silver nano particle ink. The silver nano particle ink is applied at room temperature and cures when in contact with air. The eForge uses a conductive filament which is printer through a hot-end. It has to be noted that the Voxel8 has been discontinued and is no longer for sale, and the eForge is still in development and not yet available at the time of writing.

figure 1.2: Aerosol Jet 5X & Dragonfly LDM

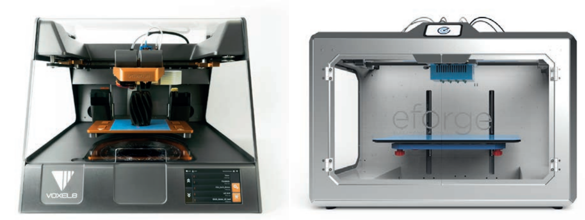


figure 1.3: Voxel8 & eForge

figure 1.4: Botfactory SV2 & Voltera v-one

figure 1.5: Conductive filaments

PCB 3D printers

The fifth and sixth printer (see figure 1.4) on the list are the Botfactory SV2 [6] and Voltera v-one [7]. They are 2D printers which can be used to produce PCB prototypes. Both printers are able to print conductive material on several substrate materials. These machines use 3D printing technologies but are in fact 2D PCB printing machines.

Conductive filaments

The last options in the list is not a printer but are conductive thermoplastic filaments like Proto-Pasta [8] and Electrifi [9]. Fine particles of conductive material are mixed into the plastic to make it conductive. The conductivity can vary from very poor to average when compared to solid copper or aluminum. The big advantage is that it can be used with almost every FDM 3D printer that is capable of printing PLA.

table 1.1: Available structural electronics 3D printers

Printer	Price	Size	Substrate	Conductive material	Printing Dimensions	Additional comments
Aerosol Jet 5X [2]	>€200.000	~1 x 2 x 2 [m]	Thermoplastic 3D print	Conductive ink	3D	
Nano dimension Dragonfly LDM [3]	>€100.000	~1 x 2 x 2 [m]	Thermoplastic 3D print	Conductive ink	2.5D (up to 3mm height)	
Voxel8 [4]	~ €7.000	~0.8 x 0.8 x0.5 [m]	Thermoplastic 3D print	Silver ink	3D	Has been discontinued
eForge [5]	~ €7.000	~0.8 x 1 x 0.8 [m]	Thermoplastic 3D print	Conductive filament	3D	Not commercially available
Botfactory SV2 [6]	~ €3.500	~0.5 x 0.5 x 0.8 [m]	FR-4 , kapton, etc...	Conductive ink	2D	
Voltera v-one [7]	~ €3.500	~0.5 x 0.5 x 0.8 [m]	FR-4 , kapton, etc...	Conductive ink	2D	
Proto-Pasta filament [8]	~ €90 /kg	-	Thermoplastic 3D print	Conductive filament	3D	Used with any dual extrusion FDM 3D printer
Electrifi filament [9]	~ €2000/kg	-	Thermoplastic 3D print	Conductive filament	3D	Used with any dual extrusion FDM 3D printer

Scoring

All printers currently on the market are scored on four main qualities that are later used in the project goal. The main qualities that are needed are: ease of use, price, quality and the ability to print 3D. In figure 1.6 the different printers and filaments are scored on these different qualities. The printers are divided into four groups with similar characteristics.

The first group are the large industrial grade 3D electronics printers. These printers deliver high quality and can work in both 2.5D and 3D. The big drawback of these printers is the very high price and the fact that additional training is needed in operating them.

The second group are the professional desktop 3D electronics printers. These printers can print 3D designs with integrated circuits using thermoplastic as a substrate. The conductivity of the printed material is better than the commercially available conductive filament (Proto-Pasta) and sufficient for producing prototypes during the design process. Both printers are around ~€7.000 in price which is in the price range of comparable desktop FDM 3D printers (the Ultimaker 5S costs ~€5000). Because both printer are operated like regular FDM 3D printer the ease of use is quite high and most designers will be familiar with them.

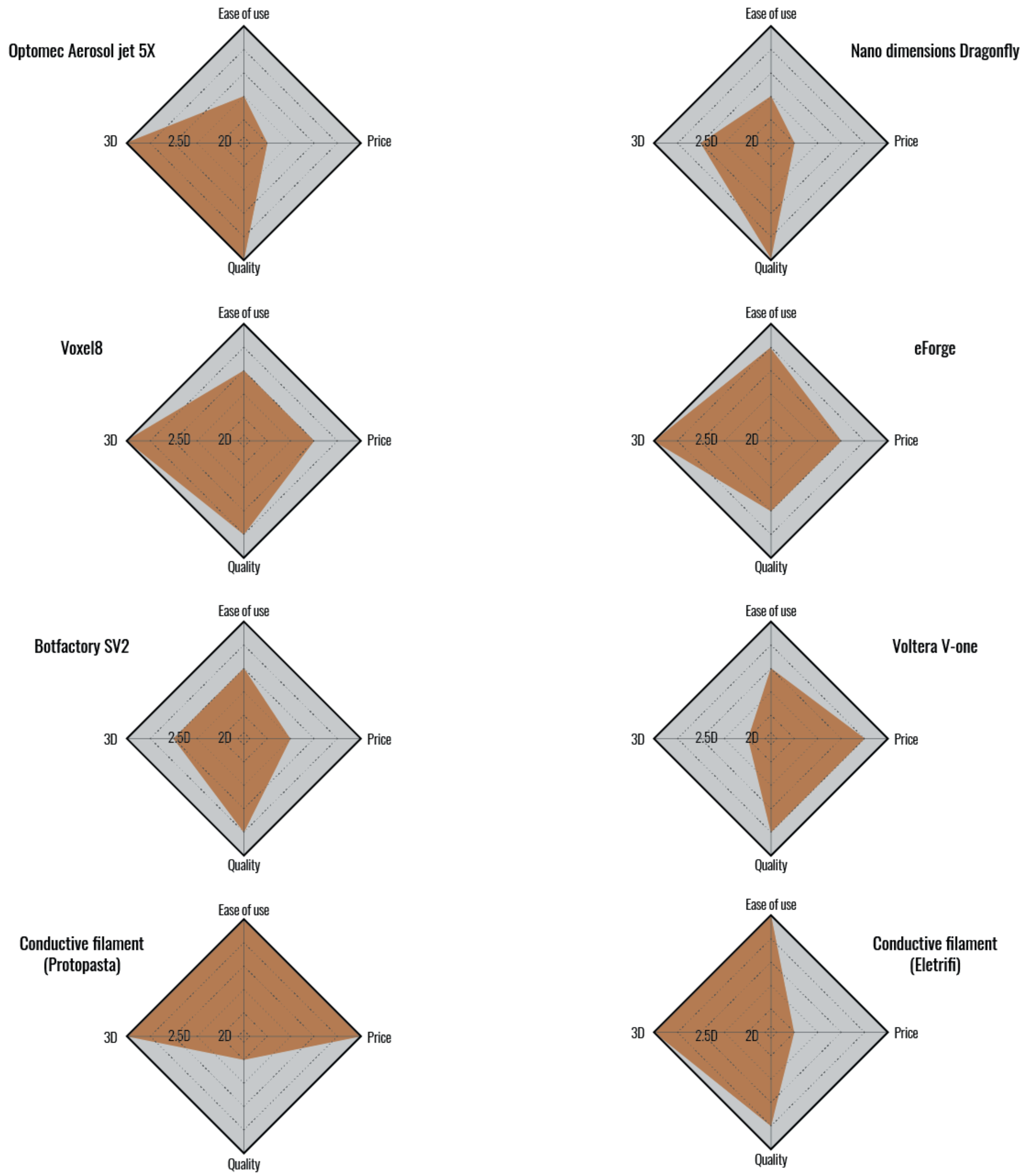


figure 1.6: Scoring of currently available printers and conductive filament for 3D printing electronics.

The third group are the 2D PCB printers. Both are around ~€3500 which is in the price range of most high end desktop FDM 3D printers. Because they both print in 2D they do not meet the requirements for printing 3D designs. The quality of the conductive traces is good compared to the conductive filament but not as good as solid copper/aluminum wires or traces. The software used to operate these machines is used often in PCB design which makes it easy to use for most designers which have experience with designing PCB's.

Lastly there is the conductive filament. This filament has mixed in particles of a conductive material making it conductive and can be low in price with bad conductive properties or high in price with good conductive properties. This is also the most easy to use option because no additional knowledge is needed, the filament can be used in any FDM 3D printer which is able to print PLA.

Conclusion

Concluding this section it can be seen that the Voxel8 and eForge are the printers that best meet the requirements. The big drawback is that the Voxel8 has been discontinued and no longer for sale. And the eForge is still a kickstarter campaign at the time of writing. Which means that no desktop electronics 3D printer is available at the moment. This gap is what this research aims to fill with developing a new easy to use and affordable desktop 3D printing method.

1.3 Current state of the project

This master thesis is a continuation of a larger project, it contineus on the master thesis of M.Bon [10]. To better understand the project brief and goals for the project it is important to understand the current state of the project. The goal of the overall project is to make 3D printing structural electronics more accessible both by means of price and ease of use. Because the goal is to make 3D printing structural electronics more accessible, a FDM 3D printer was chosen as most suitable because of its relatively simple design, low price and ease of use. It is important to note that we are not looking for the best 3D structural electronics printer that can be made but the most affordable and easy to use to be able to bring 3D printing of electronics to a bigger group of users.

Current printer

Currently the printer being prototyped is a DIY Cartesian style 3D printer , the printer features a "hot-end" extruder for printing thermoplastic materials and a solder paste syringe extruder for laying down traces of conductive material (see figure 1.7). The thermoplastic base and the extruded solder paste traces are then put in the oven and heated to "cure" the solder paste. After curing the solder paste has turned into solid conductive material. The research has shown that this is an effective way to produce 2D conductive tracks on a 3D printed substrate. Placing the design in the oven after every layer of conductive material and thermoplastic is time consuming and impractical when designs with multiple layer are needed, another method is needed to achieve this.

The main results of the previous master thesis are:

- Type of solder paste
- Type of substrate material
- Solder paste extruder
- Channel cross section
- Reflow and curing method

These results are described in more detail in the next paragraphs.

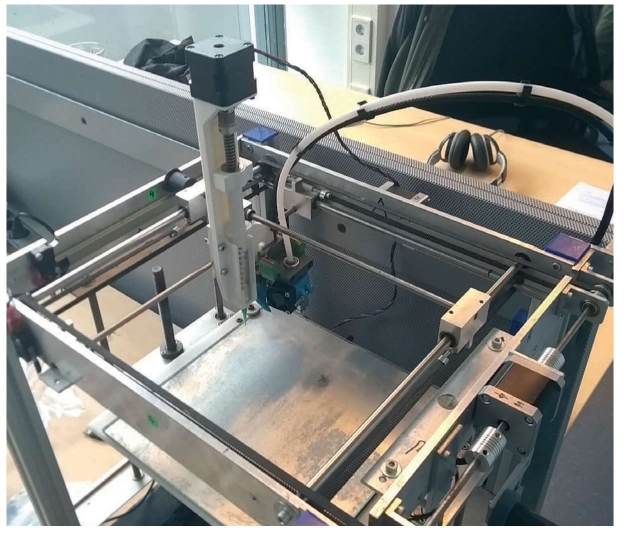


figure 1.7: DIY Cartesian style FDM 3D printer which is being prototyped in the applied labs

figure 1.8: Solder paste syringe currently used in the project for printing conductive material

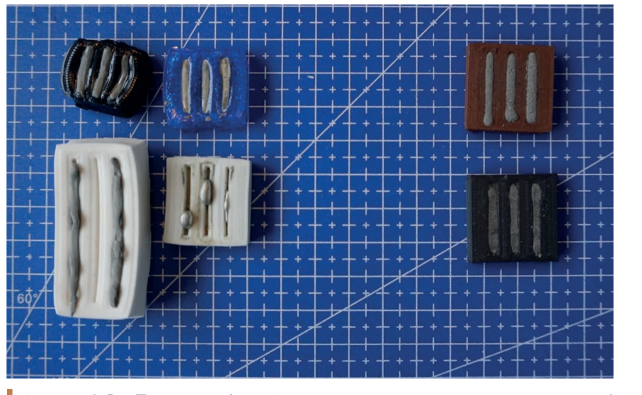


figure 1.9: Test samples after curing in convection oven, warped (left) and successful (right) courtesy of M. Bon

Solder paste

$Sn42/Bi57.6/Ag0.4$ solder paste is most effective for its low flow temperature and good conductive properties. The solder paste contains 42 % tin, 57.6 % Bismuth and 0.4 % Silver to ratio as metal compounds, and includes 86%wt metal. The solder paste melts at 139C, which is lower than most thermoplastics used in 3D printing making it very suitable. The solder paste is distributed in a syringe with 35 grams of solder paste each (see figure 1.8).

Substrate material

Because the curing of the solder paste takes place in a convection oven the substrate must also be able to withstand the heat needed to reflow and cure the solder paste. Tests were done with different kinds of thermoplastic substrate at 142C to see which do not warp when heated up again PLA x3 (made for heat treatment after printing) and copper filled PLA proved to withstand the heat in the convection oven (see figure 1.9).

Solder paste extruder

The solder paste extruder is designed around the syringe it is distributed in (see figure 1.8). The extruder works with a plunger style mechanism, a stepper motor extends a lead screw which pushes on the solder paste to extrude it. The amount of steps the stepper motor moves controls the amount of solder paste which is being extruded. The current design can be seen in figure 1.10.

Channel cross-section

The cross sectional shape and size of the channel in which the solder paste was dispensed was also researched. It was found that a channel needed a deep shape with chamfered edge (see figure 1.11), the chamfered edge is to ensure good reflow into the channel.

Reflow and curing in the oven

A convection oven is used to reflow and cure the solder paste in the channel. A slow reflow was found to be best. The sample is placed in the oven at room temperature and heated to 142C in approximately 15 minutes. When the temperature is reached the solder paste is cured at 142C for 10 minutes. After the 10 minutes of curing the sample is removed from the oven and cooled back to room temperature.

Conclusion

Concluding the current state of the project the proof of concept has been delivered that the combination of solder paste as conductive material and PLA-x3 (HT-PLA) as substrate work well.

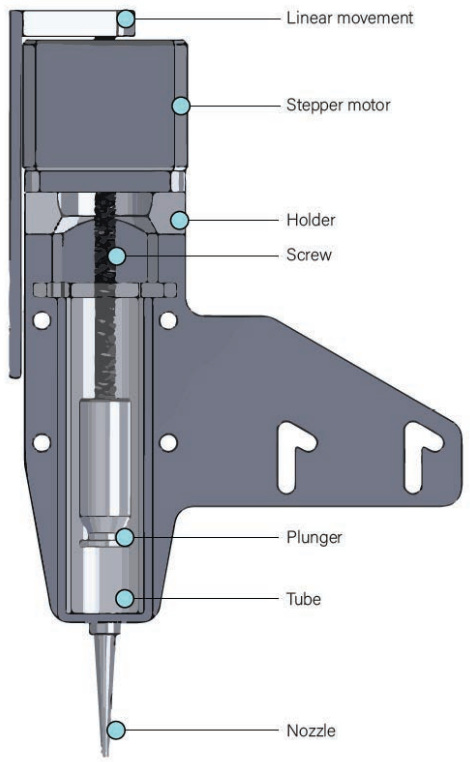


figure 1.10: Schematic overview of the solder paste extruder. Image courtesy of M. Bon.

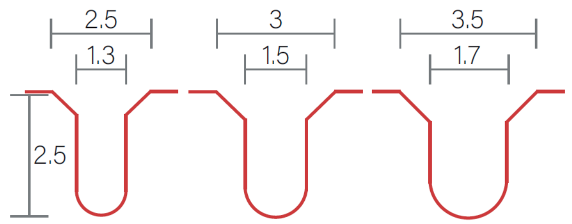
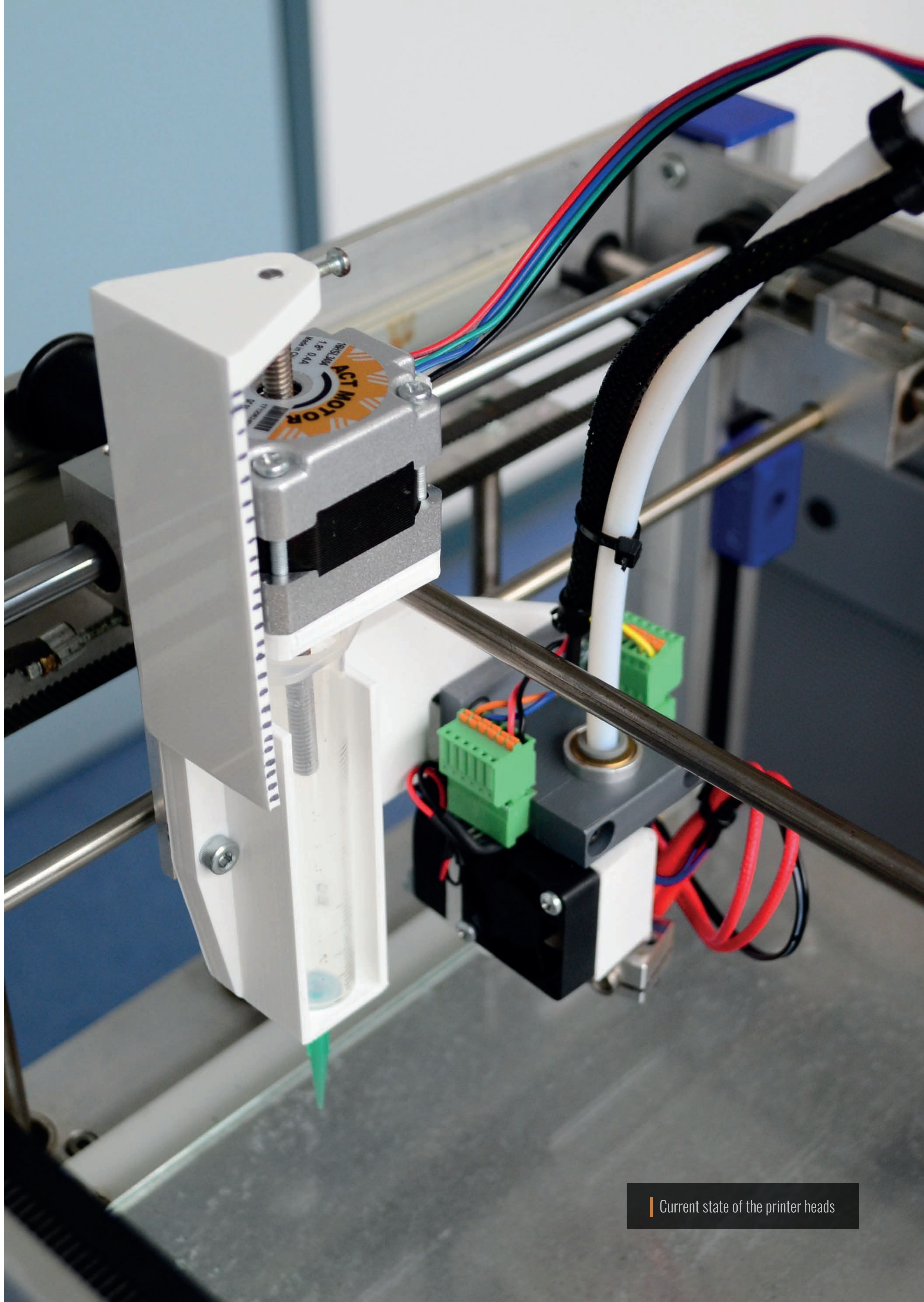


figure 1.11: Cross section of the recessed channel in the printed plastic part



Current state of the printer heads

1.4 Project brief

Problem definition:
The main problem is that there is no affordable option to use 3D printing to create physical prototypes with integrated structural electronics. The Voxel8 is affordable (~€7000) but uses silver ink paste as conductive material which is expensive. Considering the fact that multiple prototypes are usually made before the final prototype is finished a more affordable material is desirable.

The printer being prototyped in the applied labs at the IDE faculty is able to print 2D circuits with solder paste as a conductive material and temperature resistant PLA as the substrate in the current state of the project. After printing the solder paste has to be cured in an external convection oven.

To utilize this technology to its full potential the printer should work in 3D. To achieve this multiple layers of thermoplastic and conductive material should be printed on top of each other, creating 3 dimensional designs with conducting paths. Curing the solder paste after each layer in an external oven poses problems in aligning for further printing and greatly increases production time which is not desirable. The first step in achieving 3D prototypes with integrated circuits is to cure the solder paste in the printer itself during printing (on-site curing), either simultaneously or after every layer. This would enable printing multiple layers of thermoplastic and conductive material making 3D printed circuits in 3D designs.

Project goal:
The main goal of the assignment is researching which technology will be most suitable for on-site curing the solder paste in the printer and showing a proof of concept.

If on-site curing is viable and feasible the printing of multiple layers can be tested. Testing how the stacking of multiple layers of solder paste affects conductivity and structural integrity of the 3D printed structural electronics.

If these steps are successful the new technology can be integrated into the printing head of the 3D FDM printer, optimizing the design of the printer head to maximize the usable space on the bed of the printer.

The goal is to design a demo product to as a proof of concept of on-site curing the printed structural electronics either in 3D (or 2D).

"Test and prototype on-site curing of solder paste on a 3D printed substrate to enable the 3D printing of structural electronics in prototypes using an FDM 3D printer. On-site curing of solder paste would enable multiple layers of thermoplastic and conducting material being printed on top of each other. Making it possible to print 3D designs with integrated structural electronics."

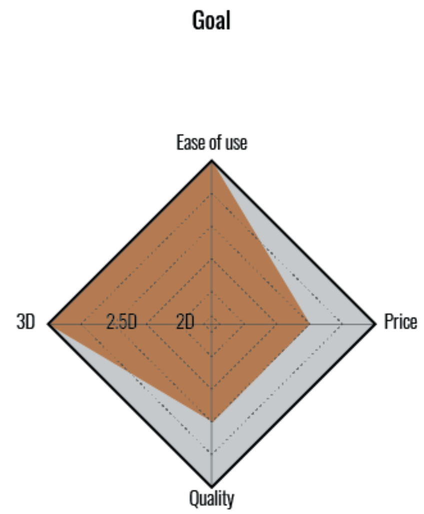


figure 1.12: The four characteristics of the project goal on which the product will be scored.

1.5 Vision

The envisioned 3D printer that will utilize the technologies that are being researched in this project has several characteristics which will be described in this section.

The same characteristics that were used to score the 3D electronics printers in section 1.2 State of the art are used in this section to describe the goal/ product vision for this project (see figure 1.12).

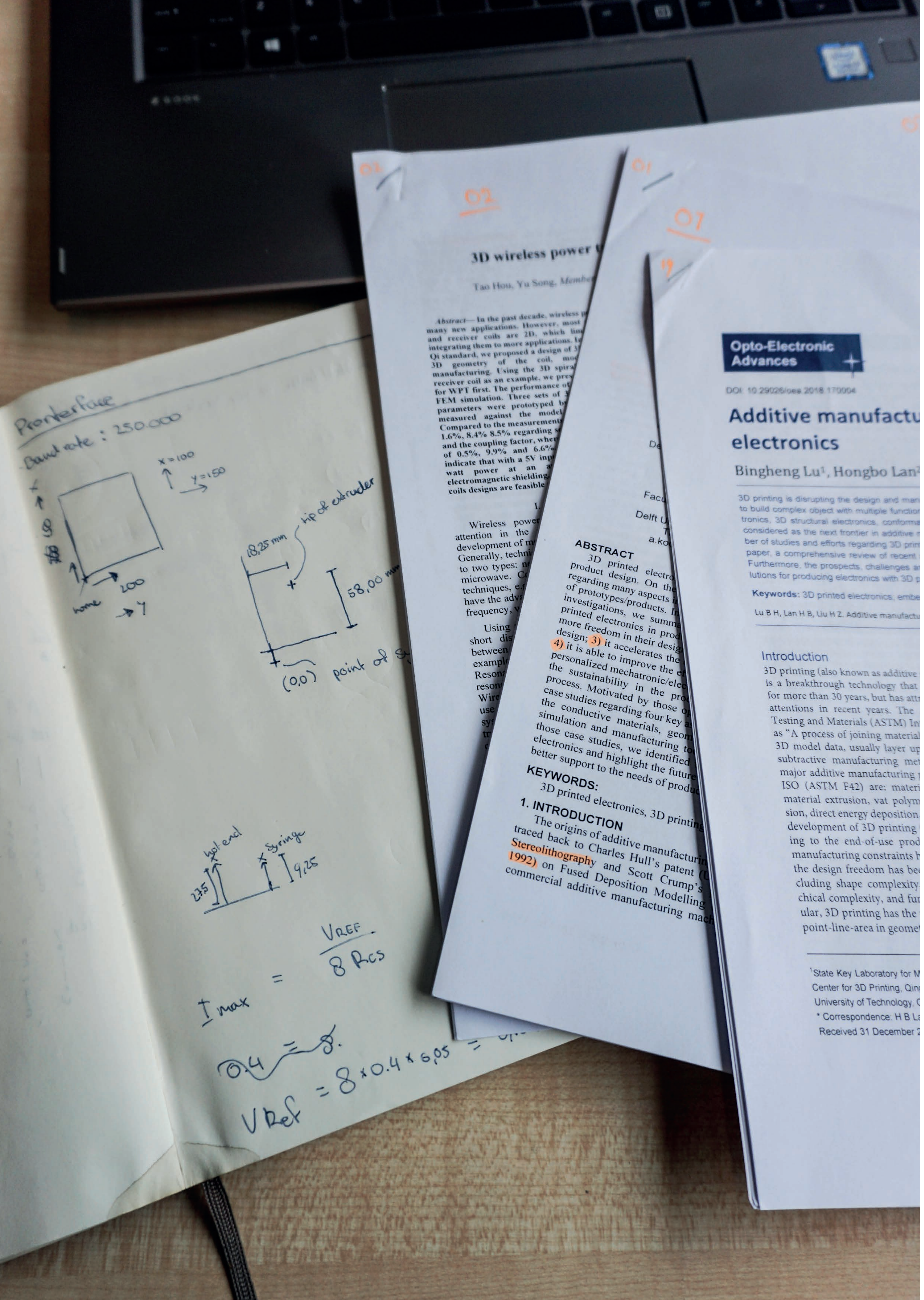
The first characteristic should be obvious that printing in 3 dimensions (3D) is paramount to creating 3 dimensional structural electronics.

The main goal for this project is to make 3D printing of structural electronics more accessible for more people. To achieve this the product has to be easy to use, meaning no specialized training or experience is required to operate it. Next to that its price needs to be accessible both the initial investment and the price of used material, characteristic two and three.

Next to the accessibility of the envisioned 3D printer the quality is also an important characteristic. The envisioned use for the printer is making quick and dirty prototypes to quickly test out ideas. The quality thus doesn't need to be as good as industrially manufactured products.

The envisioned printer can be compared to how a FDM 3D printer is used in product development. The prototypes that can be produced are useful for the shape and initial testing, but they will never reach the same material properties as a industrial manufacturing method, like injection molding. The same is true for the quality of the prototypes made by the envisioned printer.

Conclusion
To conclude the vision, the envisioned 3D printer has to be able to print in "3D" with a quality sufficient to use as prototypes. To be used for prototyping by a wide audience the envisioned product has to be easy to use and affordable.



2 Research

In this chapter the approach of the research are described. After that the reflow methods used in industry are discussed to see if there are usable methods for this project. After that a research into the solder paste, the target user group and the thermoplastics in FDM 3D printing is presented.

2.1 Approach

To achieve the goals stated in section 1.4, research has to be done into multiple different directions to get a better understanding of the different methods or technologies that can be used.

The first step in achieving 3D printed electronics is to achieve on-site curing per layer of printed solder paste in the printer itself. Solder paste is normally used in the industry to solder components to the solder pads of a PCB, this is called reflow soldering. There are different methods for reflow soldering used in the industry. To find the most suitable method for this project different methods for reflow soldering are discussed in the next section. Several viable options are selected that can move on to testing to see how they perform and how they fit with the requirements for this project.

Next the solder paste chosen in the previous master thesis of this project is discussed to understand the reasons for choosing this particular type. This type of solder paste will be used as the starting point of this research.

The electronics printer that is being prototyped also has a specific target user group. The needs and wishes of this user group are discussed here so that they can be taken into account during the project.

Lastly the thermoplastic that are used in 3D printing are discussed. The different properties are reviewed to have a clear overview for later referring back to.

2.2 Reflow soldering methods

Reflow soldering is a process that is currently used in large scale industrial PCB production. It works by applying solder paste on solder pads of a PCB after which the SMT components are placed in the desired locations onto the solder paste. This can be done either by hand or with a pick-and-place robot. When all SMT components are positioned on the board the PCB is sent to reflow soldering where the solder paste is heated, the solder paste reflows and solidifies when cooled down. This creates a solid solder joint between the PCB and SMT component

Different technologies can be used for reflow soldering, in the next paragraph the different methods are reviewed to find the most suitable for this project. A paper by Vivardi & Kasman [11] discussed multiple methods for reflow soldering. Their overview of different reflow soldering methods is used as starting point for this review. Additional methods are added so that they can be used to review the use case of the FDM 3D electronics printer (table 2.1).

table 2.1: Reflow soldering techniques ([1] Information in row from reference [8])

Method	Area Heated	Key Features
Convection Oven [1]	• Whole product	• Non-contact heating • Tight peak temperature control • Uniform heating across product • High throughput
Hot Bar/ Thermode [1]	• Area of contact and surrounding area through conduction	• Contact heating • Temperature control trough heating the nozzle (temperature sensor on nozzle) • Heat transfer dependent on surface area of contact • Thermodes wear with use
Hot Plate [1]	• Entire product through conduction from contact surface out to extremities	• Contact heating • Heating rate dependent on contact surface area • Heats from the “bottom” up
Resistance [1]	• Conductive material between electrodes	• Contact heating • Difficult temperature control • Performance partly dependent on contact area between part and electrodes
Soldering Iron [1]	• Point touched and surrounding area through conduction	• Contact heating • Heat transfer dependent on surface area of contact • Tips wear with use
Torch [1]	• Area of flame focus and surrounding area through conduction	• No physical contact, flame touches part • Available in very high energy capacity; with increased capacity comes increased flame size • Open flame ignites flammable materials
Focused Hot Air [1]	• Area defined by nozzle design, air dispersion, and conduction	• Non-contact heating • More local than convection oven • Tight temperature control
Induction [1]	• All conductive materials within inductive field and surrounding area through conduction • Field strength decreases with the square of the distance	• Non-contact heating • Available in very high energy capacity • Heats material with higher electrical resistance faster (e.g. steel faster than copper) • Field shape is a function of coil shape
Infra Red (IR) [1]	• Area of IR exposure and surrounding area through conduction	• Non-contact heating • Energy absorption is material dependent with metal being poor absorbers • Area of IR exposure can vary from as small as an 8mm spot to a theoretically unlimited area
Diode Laser	• Area of laser focus and surrounding area through conduction	• Non-contact heating • Area of focus can be as small as 0.6mm • Precise energy output control • Energy absorption is material dependent
Hot End	• Area of tip of hot end surrounding area through conduction	• Non-contact heating • Precise temperature control • Nozzle wears with use • Material must behave non-eutectic in order to be printed like thermoplastic

To review which of the methods for reflow soldering in this project the target user group must be kept in mind. The best overall method might not be the most fitting method for this project and its applications. That means that the 3D printer that is being build must be cost effective and easy to use.

Next the different reflow soldering methods are reviewed using the 3D printer in this project as a use case. After this review of the different methods we can see which methods are most promising and which will be chosen for further testing with the prototyped printer.

Conclusion

The conclusion of this section is found in table 2.2 on the next page. In this table all the different methods that can be used for re flowing and curing solder paste are judged for this particular use case and the last column shown which methods are seen as viable methods. Chosen for further testing are the thermode, laser diode and focused hot-air.

table 2.2: Review of different reflow soldering methods for the 3D printer use case

Method	Size	Ease of use	Price		Complexity	Contact with solder paste	Performance	Viable
Convection Oven	(-) Very large	(-) Time consuming to transfer workpiece to oven every layer	$$$		(-) Large machine needed, Printer in machine not viable	(+) Non-contact	(+) Even heat distribution through material	No
Hot Bar/ Thermode	(+) Small	(+) Just like printing, but without extruding plastic	$		(+) Small and compact uses existing heater outputs from printer	(-) Contact	(~) Nozzle get contaminated with solder paste, good temperature control.	Yes
Hot Plate	(+) Medium	(+) Print is already on heated print bed easy in operation	$		(+) Heated bed from printer can be used	(+) Non-contact	(-) Heats up from the bottom, will not work for layers higher up	No
Soldering Iron	(+) Small	(-) Difficult and time consuming when done by hand	$		(+)Simple equipment	(-) Contact	(-) Done by hand which is outside the scope of this project	No
Torch	(+) Small	(+) Easy to ignite and control	$$		(+) Simple equipment	(+) Non-contact	(-) Can work well, however thermoplastic are flammable	No
Focused Hot Air	(+) Small/ medium	(+) Easy to operate, set temp and airflow	$$		(+) Simple equipment	(+)Non-contact	(+) Hot air is relatively safe to work with	Yes
Induction	(~) Medium	(+) Easy to set and regulate current	$$$		(+) Simple equipment	(+) Non-contact	(-) Ferromagnetic material or coil needed	No
Infra Red (IR)	(~) Medium	() ?	$$$		(-) Complex/ high-tech equipment	(+)Non-contact	(-) Different colors absorb different amount of energy	No
Diode Laser	(+) Small	(+) Easy to set focus area and power with PWM/TTL signal	$$		(~) Complex/ high-tech equipment	(+)Non-contact	(+)Small focusing spot, can be controlled	Yes
Hot End	(+) Small	(+) Easy to set extrusion amount and temp control	$		(+) The existing equipment can be used	(-) Contact	(-) Earlier tests show that the flux in the solder paste wears out the nozzle really quick. [9]	No

2.3 Solder paste

Sn42/Bi57.6/Ag0.4 solder paste (Chipquick SMDLTLFP10T5) [12] was considered to be most effective by the previous master student for its low flow temperature and good conductive properties (see figure 2.2). The solder paste contains 42 % tin, 57.6 % Bismuth and 0.4 % Silver to ratio as metal compounds, and includes 86%wt metal, the rest being flux and other components. The solder paste melts at 138°C, which is lower than most thermoplastics used in 3D printing making it very suitable for this application.

The solder paste used by the previous graduate student in this project will be the starting point for my project. The first important aspect of the solder paste is the fact that it has to be lead free. The reason we are talking about this is because of the Restriction of Hazardous Substances directive. RoHS was adopted in February 2003 by the European Union; all electronics sold here must comply.

Solder paste has a shelf life of 6 months when refrigerated, and just 2 when kept at room temperature. This is a important property to take into account, the user will need to have a fridge or cool-box available for utilizing the maximum shelf life of the solder paste.

The solder paste has a low melting point due to the addition of bismuth. Without bismuth in the solder paste the melting temperature is above 200C making it harder to work with in this application. Most thermoplastic that are used in 3D printing become very soft above 200°C.

In figure 2.1 the reflow diagram for the Sn42/Bi57.6/Ag0.4 solder paste is shown. The maximum temperature during reflow is 165° which is more than 25°C above the melting temperature of the solder paste (138°C).

figure 2.2: The packaging of the currently used solder paste, packaged per 35 grams in a syringe.

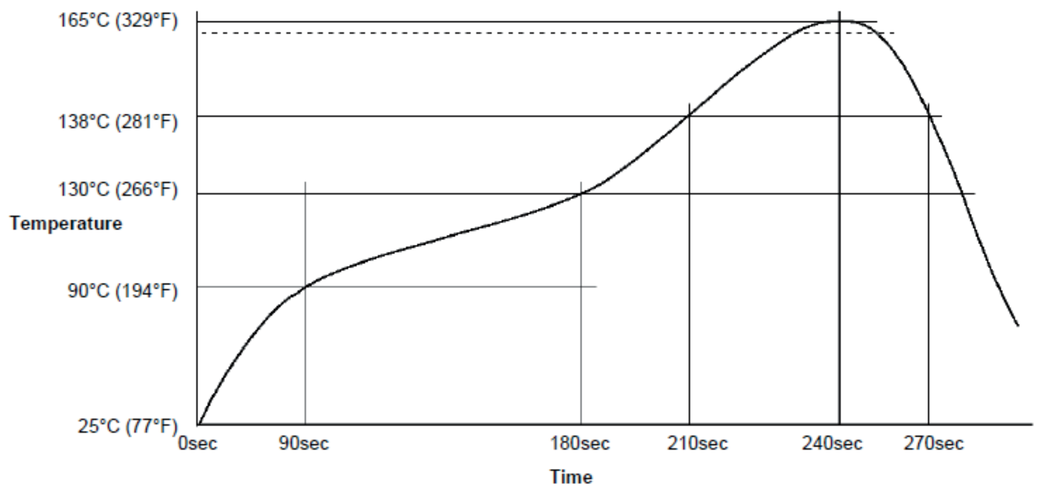


figure 2.1: The reflow diagram for the Sn42/Bi57.6/Ag0.4 solder paste.

2.4 Target group

The main goal of the 3D electronics printer that is being developed in this project is to make 3D printing electronics more accessible. Making electronics 3D printing more accessible means multiple things in this project. Firstly the printer has to be affordable so that universities and smaller companies can actually afford to buy it and start using it, both initial investment and the price of consumables is important here. Affordable is in the price range €5.000-10.000 initial investment.

Secondly the way of controlling the printer has to be accessible. If there is complicated software needed to operate the machine it hinders the users in using the machine to its full potential. The printer should be controlled by slicing software which is similar to currently used slicing software (Cura, Slic3r, Simplify3D).

Thirdly the printer has to be safe to work with and not require extra processing steps after printing, like most resin printers need washing and curing after printing to result in a usable part.

The user target group is students and designers to bring the 3d printing of electronics to a bigger audience. Currently there are 3D electronics printers on the market as discussed in section 1.2. The printers that are currently able to 3D print designs with integrated electronics are very expensive and thus not available to a large group of designers.

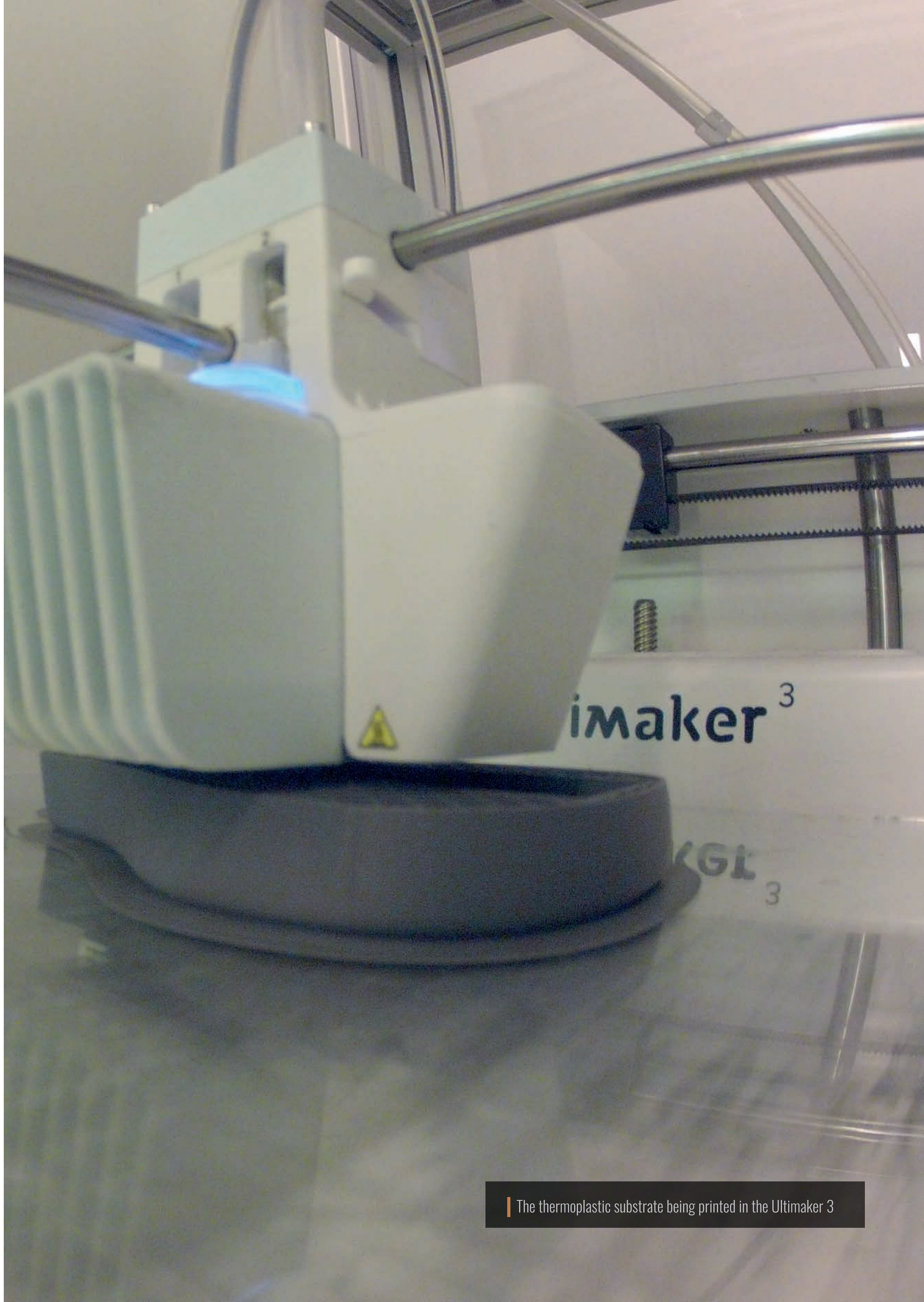
2.5 Thermoplastic

The thermoplastic material used by the previous student was PLA-X3 which is a heat resistant PLA that can be annealed in the oven at a certain temperature to create properties close to ABS. This material was chosen to withstand the heat without warping/deforming of the convection oven which was used for curing the solder paste.

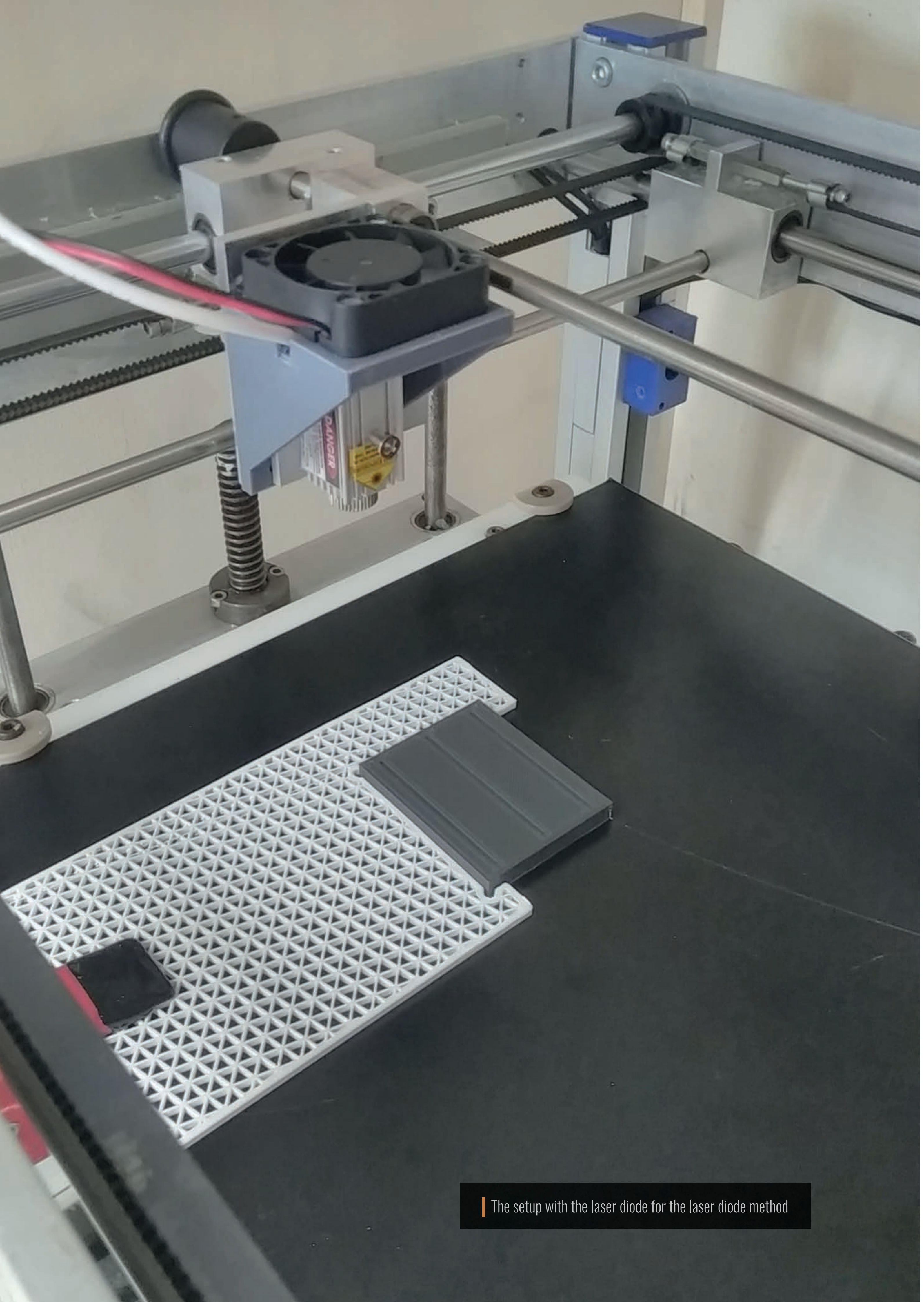
With other methods for curing the solder paste with more locally applied heat, the need for this special heat resistant type of filament might not be needed anymore. Other materials can be tested to see if the localized heating of the solder paste works with regular PLA, ABS and PETG. These types of plastic are most frequently used is FDM 3D printers.

table 2.3: Different types of thermoplastic used in 3D printing with their printing temperatures and melting temperatures

Type of thermoplastic	Printing Temp	Melting Temp
PLA	190 - 210 C	130 - 180 C
PET-G	220 - 250 C	260 C
ABS	220 - 260 C	-
PLA-X3	220 - 240 C	190 - 220C



The thermoplastic substrate being printed in the Ultimaker 3



The setup with the laser diode for the laser diode method

3 Testing of methods

Research resulted in three promising methods for curing the solder paste on-site. These methods are tested in the printer to see which of them would work the best in real life. First the setup of the tests is discussed after which the testing of each of the three methods is discussed. At the end of the chapter the three methods are reviewed and the best method is chosen.

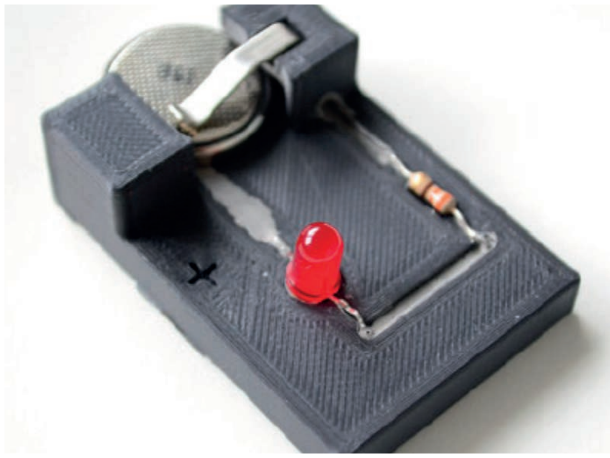


figure 3.1: The results of curing the solder paste in a convection oven from the previous master thesis research by M. Bon.

3.1 Test setup

The setup for testing the three promising methods found in section 2.2 is as follows. For each methods a test setup was build (see figure 3.2). For each method different tests were conducted change a different parameter each time to see which is a conductive trace comparable to the results (see figure 3.1) of curing in a convection oven which was used in the previous master thesis research by M. Bon.

The thermoplastic material used in the tests is PLA x3 (or PLA-HT as its sold elsewhere) like recommended by the previous master student M. Bon. Later also regular PLA is tested to see if the localized heating has less effect on warping.

The solder paste used is Sn42/Bi57.6/Ag0.4 solder paste (Chipquick SMDLTLFP10T5) as recommended by the previous master student (M. Bon). The solder paste is chosen for it low melting point so it can melt without the plastic substrate melting as well.

After multiple tests with each methods the best method was chosen, a full test logbook van be found in appendix B.

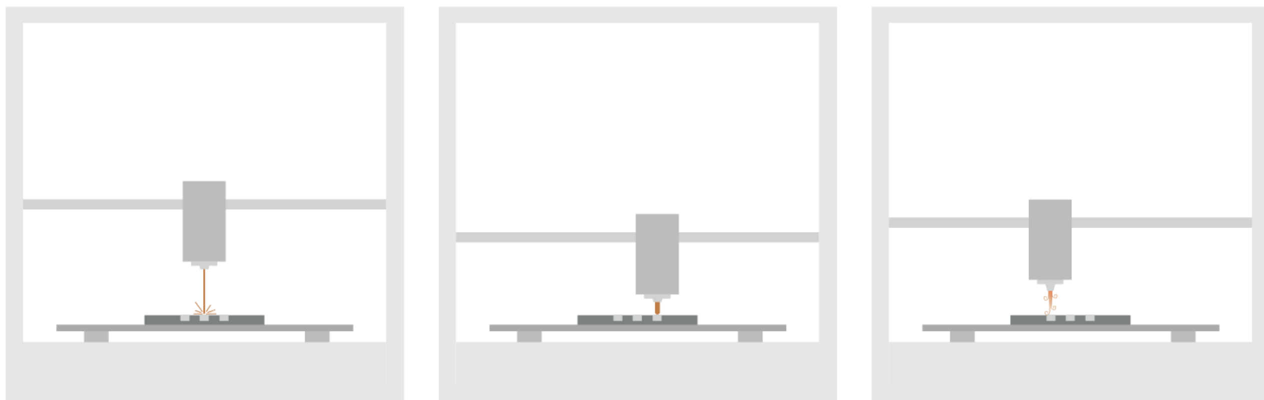


figure 3.2: A schematic overview of the three test setups built for testing. From left to right, the laser, the thermode and the hot air method.

3.2 Thermode method

The thermode is actually just a blind nozzle which is mounted in the hot end of the printer (see figure 3.3) which can be heated to a desired temperature. The nozzle than moves over the dispensed solder paste line like a clothes iron and heats the solder paste by conducting heat into it.

Thermode parameters that can be changed are the movement speed of the head of the printer and the temperature of the thermode rod.

The first test posed some problems with the solder paste cured on the thermode rod pushing all the solder paste from the channel leaving a messy result (see figure 3.4).

For further tests the thermode rod was wrapped in PTFE (teflon) tape to prevent sticking, teflon is stable up to 260C. The result was that the solder paste was not sticking to the thermode rod anymore (see figure 3.5).

With no more solder paste sticking to the tip of the thermode the solder paste stayed in the channel to be cured. In figure 3.6 the result of the following test can be seen. The thermode rod pushes the solder paste next to the channel and does not fully cure the solder paste. The fact that the solder paste does not fully cure could be because there is no room for the flux to evaporate from where the thermode tip is on top of the channel.

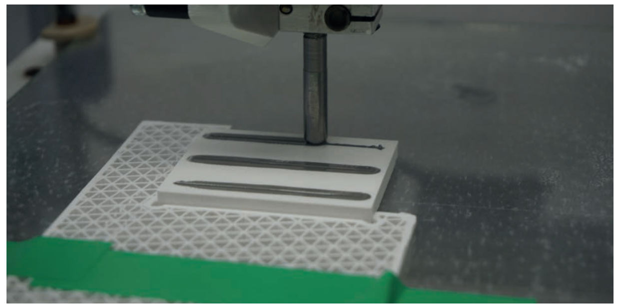


figure 3.3: The hot-end of the 3D printer with the metal rod which act as a blind nozzle.

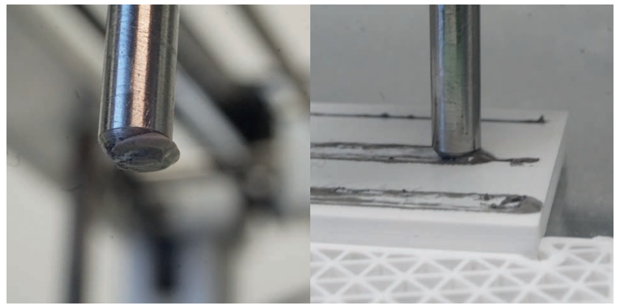


figure 3.4: Solder paste curing on the thermode rod and pushing the solder paste out of the channel.

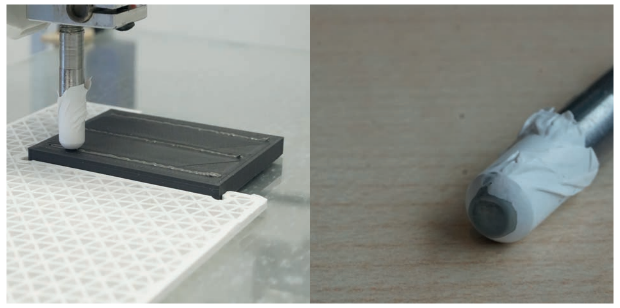


figure 3.5: The thermode rod with the PTFE tape, (left) and the tip of the thermode rod after curing (right).

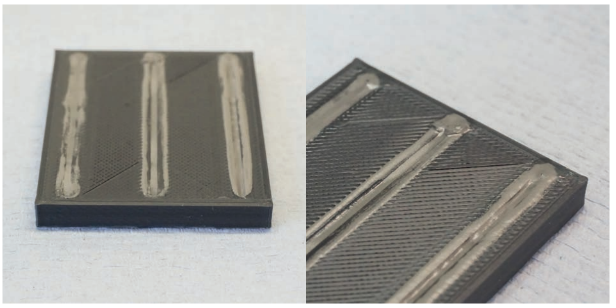


figure 3.6: The result of the last test with the thermode method.

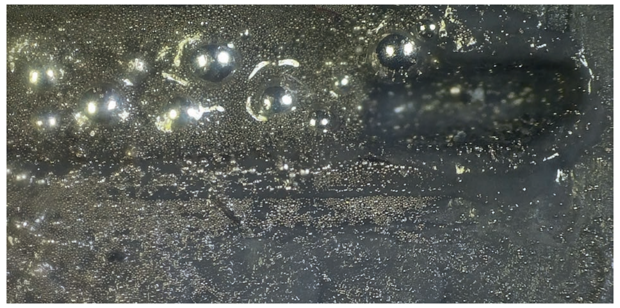


figure 3.7: Close up of one of the samples, the small focus area burns a scar in the sample but does not fully cure the solder paste.

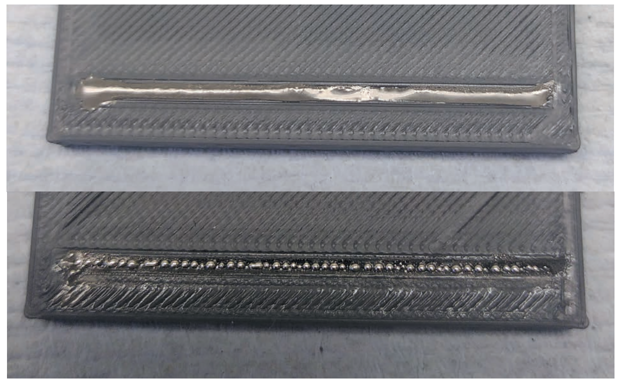


figure 3.8: Samples with the results of further test with a larger focal area.

figure 3.9: Final results with uncured solder paste and solder balls.

3.3 Diode laser method

The diode laser method utilizes a 2.8W 445nm diode that is mounted in the printer. The laser is focused on the solder paste in the channel and heats up the solder paste. The intensity, movement speed and the focus area of the laser can be adjusted.

First tests were done with a small focus area and a constant speed of F100 increasing the intensity of the laser from 40/255 up to 210/255 (see figure 3.10). From this test it became clear that the focus area of the laser concentrated the heat too much and burned a scar in the plastic substrate (see figure 3.7).

Further tests were done with a larger focal area to spread the energy of the laser over a larger area and thus heat up the solder paste slower, as well ass prevent burning the thermoplastic substrate. Further test results can be seen in figure 3.8. The larger focal area did not leave burn scars in the substrate material but the solder paste did not cure as desired, either the solder paste stayed liquid or bigger solder paste balls formed. Adjusting the setting to further to heat up the solder paste slower resulted in cured solder balls and uncured solder paste (see figure 3.9). No usable results were found using this method.

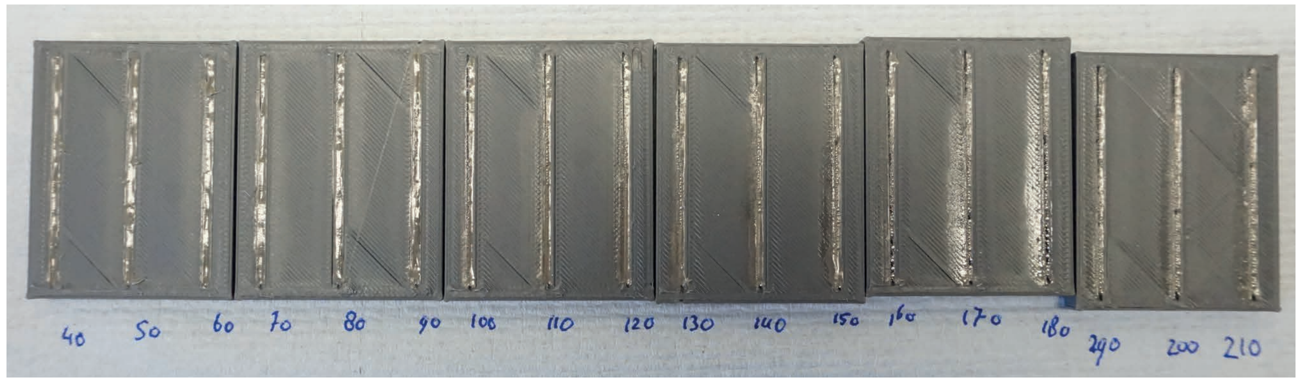


figure 3.10: The tests done with laser intensity from 40/255 to 210/255

3.4 Hot air method

The hot-air method uses a small hot-air gun which is focused on the solder paste in the channel. The first tests were done with a hand-held hot air gun to see if and how the solder paste would cure. In figure 3.11 the first result can be seen where the solder paste was blown out of the channel. This test showed that a low air flow was needed to keep the solder paste inside of the channel.

After lowering the airflow more tests were done but here another problem arose. The high temperature caused the solder paste to cure and form large balls in the channel as can be seen in figure 3.12.

After lowering the airflow and the temperature sufficiently the results looked similar to the results with curing in the convection oven. The results can be seen in figure 3.13. The solder paste is fully cured and forms a solid trace in the channel and is conductive.

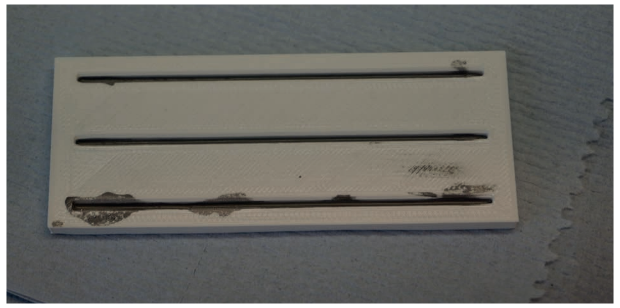


figure 3.11: First test with hand held hot-air gun.

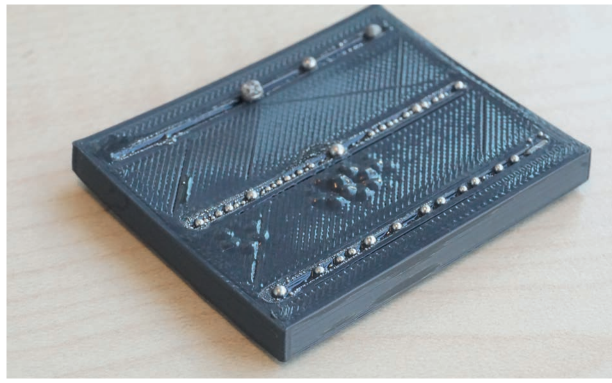


figure 3.12: Test results with high temperature, big solder balls are formed and the sample is warped.

figure 3.13: Later test where the right temperature and air flow were used with good results.

3.5 Comparison of methods

In the previous three sections a summary of the testing for each method was shown and in this section the best method for continue further with is chosen. The obvious method to continue with is the hot-air curing method as it was the only method which produced usable results. Nevertheless the methods are still compared on their pros and cons for the product vision for this project.

Ease of use

When the three methods are scored on ease of use there are several factors that must be considered. First the actual operating of the method. All three methods can be controlled via G-code through the motherboard of the 3D printer and because of this are similar in usability.

Secondly the safety precautions that have to taken to use the method. The class IV diode laser is considered to be the worst. There are risks of serious eye damage as well as igniting the thermoplastic substrate material when focused in one stop for a long time.

The thermode is similar to a regular 3D printer hot-end, the thermode itself heats up to 155 °C and can cause skin burns when touched.

The hot air gun is similar to the thermode, the outer part of the hot-air gun can be insulated to prevent skin burns. The hot air that exits the nozzle cools down quickly after leaving the nozzle with minimal chance of skin burns.

Cost

Another important part of the method is the cost. Following the product vision in section 1.5 the future printer has to be cost effective in initial investment.

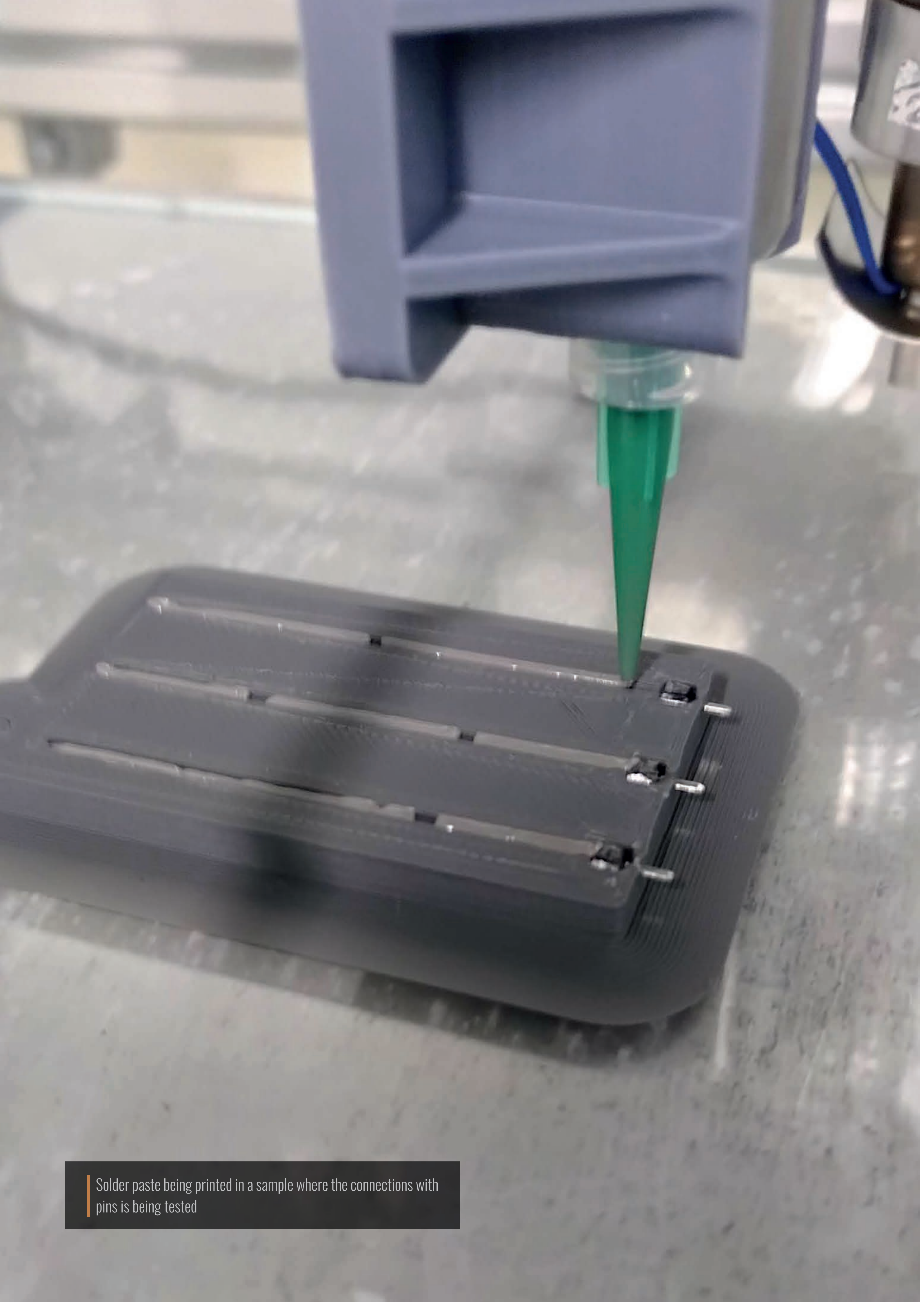
The thermode is the cheapest option (~€65) only requiring a heating block with heating cartridge and thermistor, similar to a regular FDM hot-end but without needing to feed thermoplastic filament through the nozzle.

The hot-air gun similar in price (~€65) comparable to an additional hot-end of an FDM 3D printer. Which can be argued to be within a reasonable price range.

The laser diode is most expensive (~€350) when taking into account that additional safety measures have to be integrated into the 3D printer adding to the cost of the 3D printer.

Conclusion

To conclude this section, the hot-air curing method was the only method that produced usable results and will thus be chosen to continue with. When taking the other factors like ease of use and price into account the hot-air gun still scores close to the top with the thermode, with the laser scoring lower due to cost and safety measures.



Solder paste being printed in a sample where the connections with pins is being tested

4 Architecture of the system

In this chapter the architecture of the system used in printing thermoplastic and printing and curing solder paste is presented. First the overview of the system is discussed after which the separate parts of the system are discussed in detail.

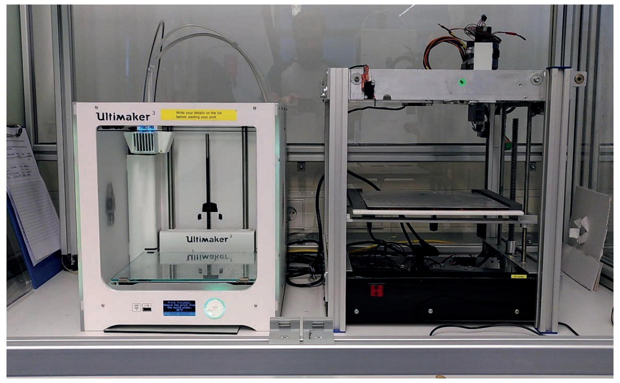


figure 4.2: The Ultimaker 3 (left) for thermoplastic extrusion and the DIY printer (right) for solder paste extrusion and curing.

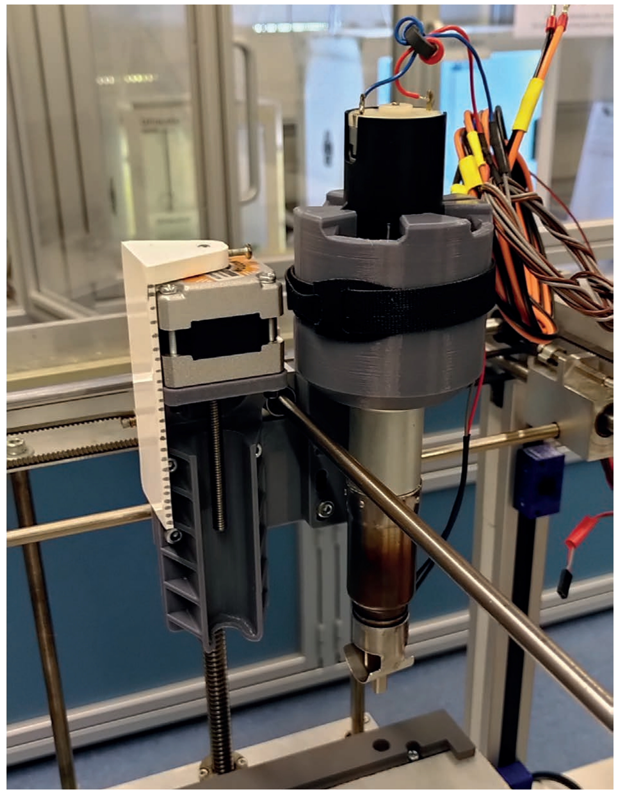


figure 4.1: Closeup of the DIY printer print heads, the solder paste extruder (left) and hot air gun (right).

4.1 System overview

The overall architecture of the system consists of a combination of two 3D printers (see figure 4.2). One part, the printing of thermoplastic is done in an Ultimaker 3. The other steps, printing and curing the solder paste are done in a DIY printer build at this research lab. The DIY printer includes the solder paste dispenser and the focused hot air gun for curing (see figure 4.1). The build plate is manually moved between the two printers when switching from printing thermoplastic to printing and curing solder paste.

4.2 Thermoplastic extruder

To 3D print the thermoplastic a Ultimaker 3 is used (see figure 4.3) with a 0.4mm AA printing core during this experiment. Any well working FDM style 3D printer would work equally well. The filament used is 2.85mm HT-PLA (PLA-x3).

4.3 Pick and place

After printing several layers of thermoplastic substrate the components need to be placed in the design in order for the solder paste to be printed over the leads of the component and cured in place to form a conductive interface between the leads an the solder paste. Pick and place is done by hand in this system to simplify the system, an example of how this is done is seen in chapter 7 where the making of a demonstrator product is described. Pick and place solutions exist like described in section 2.2.4. It is therefore viable that these solutions can be integrated in a machine together with thermoplastic and solder paste extrusion and focused hot air curing.

figure 4.3: The dual extrusion head of the Ultimaker 3

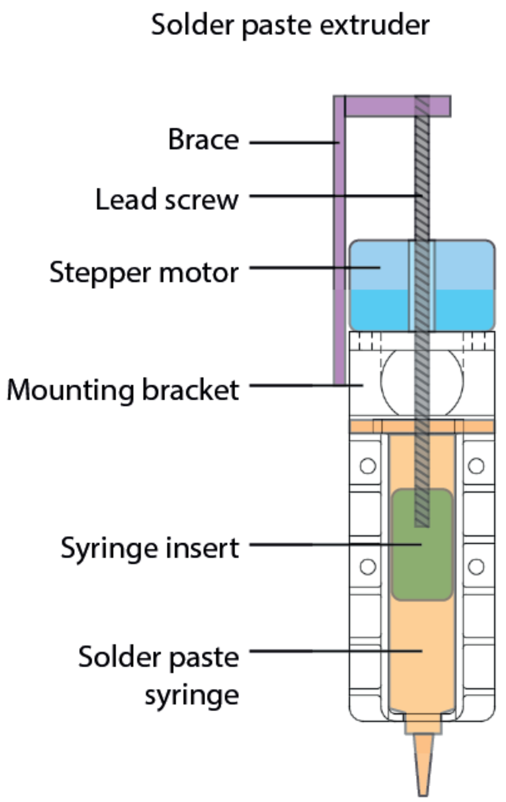


figure 4.4: Schematic view of the solder paste extruder.

4.4 Solder paste extruder

The solder paste extruder is based around a syringe the solder paste is packaged in. The solder paste syringe is mounted vertically in a mounting bracket (figure 4.4). The solder paste is pushed out by a stepper motor via a lead screw through its center. The stepper motor rotor has a threaded hole in its center through which the lead screw can move. The rotation of the lead screw is restricted by a brace which can move along the side of the stepper motor. This configuration provides linear vertical motion of the lead screw when the stepper motor moves. The stepper motor has 200 steps per rotation and the pitch of the lead screw is 2*1mm per rotation which results of a resolution of 0.01mm vertical motion per step of the stepper motor. The stepper motor is controlled by the motherboard of the 3D printer in a similar fashion to a filament extruder in an FDM 3D printer.

4.5 Hot-air gun

Curing is done with focused hot air from a hot air gun. The hot air gun is mounted vertically in the 3D printer and consists of a metal tube housing a heating cartridge through which air flows to the nozzle on the bottom. The air is pushed through the heating cartridge with a radial fan (see figure 4.5). The temperature of the airflow is measured of the inside of the barrel close to the nozzle with a 100K thermistor. The temperature is controlled with a PID controller which is integrated in the motherboard of the 3D printer. This works in a similar fashion to heating up the hot end of the nozzle of a 3D printer. The nozzle of the hot air gun is square and 8x8mm in dimension.

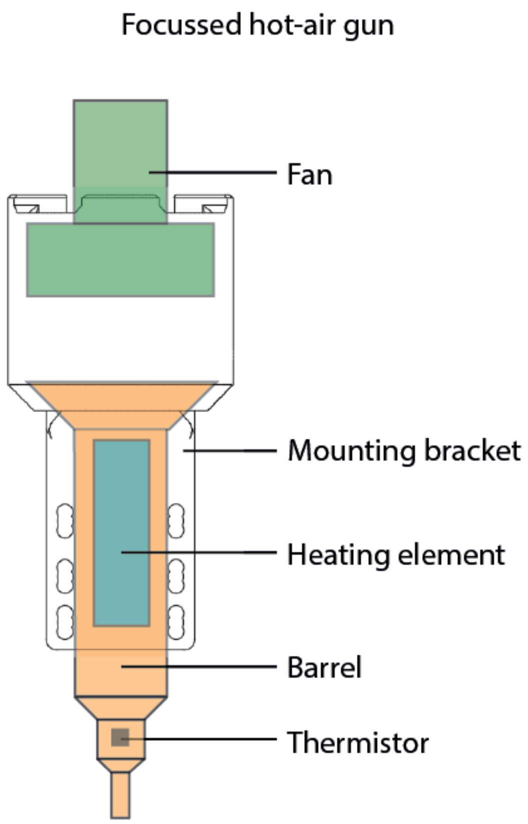


figure 4.5: Schematic view of the hot-air gun

The focused hot-air gun print head

All test samples used in the testing phase

5 Hot-air curing detailed testing

In this chapter the capabilities and limitations of the hot-air curing methods are further researched and discussed. Firstly the integrating printing and curing of solder paste is tested. After which several capabilities like minimum line pitch, overlapping solder paste traces and connecting components are tested and discussed. And lastly the resistivity of the printed traces is discussed.

5.1 Integrated testing

The first step in continuing with more detailed testing of the hot air curing method, the hot air gun and solder paste extruder need to be integrated into the same 3D printer and controlled by Gcode. The results of the first test can be seen in figure 5.1. The traces of solder paste are fully cured and conductive.

figure 5.1: Test results with integrated solder paste printing and hot-air curing.

5.2 Overlapping traces

To achieve full 3D capabilities the printer has to be able to print overlapping lines of solder paste which have to be conductive at the interface where they overlap. In figure 5.2 the two steps of printing overlapping layers can be seen. The part has three different length overlaps, 2mm, 4mm and 6mm, from top to bottom respectively.

These different length overlaps are chosen to see if they effect the conductivity of the interface between the overlapping layers. All of the three lines were conductive so a 2mm overlap is sufficient for a conductive interface.

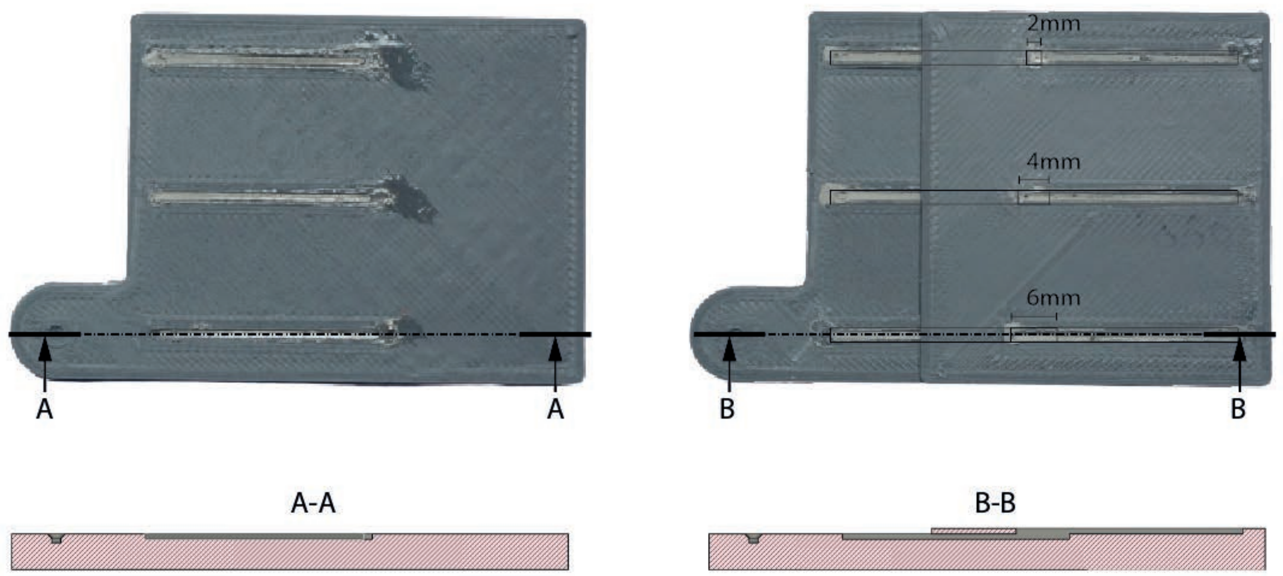


figure 5.2: The first part printed with the first solder paste trace printed into the channel (left) and the second part printed with the overlapping solder paste trace printed over top.

5.3 DIP trace pitch

To utilize this method for creating prototypes an minimum usable pitch between lines has to be chosen. A DIP pitch of 2.54mm or 1/10 inch is chosen because of its wide application in prototyping electronic components.

In figure 5.3 the results of this test can be seen. On the left the DIP pitch can be observed. The zoomed in figure shows no deformation of the thermoplastic substrate between the solder paste traces.

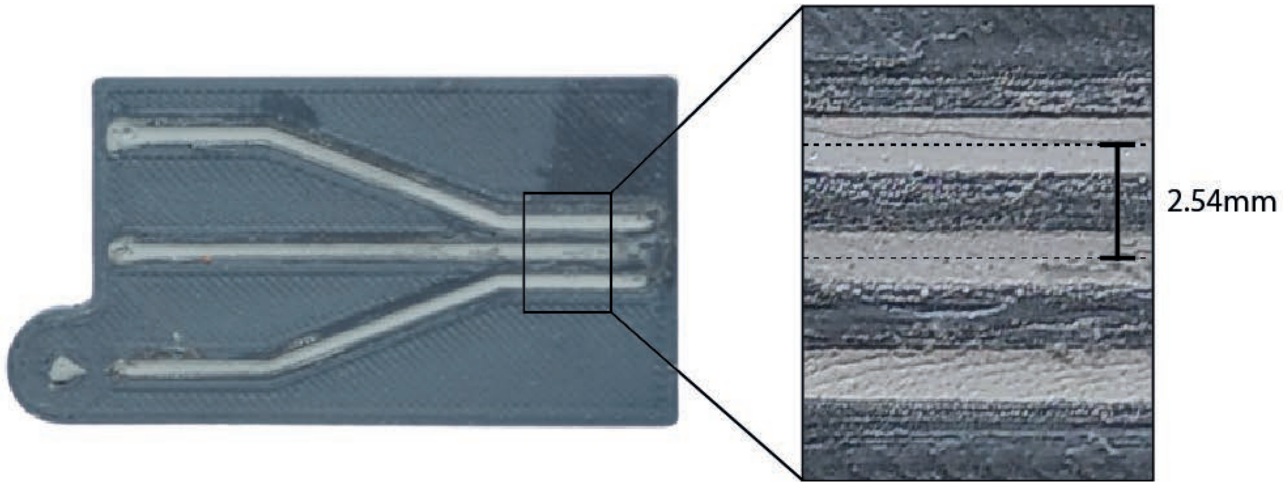


figure 5.3: A sample with DIP pitch on the left side of the sample (top) and a zoomed in view (bottom).

5.4 Connecting components

Another important part of using this method for prototyping purposes is the ability of connecting components with each other with solder paste traces. The solder paste can be printed over the leads/pins of a component and than cured to form a conductive interface between the pin and the solder paste trace.

In figure 5.4 a step by step approach can be seen. First (1) the thermoplastic substrate is printed with recessed space for pins after which (2) they are placed in the recessed spaces. Then (3) more thermoplastic layers are printed with a recessed channel which overlaps the pin below after which (4) the solder paste can be printed and cured in the recessed channel forming a conductive interface between the pin and the trace.

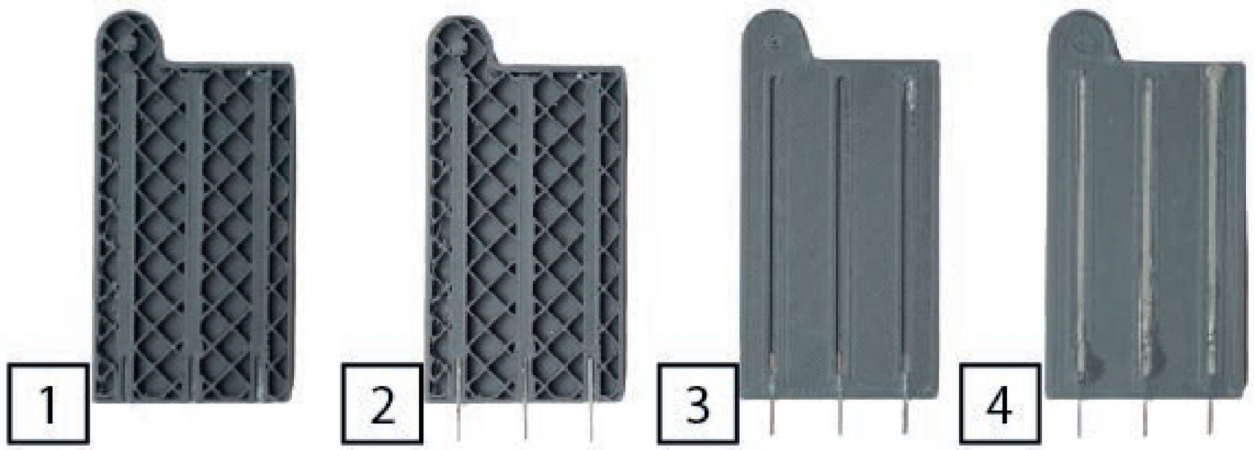


figure 5.4: The sample with channel printed over the leads of the component (top) and the solder paste printed and cured over top (bottom).

5.5 Resistivity

The channel with the cured solder paste, and microscopic images of its surface and a cross section can be seen in Fig.16, the cured solder paste is not a solid metal trace but rather small metal balls tightly packed together. In Table 3 the resistivity of the printed trace is presented where the resistivity of the conductive filament (Proto-Pasta conductive filament) and the jumper wire with copper core are used as reference. The resistivity of the trace was measured over a 45mm trace, and the values for the conductive filament and the jumper wire are both from literature. It can be seen that the difference between the printed solder paste and the jumper wire of the same length differs with an order of magnitude in favor of the jumper wire. The conductive PLA filament has a resistance which is 5000 times greater than the printed solder paste which is outside of the usable range. In 3D printed electronics, a low resistivity or high conductivity of the trace is desirable, as a high resistance often result in high energy consumption and in the generation of heat. This is especially true for 3D prints, as the Tg of the PLA is lower than that of conventional plastics, e.g. PP, PVC.

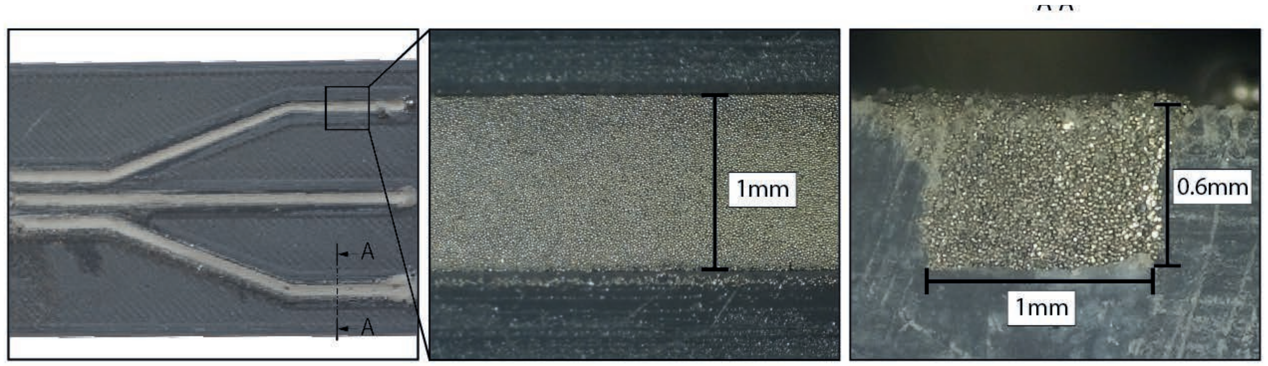
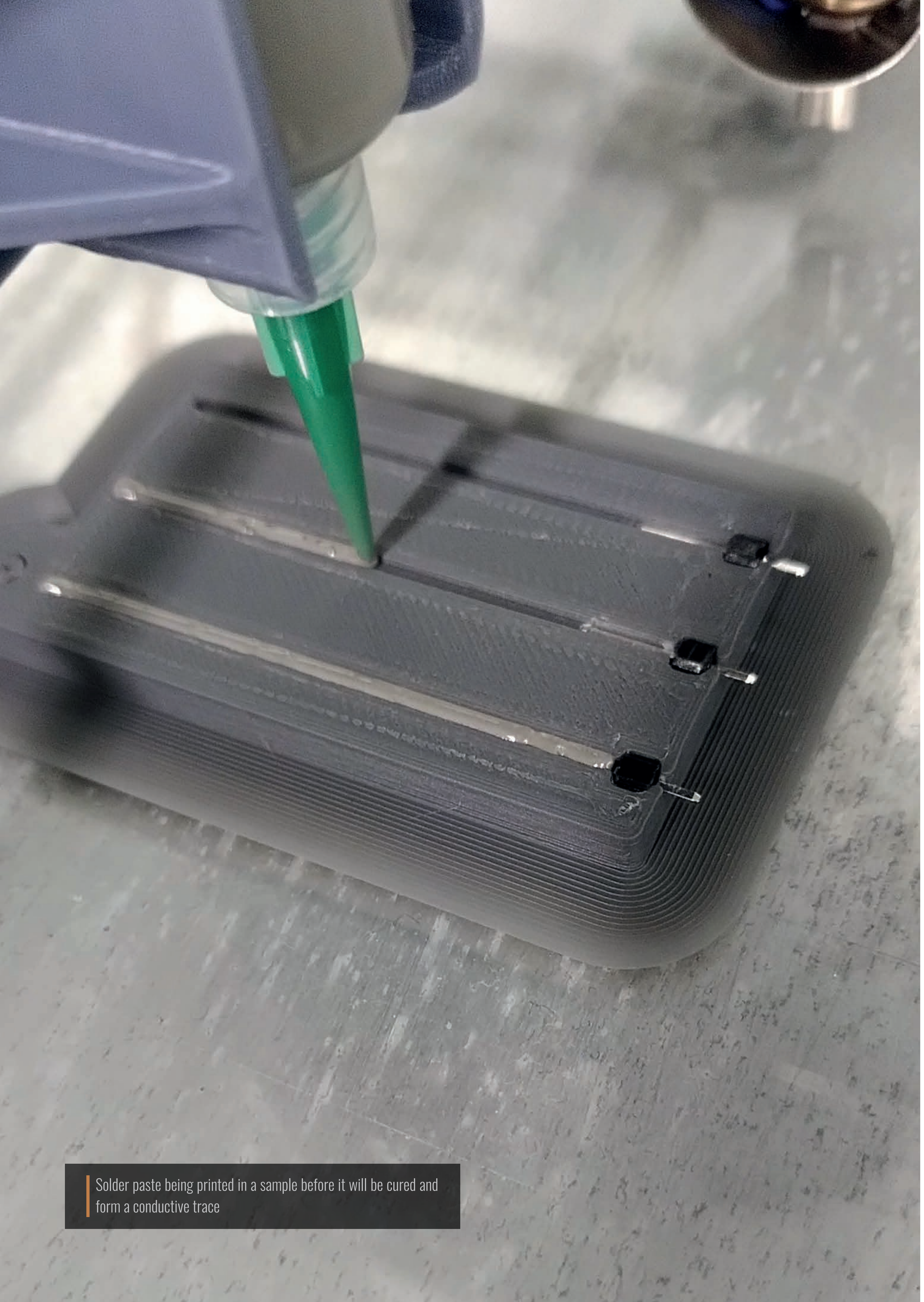


figure 5.5: Overview of a sample with microscopic image of top of the solder paste trace and a microscopic image of the cross section of the solder paste trace. The microscopic images show the micro-structure of the cured solder paste trace.

table 5.1: Properties of different conductive materials used in prototyping.

Type of conductive material	P (Ω.mm)	A (mm²)	L (mm)	R (Ω)
Printed solder paste	~$6.7 * 10^{-3}$ - $6.7 * 10^{-2}$ (measured)	0.6	45	~0.5- 5.0 (measured)
Jumper wire (copper core)	$1.68 * 10^{-5}$ (from literature)	0.14	45	$5.4 * 10^{-3}$ (from literature)
Electrifi filament	$6.0 * 10^{-2}$ (from literature [9])	0.6	45	4.5 (from literature)
Silver paste	$3.0 * 10^{-4}$ (from literature [12])	0.6	45	$2.25 * 10^{-2}$ (from literature)
Conductive PLA filament	$3.0 * 10^{2}$ (from literature [8])	0.6	45	$2.25 * 10^{4}$ (from literature)



Solder paste being printed in a sample before it will be cured and form a conductive trace

6 Design guidelines

This chapter will describe the design guidelines for using the developed methods of printing and curing solder paste as conductive trace in a 3D printed thermoplastic substrate. These guidelines can be used for creating new designs and for further testing.

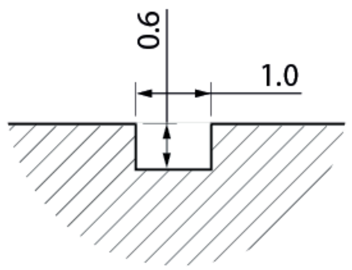


figure 6.1: A schematic cross section of the channel that is made for the conductive trace. Dimensions in mm.

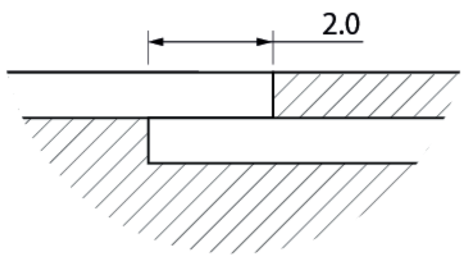


figure 6.2: Cross section of the overlap between a pin or trace below and a channel with solder paste that is printed over top. Dimensions in mm

6.1 CAD design of thermoplastic substrate

When printing a prototype with integrated structural electronics the first step is to design the prototype so that is can accommodate the components and solder paste traces.

The design of the channel

The substrate must accommodate space for the solder paste to be printed and cured in to form a conductive trace. The channel has specific dimensions which can be seen in figure 6.1 which are needed for good printing and curing in later steps.

Overlap with underlaying pin/trace

In case the conductive trace is connected to another trace or pin underneath there is a 2mm overlap needed so they can create a conductive interface in the vertical direction. In figure 6.2 a cross section from the side is seen where room for a pin or another conductive trace is seen and the channel in which the overlapping conductive trace will be printed.

Room for components

When placing components in the designed part it has to be taken into account that they have be placed beneath the printing layer, otherwise a collision between the nozzle of the 3D printer and the placed component can damage the design. In figure 6.3 a cross section can be seen showing how the component needs to be placed in the design to avoid collisions.

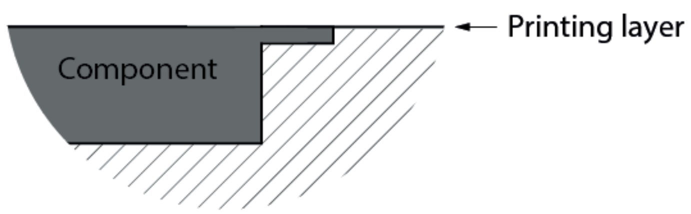


figure 6.3: Placing components in the design underneath the printing layer

6.2 CAM design

When the design for the prototype is made in CAD the CAM process has to be prepared.

Thermoplastic print

The thermoplastic print is 3D printed with the Ultimaker 3 and is sliced with Cura to make the Gcode for the 3D printer. The code has to be modified after to make to make the printer pause at when a component needs to be placed or when the build plate needs to be moved to the solder paste printer. The command M25 can be inserted in the G code when the printer needs to pause.

Printing solder paste

The G code for printing and curing the solder paste is written by hand. First the nozzle is moved to the start of the trace that is printed. Then the solder paste nozzle needs to be primed by compressing the solder paste (E3.0). Now the nozzle can move and extrudes E0.01 per mm of line. At the end of the line the decompressed by using E-3.0. This example shows only a straight line, for every line segment the E movement needs to be defined.

Curing solder paste

The solder paste is cured by passing over it twice with the hot air gun. The fan is started at 50% power (M106 S123) and the hot air gun heated up to 155°C (M109 T0 S155) after which it can start curing. The first pass is 10mm above the sample (Z10.0) at 100mm/min (F100). After the first pass the hot air gun moves around the sample back to the start of the trace. The second pass is 5mm above the sample (Z5.0) at 30mm/min (F30). When curing solder paste over pin from components or other solder paste trace the second pass moves at 15mm/min (F15) because the extra thermal mass of the pin or trace also heats up slowing the curing process.

figure 6.4: The result of printing and curing solder paste using the example Gcode.

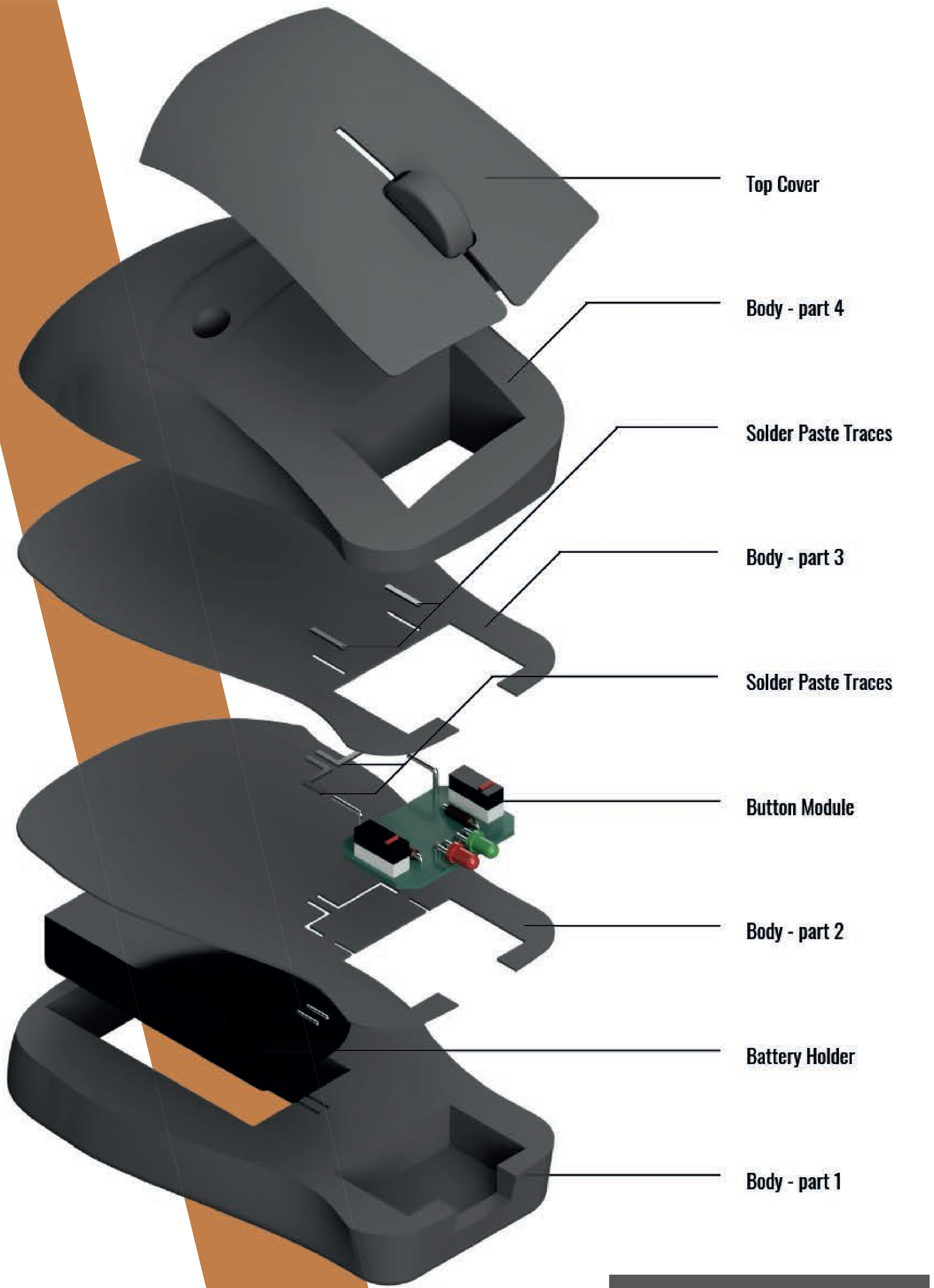
```
;INITIALISATION
T0                              ;use tool 0
G21                             ;metric values
G90                             ;absolute positioning
G28 X0 Y0                       ;move X/Y to min endstops
G28 Z0                          ;move Z to min endstops
G92 E0                          ;reset extruder

;PRINTING SOLDER PASTE
T1
G1      X26.25   Y6.0     Z3      F1000           ;move to start of sample
G92     X0       Y0                               ;set as new home point to start printing
M83                                               ;E stepper relative positioning
;print line 1
G1      X0       Y0                       F1500
G1                        Z0
G1                                E3.0    F200
G1      X0       Y45              E0.45
G1               Y50      Z2.0    E-3.0   F1500
;print line 2
G1      X15      Y0                       F1500
G1                        Z0
G1                                E3.0    F300
G1      X15      Y45              E0.45   F200
G1               Y50      Z2.0    E-3.0   F1500
;print line 3
G1      X30      Y0                       F1500
G1                        Z0
G1                                E3.0    F300
G1      X30      Y45              E0.45   F200
G1               Y50      Z2.0    E-3.0   F1500

;CURING SOLDER PASTE
G1      X-26.25 Y-6.0
T0
M106    S123
M109    T0       S155
M400                              ;Run all code before continuing
G1      X0       Y0
;Line 1
G1      X0       Y0       Z10     F1500
G1      X0       Y50              F100
G1      X0       Y75              F1500
G1      X-25     Y75
G1      X-25     Y-25     Z5
G1      X0       Y-25
G1      X0       Y0
G1      X0       Y50              F30
G1      X0       Y75              F1500
G1      X-25     Y75
G1      X-25     Y-25
;print line 2
G1      X15      Y-25     Z10
G1      X15      Y0
G1      X15      Y50              F100
G1      X15      Y75              F1500
G1      X-25     Y75
G1      X-25     Y-25     Z5
G1      X15      Y-25
G1      X15      Y0
G1      X15      Y50              F30
G1      X15      Y75              F1500
G1      X-25     Y75
G1      X-25     Y-25
;print line 3
G1      X30      Y-25     Z10
G1      X30      Y0
G1      X30      Y50              F100
G1      X30      Y75              F1500
G1      X-25     Y75
G1      X-25     Y-25     Z5
G1      X30      Y-25
G1      X30      Y0
G1      X30      Y50              F30
G1      X30      Y75              F1500
G1      X-25     Y75
G1      X-25     Y-25

;ENDING
M400             ;Run all code before continuing
M104 S20         ;hot-air temp to 20C
G91              ;relative positioning
G28 X0 Y0        ;move to x and y endstops
G1 Z100   F500   ;move bed down
M84              ;Disable steppers
```

An example of Gcode for the solder paste printer, this example prints 3 45mm long traces



Exploded view of the demonstrator model

7 Demonstrator

To showcase the capabilities of the method developed to use solder paste as a conductive material in a FDM 3D printer a demonstrator product is designed and made as a showcase. The product chosen is a computer mouse design showcased in the master thesis of B. Kromhout [13] about mass production of mass customized products using FDM 3D printing.

figure 7.1: The first part of the demonstrator printed with room for the battery holder.

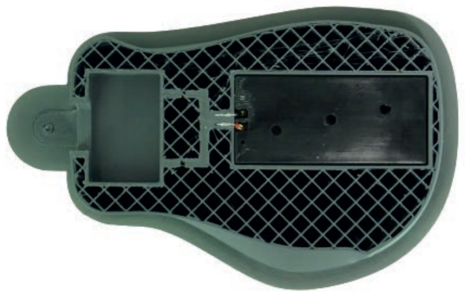


figure 7.2: The battery holder inserted into the demonstrator.

figure 7.3: The next layer of plastic with two recessed channels for solder paste and two small channels for the leads of the button module.

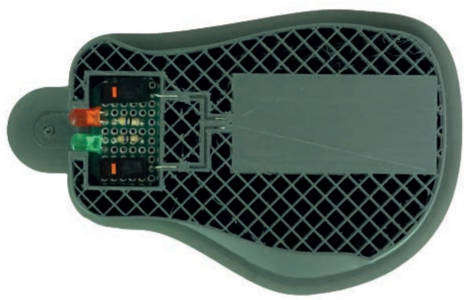


figure 7.4: The button module place in the demonstrator with the leads in the two recessed channels.

The computer mouse is designed to be a dummy and not a fully working product. The dummy mouse consists of a battery holder and a separate module with buttons and LED's inside a plastic body. Both modules are connected with each other by conductive solder paste traces. The demonstrator is printed with the two printers described in chapter 4.

The first step is printing the base of the model with a recessed space for the battery holder and the leads from the battery holder (see figure 7.1). Here the print is paused so the battery holder can be placed by hand (see figure 7.2).

The next step is continuing with printing the next couple of layers of thermoplastic (see figure 7.3). These layers have a recessed channel for the first solder paste line which prints over the leads of the battery holder. On the other side there are two small recessed channels for the leads of the button module. The build plate is now moved to the solder paste printer and the solder paste is printed and cured (see figure 7.4). After printing and curing the solder paste the button module can be placed in the demonstrator by hand (figure 7.5).

The build plate is than moved back to the Ultimaker 3 to print the next layers of thermoplastic. In these layer there are two more recessed channels which overlap over the leads of the button module and the two solder paste lines (see figure 7.6). The build plate is now moved to the solder paste printer again to print and cure the solder paste (see figure 7.7).

After printing the solder paste the build plate is moved back to the Ultimaker 3 and the remainder of the model is printed (see figure 7.8).

The top cover of the demonstrator is printed separately and placed of the model to complete the dummy computer mouse (see figure 7.9 & figure 7.10). On the page to the left the working mouse can be seen.

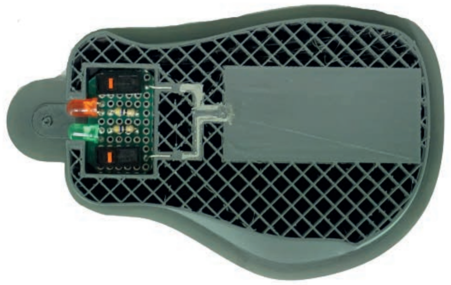


figure 7.5: The solder paste printed and cured in the recessed channels

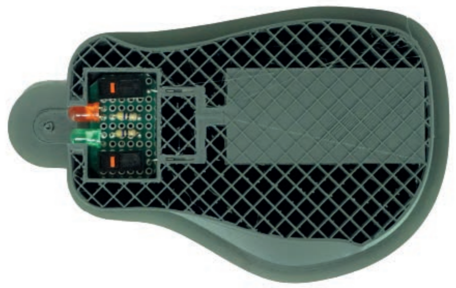


figure 7.6: The next layers of thermoplastic with two recessed channels connecting the leads to the solder paste traces.

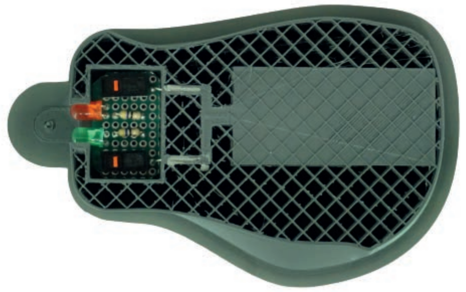


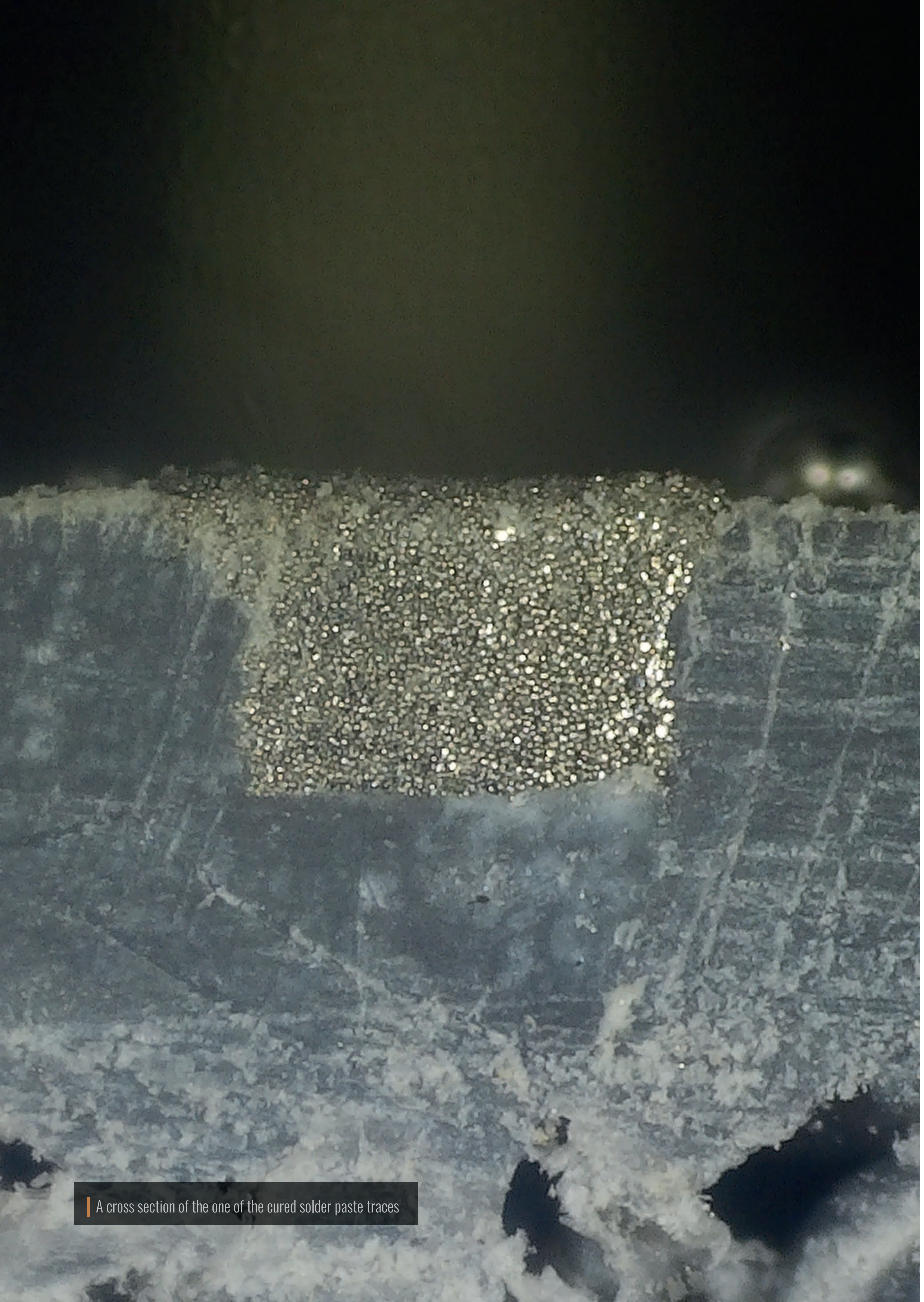
figure 7.7: The solder paste printed and cured in the recessed channels

figure 7.8: The remainder of the model printed on top of the demonstrator.

figure 7.9: The separately printed top cover of the demonstrator.

figure 7.10: The completed demonstrator mouse

The demonstrator in action, the led is turned on because the battery and the button module are successfully connected with each other



A cross section of the one of the cured solder paste traces

8 Conclusions and recommendations

To conclude this project, this chapter reflects on the project goal and evaluates the results. The conclusions of this project are summed up and recommendations for the future are given.

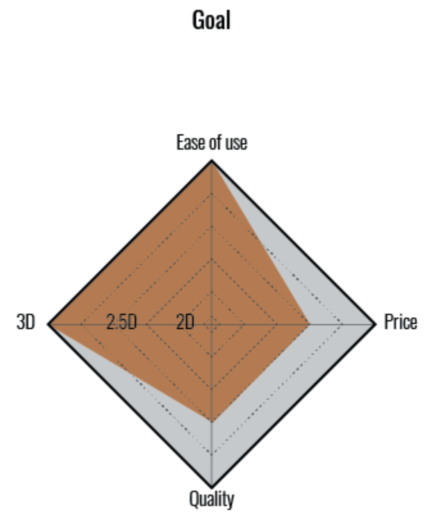


figure 8.1: The four characteristics of the project goal on which the product was scored.

figure 8.2: The four characteristics of the project goal on which the product is scored after completion of the project.

8.1 The goal

The main goal of the project was to further develop the method for printing and curing solder paste for 3D printing structural electronics. A simple to use and cost effective printer was needed to fill the gap between very cheap and low quality conductive PLA and very high end and expensive industrial printers using conductive silver ink.

To achieve this goal four properties were used to score the printer on as seen in figure 8.1. Firstly the printer has to be able to print in 3D to enable full design freedom when using this printer in the design process. Secondly the printer must be easy to use, meaning that people who posses the skill to use common FDM 3D printers can use this printer with little to no training. The printer also has to be cost-effective both in cost of the printer and the materials that are used. And lastly the printer deliver sufficient quality for producing prototypes, achieving the quality of end product is not necessary.

8.2 Conclusions

The conclude this project the same four properties were used to evaluate the results of the project. The results show that two traces could overlap and that could be considered 2.5D printing. The ease of use of the realized printer in operation scores not as high as what the initial goal was, because the Gcode for the solder paste printer is still written by hand. Integrating this in the future would improve the ease of use. The price scores right in the middle like envisioned in the goal. The solder paste is an order of magnitude cheaper than conductive silver paste but still not as cheap as conductive PLA. The quality resulted in being better than expected. The conductivity is not as good as silver paste yet but the mechanical properties are better than silver ink.

8.3 Recommendations

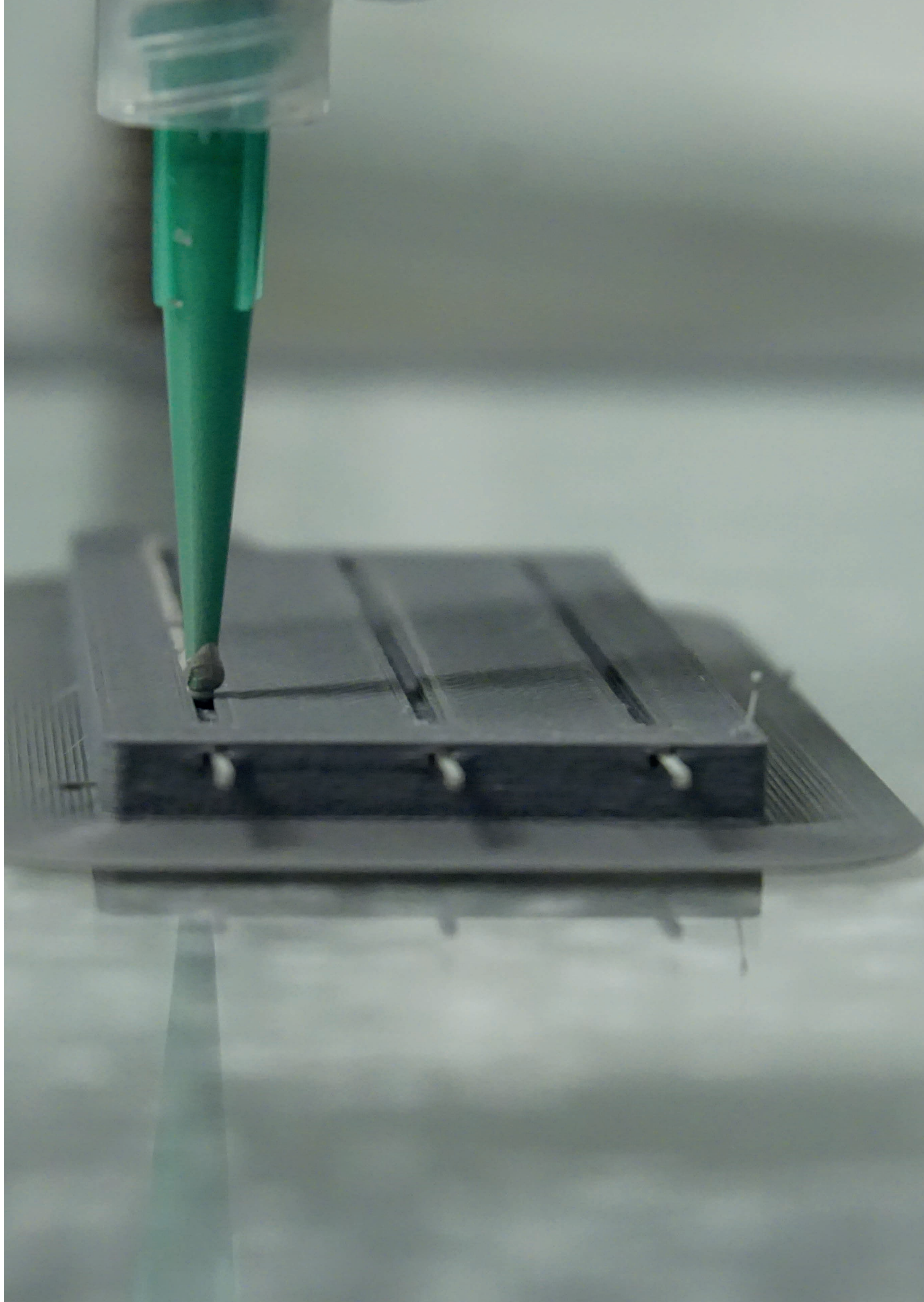
For the continuation of this project there are several recommendations on how to move forward.

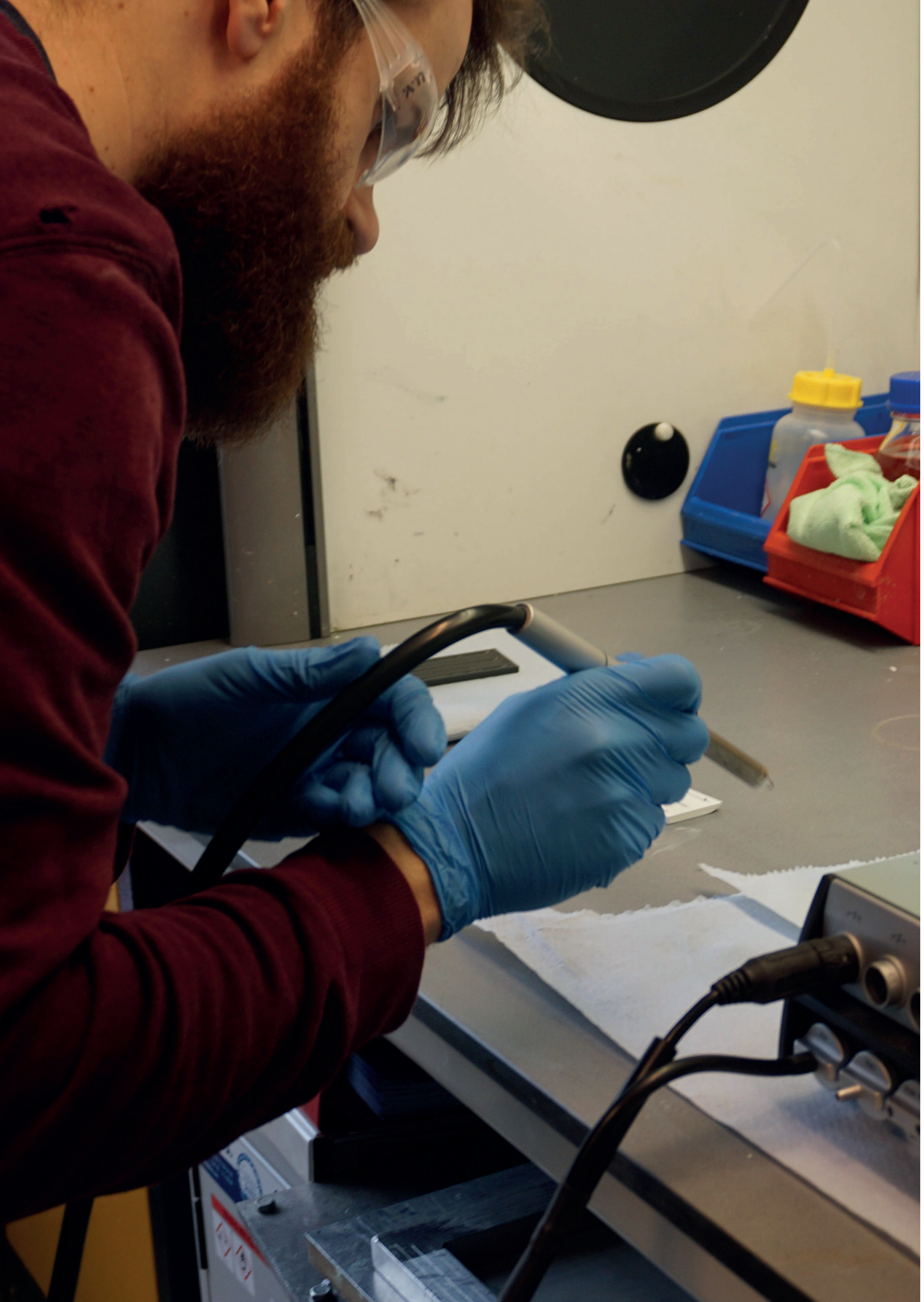
First off it would be beneficial to move each of the 3 printing heads to a single system to prevent errors in manual handling of the build plate between printers. Which would also speed up the printing process. A platform like the E3D toolchanger platform would be very useful. Each print-head could be stored to the side when not in use and the Duet control board it features has a lot of capabilities for connecting custom tools.

Secondly the biggest shortcoming of the current setup is the inaccuracy of the solder paste extruder. Solder paste is stored in the fridge when not in use and moved to the printer when it is used. This causes a fluctuation in temperature which in turn causes a fluctuation in viscosity with uneven extrusion as a result. A way to mitigate this would be to use a insulated jacket for the solder paste syringe. Another improvement on the solder paste extruder would be to improve the resolution of the stepper motor/ lead screw combination. The resolution is now 200 steps per revolution with 2mm travel per revolution. This results in 0.01mm travel per step and 1.8mm^3 minimal extrusion volume.

More tests can be done with varying the particle size of the solder paste. The solder paste used now is T5 solder paste which has 80% of the particles between 15-25μm. There also exists T3 and T4 which have larger particles sizes, 25-45μm and 20- 38μm respectively. The larger particle size make these solder pastes cheaper but the effect on conductivity has to be researched.

When solder paste extrusion is better controlled and the manual handling error is removed from the system more tests can be conducted with stacking multiple layers of conductive traces, this would make the method truly 3 dimensional.





9 Reflection

Looking back on this project I imagined the project going differently than how it ended up going, but I guess that I always the case. I this reflection I will tell you how the project ended up being different from my expectations.

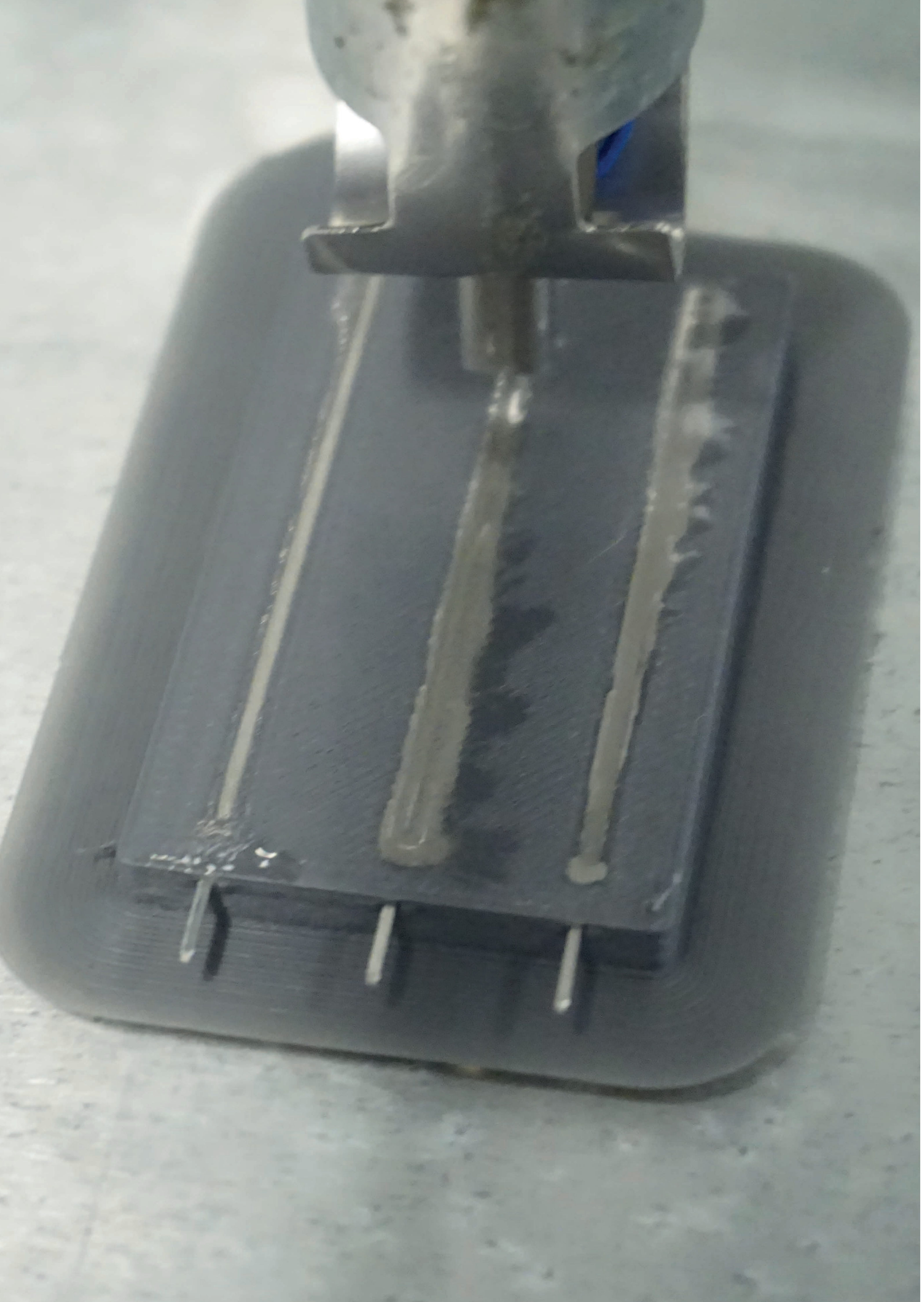
To start off I thought that testing the three methods for curing the solder paste would just be mounting it in the printer and running some tests. I imagined that all three methods would produce usable results but that was not the case, I was very wrong to think everything would go so smoothly.

The original plan was to write a paper about the three most promising method and to compare the results with each other and choose the method that would fit this project the best. However only one of the methods did yield usable results and plans for writing this paper had to be changed. Changes like this had a big effect om my motivation, I had the feeling the project failed sometimes when the initial gaols were not met, but with the coaching of my mentors we always found a new goal and a plan to achieve it. Learning to improve my planning was a mayor learning point here as well. I was never very good in planning but it helped me to manage my time more efficiently.

Doing the majority of the project during this strange corona lock-down time was difficult sometime as there were no friends at the faculty with whom I could discuss the project and share thoughts with. However it was very lucky to have the opportunity to keep coming to the lab and continue working. A lot of graduate students had to do all their work from home and I am grateful that I could work away from home. Because of the corona lock-down the contact with my mentors also became less informal because they wouldn't walk by and see what I was working on in real life, showing all the tiny details was sometimes hard to do over zoom/ skype, however I kept weekly contact with both of them either meeting together or 1 on 1.

One of my personal goals which I described in my project brief in the beginning of the project was that I wanted to work more with electronics and get more experience working with it. During this project I had the chance to work a lot with the electronics which are at the heart of the 3D printer that was modified for this project. Because of this goal I did not always chose the easy way to integrate the final hot-air curing method into the printer, but in doing so I learned a lot.

To conclude this section I would like to reflect on the approach of this project. I chose to do a more hands on approach to learn while I was testing and doing instead of doing lots of research beforehand. An example was the laser method which my mentors, people in the lab and me though was going to be the best method, but ended up not working at all. We cannot predict everything so quick testing end up being very useful. I like this approach very much and would like to work this way in a future job as well.



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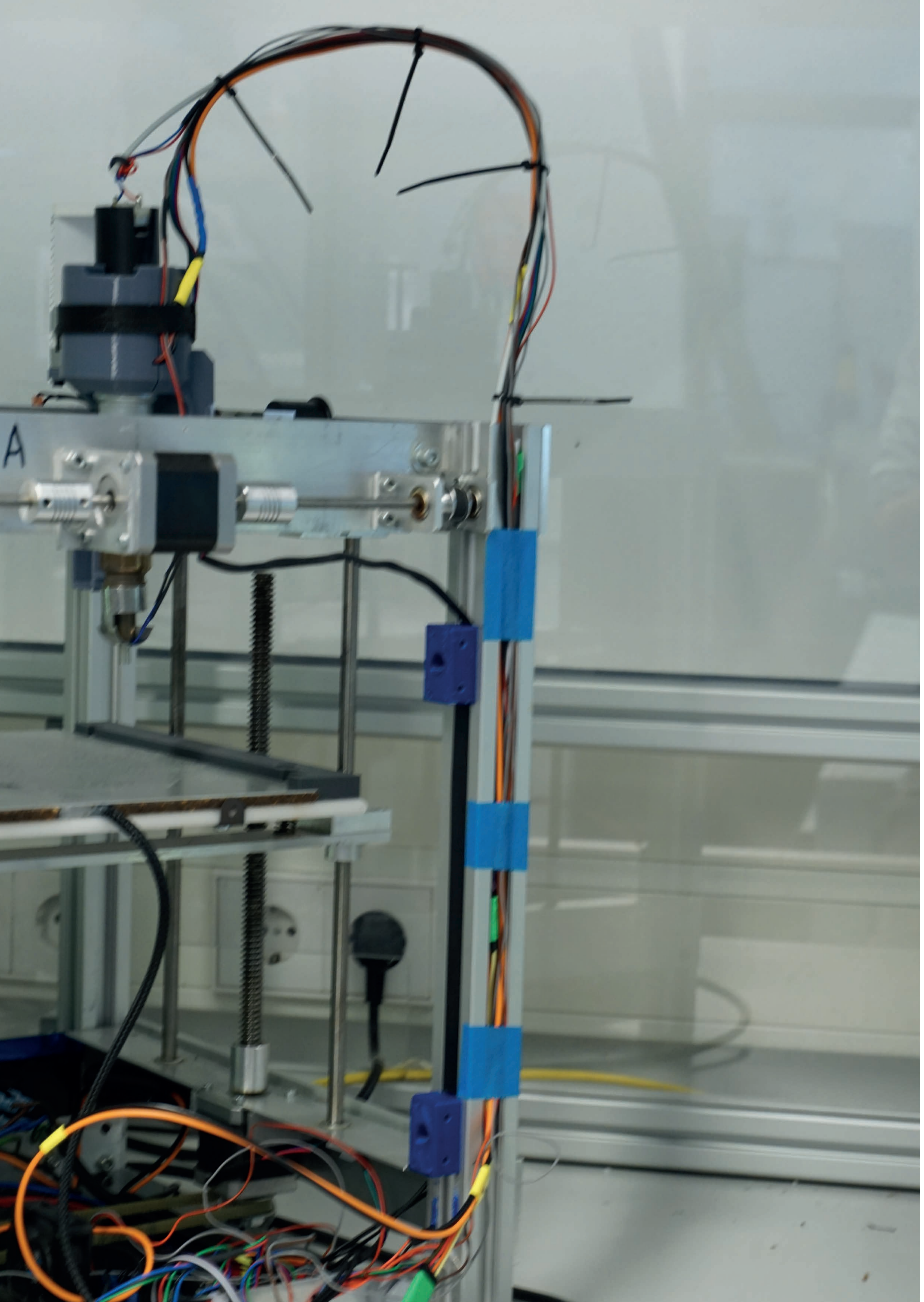
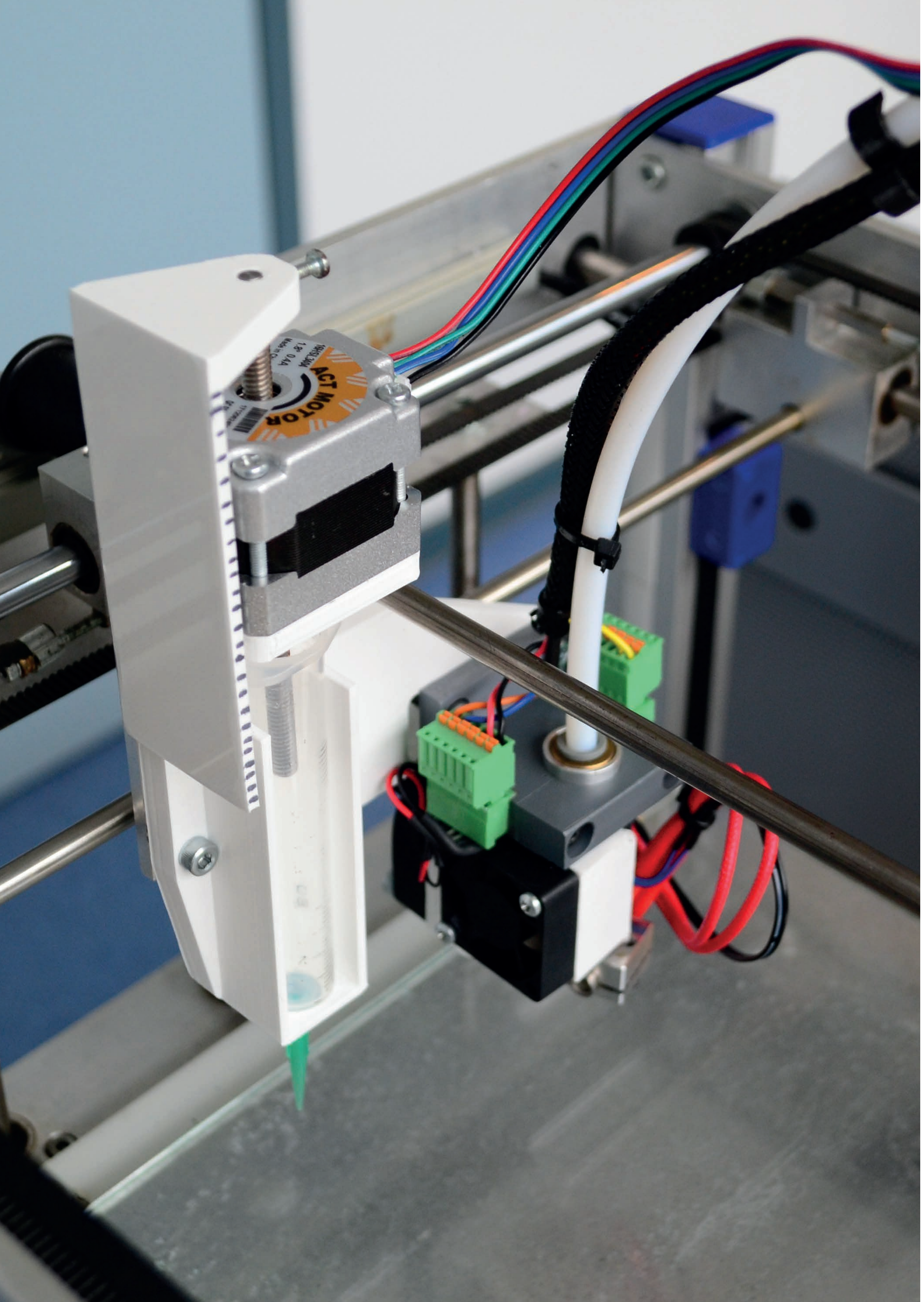


Appendices



A Testing logbook

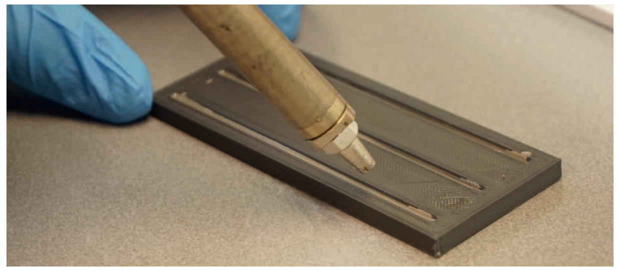


figure A.1: Heat gun from the solder station when heating up the solder paste.

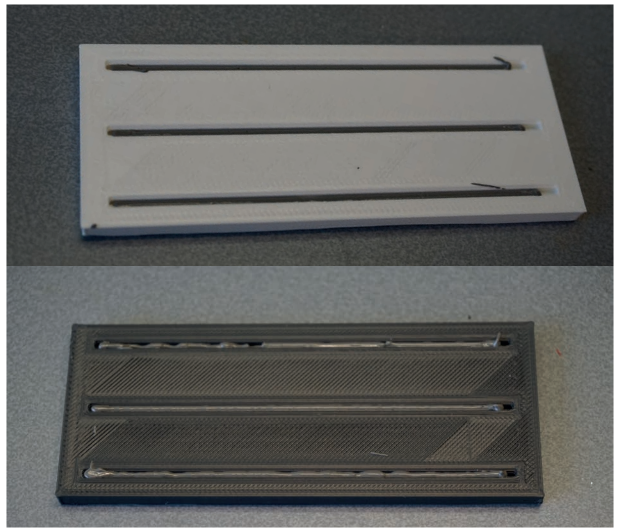


figure A.2: Solder paste dispensed into the channels of PLA (left) and PLA x3 (right)

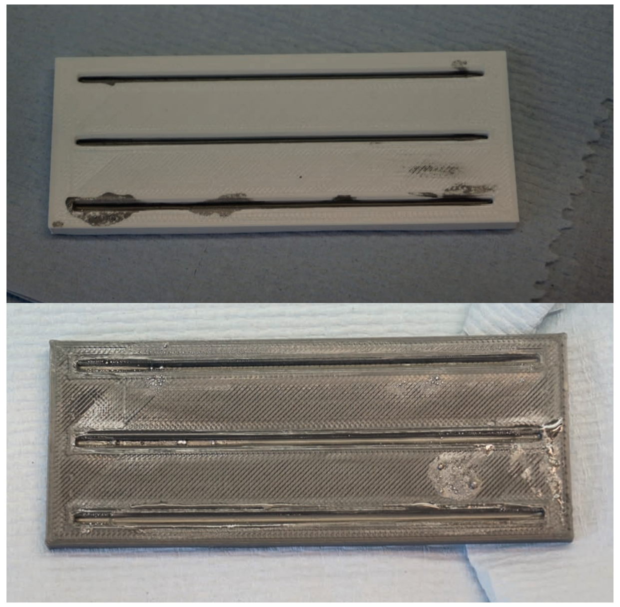


figure A.3: The PLA (left) and PLA x3 (right) samples after heating with the solder station heat gun.

A.1 Hot-air test 1

Testing with a handheld heat gun for a solder station, the solder paste is dispensed into 3 channels with the DIY printer and with the heat gun the trances are heated to be cured. Tests were done with regular PLA (white sample) and PLAx3 (grey sample).

As can be seen from figure FIXME the solder paste was blown out of the channel by the hot air gun during the first, during this test the airflow was adjusted and another attempt was taken to cure the solder paste with adjusting the airflow, this reduced airflow was enough to let the solder paste flow but after passing over the trace multiple times it did not cure. Next the temperature was increased to 400C to see if this was sufficient to cure the solder paste. After passing over the trace with this setting the solder paste did not cure either.

Take aways from this test

- Airflow very low otherwise the solder paste is blown/pushed out of the channel (figure FIXME). It can be seen that the solder paste is blown out of the channel
- Channel too deep for curing the solder paste.
- Solder paste wouldn't cure completely The layer seems too thick.

Table A.1: Setting used for the hot air gun from the solder station

	Airflow	Temperature
Setting 1	50%	300 C
Setting 2	10%	300 C
Setting 3	10%	400 C

A.2 Hot-air test 2

For the second test a hand held hot-air gun was modified to be able to adjust the speed of the fan (figure FIXME). From the first test it seemed that with a high airflow the solder paste was blown out of the channel so the ability to reduce the airflow was needed make sure this would not happen. Also the channels in the test sample have been made less deep to speed up the curing time.

In figure FIXME the result of the test with this heat gun can be seen. The solder paste has cured completely but has formed little balls of solder in the channel. The solder forming balls in the channel can also be seen in tests done by Milly Bon (reference FIXME). The cause of the solder paste curing into balls was too high heat. The high heat also caused the sample to deform/warp slightly, and even blister locally.

Take aways from this test

- Heat of the heat gun too high
- Sample warped/deformed
- Solder paste cures weirdly

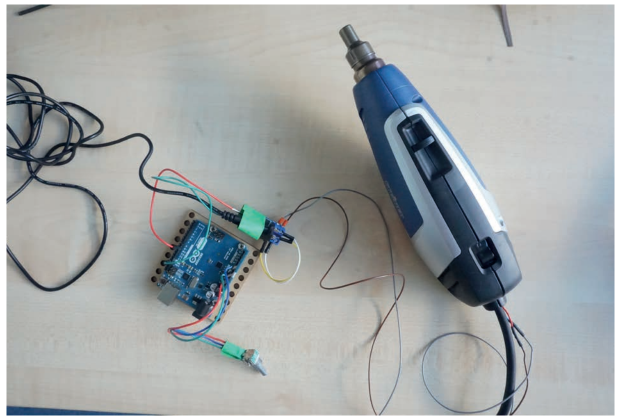


figure A.4: The hot air gun that has been modified to adjust the airflow

figure A.5: Result of the test with the modified heat gun,

figure A.6: Result of hot-air test 3 with the Weller solder station.

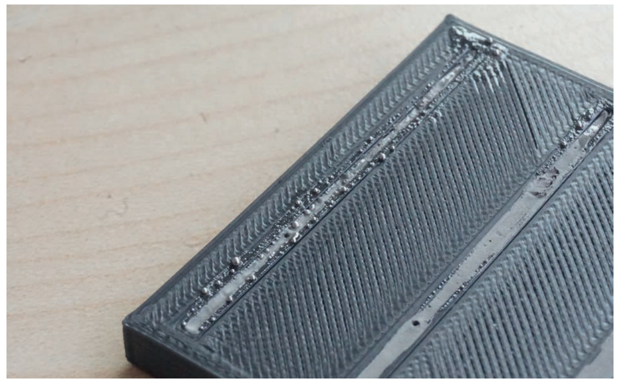


figure A.7: Close up of the result of hot-air test 3 with the Weller solder station.

A.3 Hot-air test 3

From the previous test it was evident that the temperature used was too high, before starting to modify the hand held hot air gun with a temperature sensor to control the temperature. The Weller solder station that was used in hot-air test 1 is also able to control the temperature to lower temperature and was used for this test to see if a lower temperature would work.

In figure FIXME the test sample can be seen with from top to bottom line #1 to #3. The first line was done with 165 degrees following the reflow soldering diagram in section FIXME. At 10% airflow and 165C it took relatively long to cure the solder paste. Line #2 and #3 were done with a higher temperature and a higher airflow respectively to see if the solder paste could be cured faster.

Take aways from this test

- Lower temperature given good results
- Small channel depth works well for fully curing.

Table A.2: The setting of the Weller solder station heat gun used in hot-air test 3.

	Airflow	Temperature
Line #1	10%	165 C
Line #2	10%	175 C
Line #3	20%	165 C

A.4 Hot-air test 4

The goal of this test id to find the right feed rate of the 3D printer movement to compare the speed to the other methods. The temperature and fan speed in this test is kept constant.

A feed rate between F40 and F60 is a good region further investigate. F100 and F80 were too fast and the solder paste is not really cured. And F20 and F10 were too slow and cured the solder paste in a big ball.

From the results of test 4.3 and 4.4 it can be seen that a feed rate between F30 and F35 works best for this test. This is used in further test to investigate further.

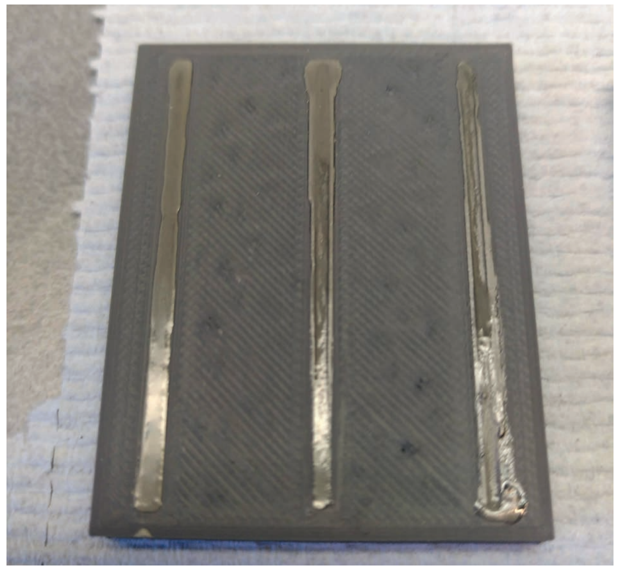


figure A.8: Result of test 4.1

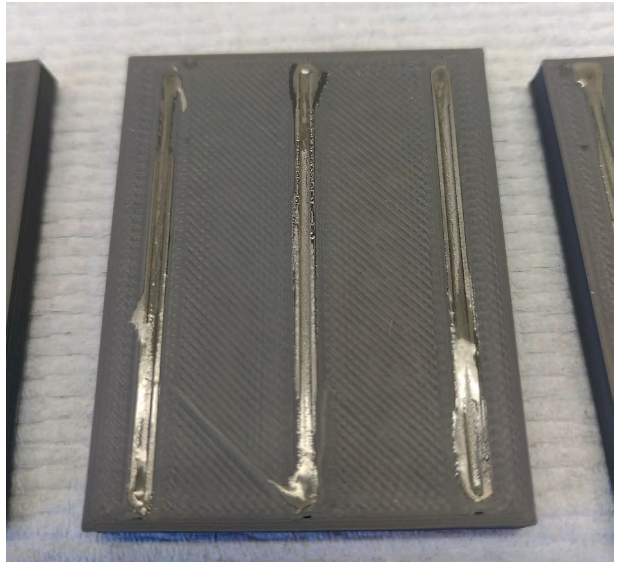


figure A.9: Result of test 4.3

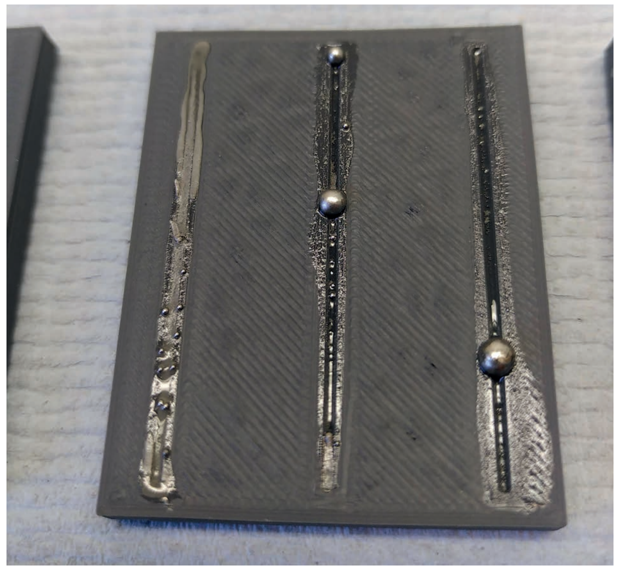


figure A.11: Result of test 4.2

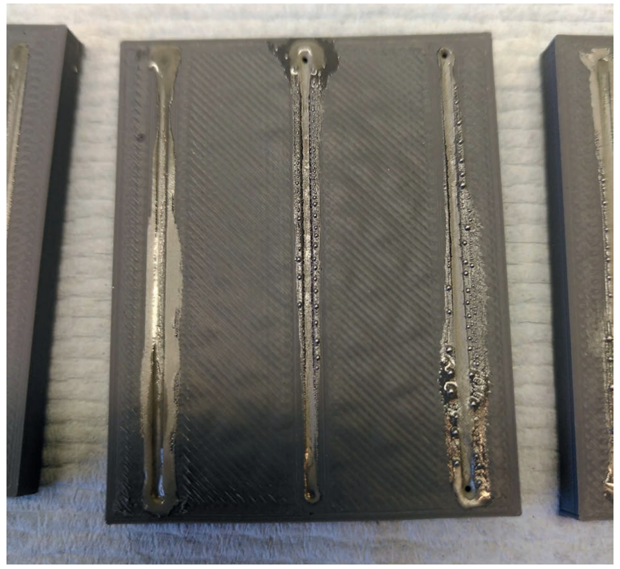


figure A.10: Result of test 4.4

In test 4.5 and 4.6 feed rates of F30 F32.5 and F35 and further investigated. The sample from 4.5 looks messy with a lot of solder paste next to the channel. The result of sample of test 4.6 was much cleaner.

For test 4.7 the same settings were repeated with a sample that hold place for pieces of wire to easily connect to measuring equipment to measure resistivity. The trace with F32.5 and F30 seem to be completely cured. The solder paste near the wire connections are not fully cured. This could be accounted to the fact that the wire also heat up with the solder paste leading to more material being heated up and thus a too low temperature to fully cure the solder paste.

To try to cure the solder paste better at the wire connections each lines is passed over twice (test4.8) . The first pass is for the wetting phase to get the solder paste to flow the feed rate here is high F100. And the second pass is the curing phase where the feed rate is much lower. It can be seen in figure FIXME that the lines with a feed rate of F40 and F30 did fully cure and did conduct electricity. The solder paste at the wire connectors did still not fully cure however.

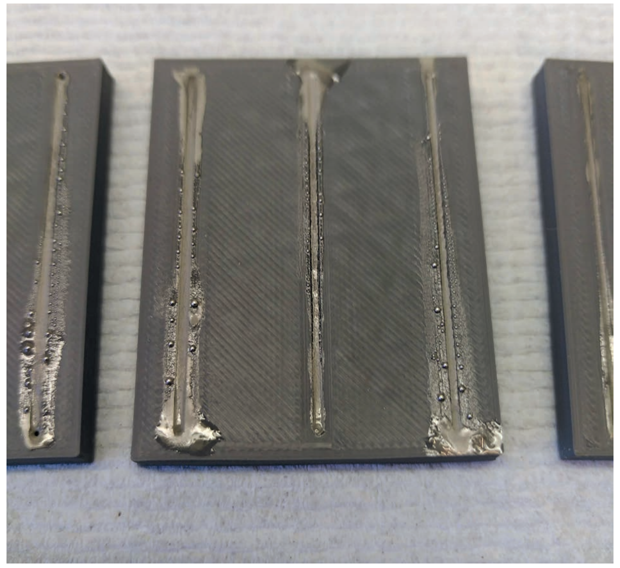


figure A.12: Result of test 4.5

figure A.14: Result of test 4.7

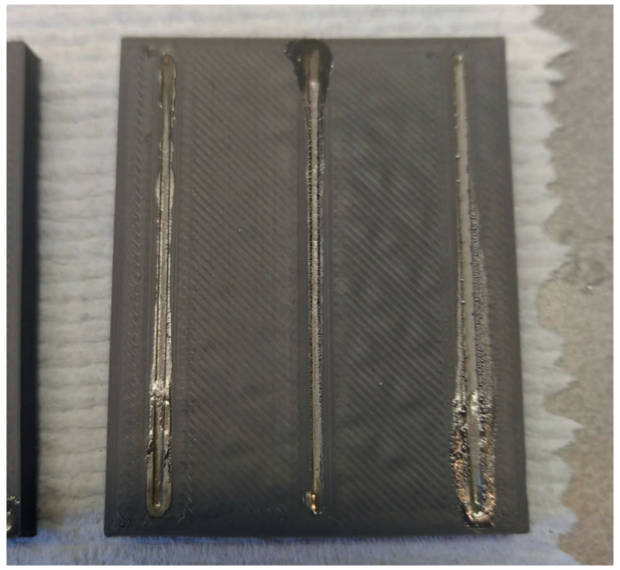


figure A.13: Result of test 4.6

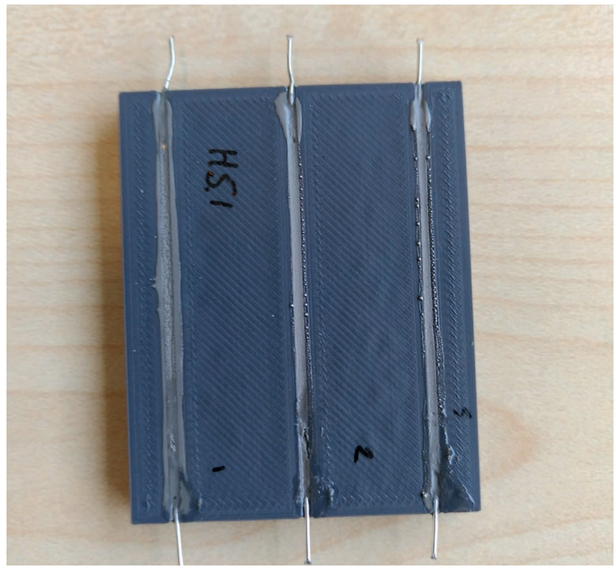


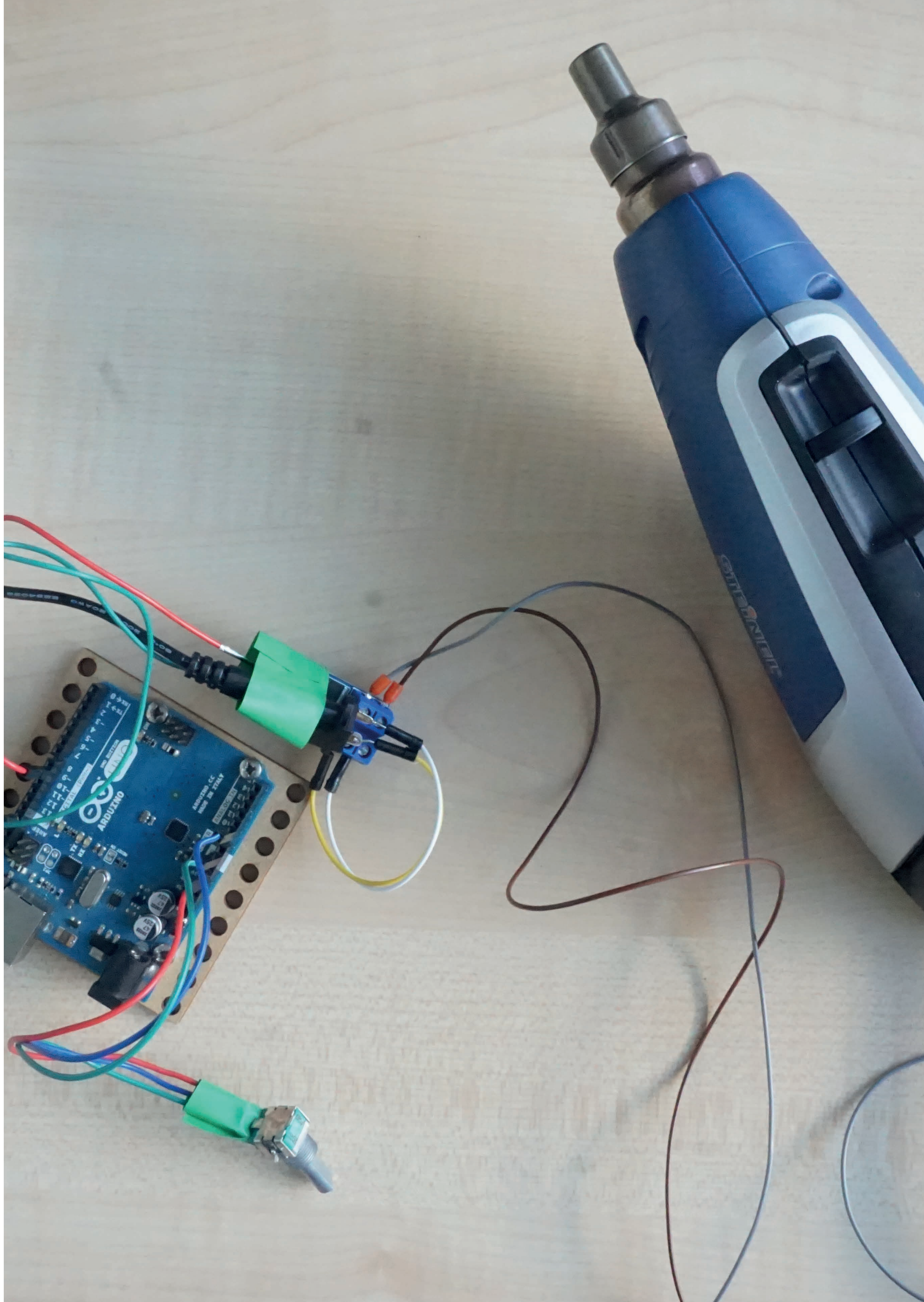
figure A.15: Result of test 4.8

Take aways from this test

- Feed rate of F30 works well (at this temperature, airflow and channel geometry)
- Wire inserts absorb heat preventing the solder paste around them from curing. And thus the solder paste at the inserts does not conduct electricity

Table A.3: Settings for Hot-air test 4

Test Sample #	Line 1	Line 2	Line 3
4.1 (PLA x3)	25% 165C F100	25% 165C F80	25% 165C F60
4.2 (PLAx3)	25% 165C F40	25% 165C F20	25% 165C F10
4.3 (PLAx3)	25% 165C F55	25% 165C F50	25% 165C F45
4.4 (PLAx3)	25% 165C F40	25% 165C F35	25% 165C F30
4.5 (PLAx3)	25% 165C F35	25% 165C F32.5	25% 165C F30
4.6 (PLAx3)	25% 165C F35	25% 165C F32.5	25% 165C F30
4.7 (PLAx3) With wire connectors	25% 165C F35	25% 165C F32.5	25% 165C F30
4.8 (PLA x3) With wire connectors	1st pass: 25% 165C F100 2nd pass: 25% 165C F50	1st pass: 25% 165C F100 2nd pass: 25% 165C F40	1st pass: 25% 165C F100 2nd pass: 25% 165C F30



A.5 Thermode test 1

This test is done with a solid steel nozzle to heat up and "iron" (strijken) over the channel with the solder paste. Both test samples were made from PLA x3. The shape of the nozzle was pointed and sharp (figure FIXME) to ensure contact with the solder paste in the channel and the channel was made less deep to ensure less power needed to cure the solder paste.

After the first test (figure FIXME (left)) it can be seen that the solder paste has flowed nicely but is still glossy, indicating the the solder paste has not cured. A second pass over the traces of the solder paste with increased temperature was done, during this the solder paste was pushed out from the channel and got smeared next to the channel. The reason for this behaviour was cured solder paste on the tip of the thermode, or the fact the the tip of the thermode come loose slightly. The third test was done with the higher temperature and slower feedrate, but here the result (figure FIXME) also show that the solder paste is pushed out of the channel.

Take aways from this test

- Shape of the hot end damaged the plastic
- The pointy shape pushed the solder paste out of the channel when curing.
- Very slow movement needed for solder paste to cure (two passes on first sample) .

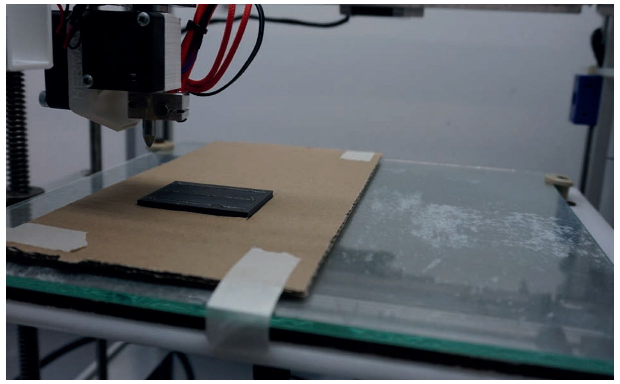


figure A.16: The set-up for testing, the sample is held in place by a cardboard template

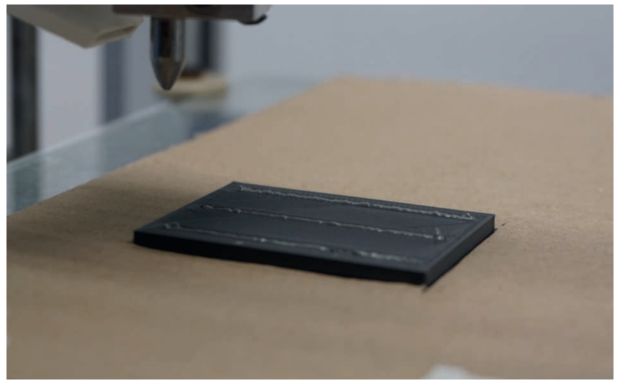


figure A.17: A close up of the steel insert for the nozzle of the 3D printer

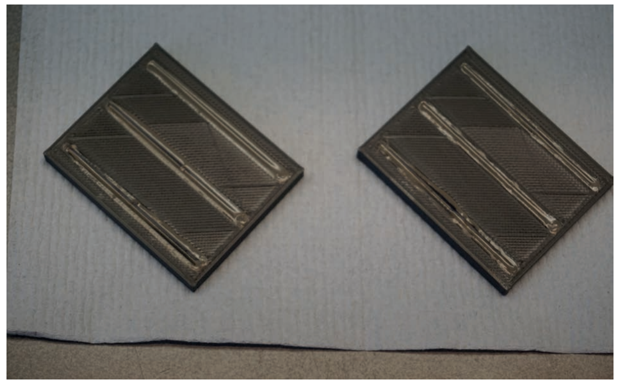


figure A.18: The two samples after heating the up with the solid nozzle for curing.

Table A.4: Settings for G-code while printing the different lines on the different test samples

Test sample No	Line 1	Line 2	Line 3
#1	150C F50	150C F100	150C F150
#1 (2nd pass)	170C F50	170C F100	170C F150
#2	170C F50	170C F50	170C F50

figure A.19: The two tips of the thermode.

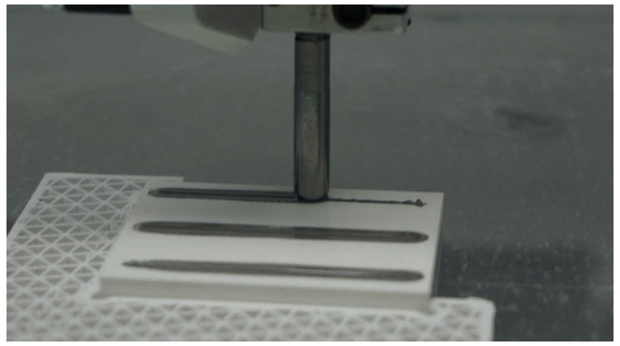


figure A.20: The tip of the thermode ironing the solder paste in the sample

A.6 Thermode test 2

For the second test the tip of thermode has been changed (figure FIXME). One tip is has a smaller area through where the solder paste is heated and the other has a larger area. The smaller area tip will probably only heat the solder paste wehereas the larger area tip will also heat the surrounding plastic, as well as more of the solder paste.

The first round of tests was done with just the small top of the thermode. In table FIXME the setting for the g-code used for the different lines can be found.

The results of test sample #1 can be seen in figure FIXME, it can be seen that the tip of the thermode smears the solder paste over the sample and the solder paste is not cured yet. An explanation of the this is that the thermode moves too fast over the sample.

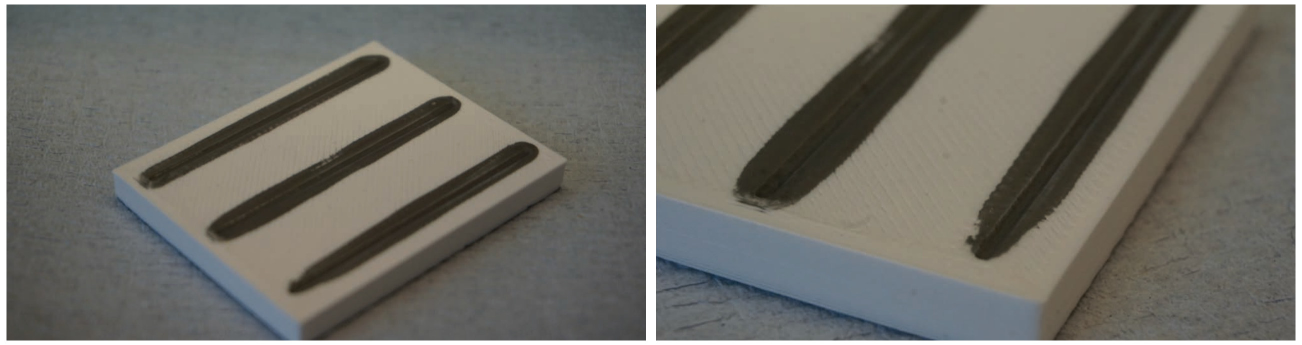


figure A.21: Results for sample #1

Table A.5: G-code setting for thermode test 2

Test sample No	Line 1	Line 2	Line 3
#1 (PLA)	165C F50	165C F40	165C F30
#2 (PLA)	165C F20	165C F15	165C F10
#3 (PLA)	175C F10	175C F10	175C F10

Test sample #2 uses lower feed rates to see if the solder paste cures with lower speeds. The results of this sample can be seen in figure FIXME. It can be seen by the glossy surface finish that at lower feed rates the solder paste still does not fully cure. The lower feed rate also gives more time for the solder paste to stick on the thermode tip and cure there and accumulate over time. The solder paste in the third line seems to be almost cured so that will be the starting point for test sample #3.

Test sample #3 used F10 as feed rate for each of the three lines the temperature has been increased to cure the solder paste faster. The results of this sample can be seen in figure FIXME. It can be seen that the slow feed rate and the higher temperature melted the plastic partially, also more solder paste accumulated on the tip of the thermode pushing the solder paste out of the channel and to the sides. An additional con of the slow feed rate is that it takes about 4 minutes to pass over one 45mm long line.

Take aways from this test:

- Slow feed rate needed to get the solder paste to cure
- Slow feed rate causes complications like melting of plastic
- Slow feed rate causes solder paste to cure on the tip of the thermode pushing solder paste from the channel.

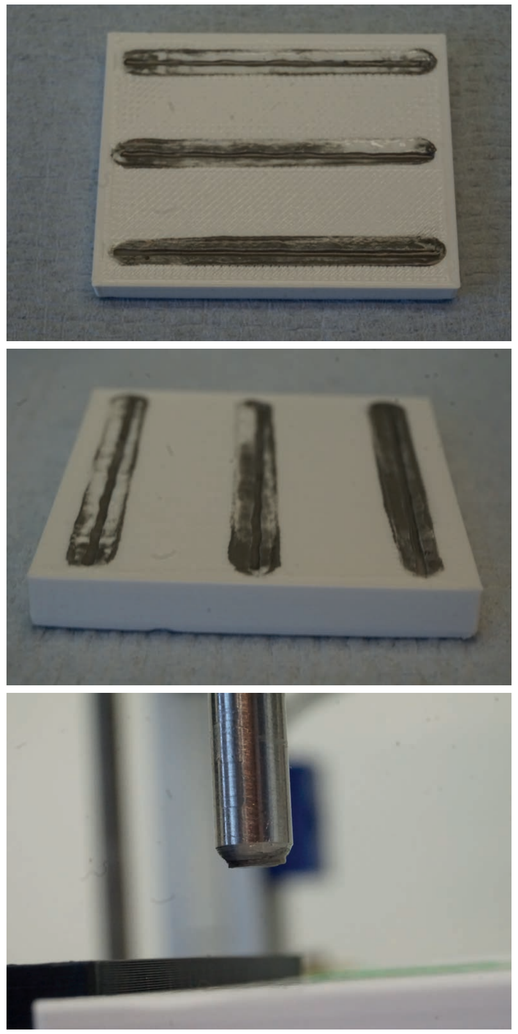
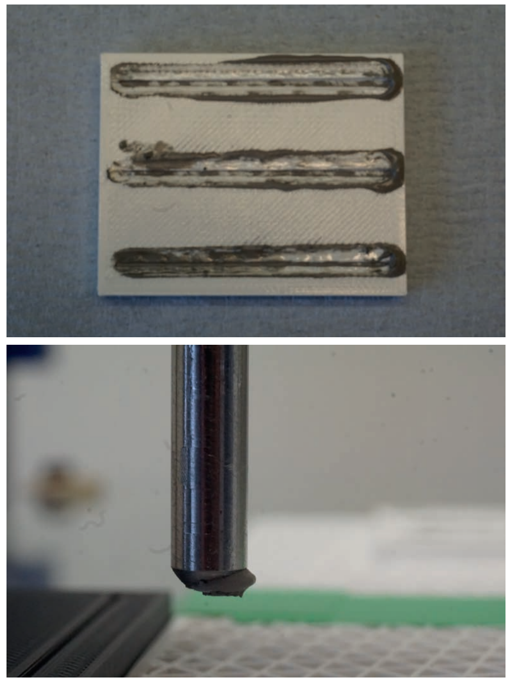


figure A.22: Results for sample #2



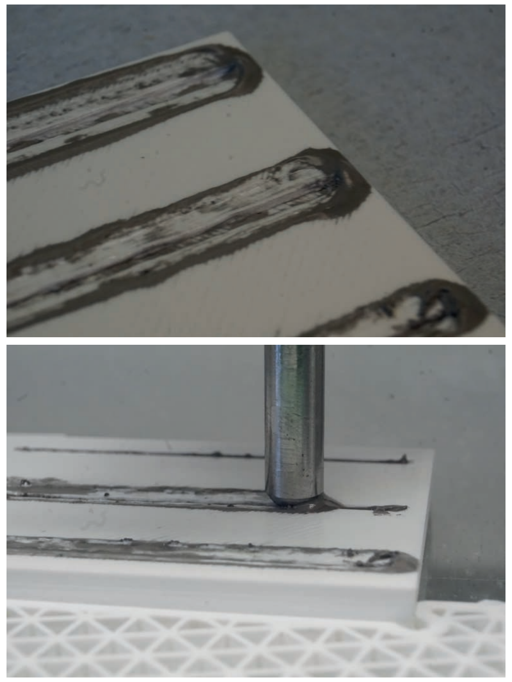


figure A.23: Results for sample #3

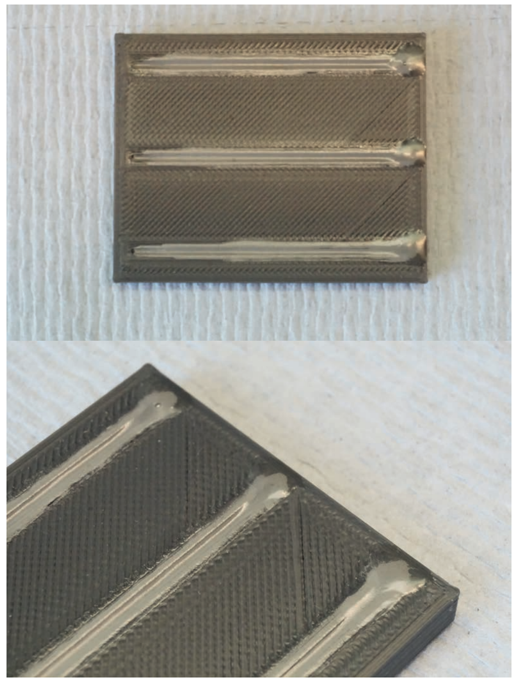


figure A.24: Results of sample #1

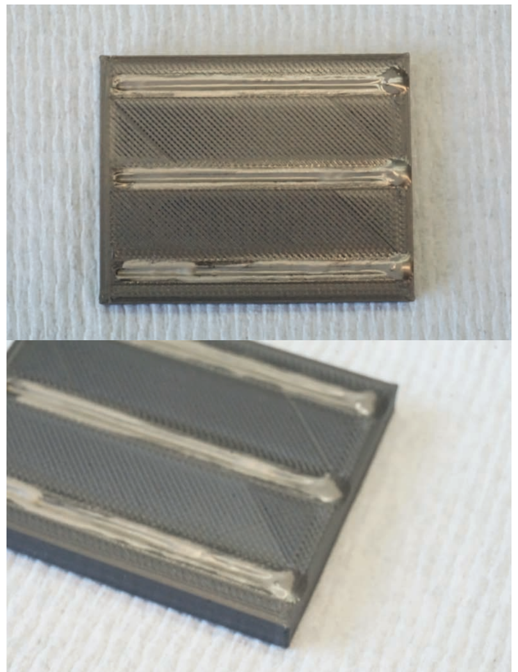


figure A.25: Results of sample #2

A.7 Thermode test 3

Following the previous test it could be seen that one of the problems was that the solder paste cured on the tip of the thermode which caused the solder paste to be pushed out of the channel. This test uses a teflon (PTFE) plastic coating to try to counteract that. PTFE is stable to temperatures to 260 C.

In figure FIXME and FIXME the results of this test can be seen. Both tests were done with the same feed rate of F10 and a temperature of 165C. The temperature of 165C and low feed rate was not enough to cure the solder paste fully.

From figure FIXME it can be seen that far less solder paste stuck to the tip of the thermode and cured there, this could be a good solution to the problem of solder paste stuck to the tip of the thermode. Solderpaste could still accumulate on the tip of the so some sort of cleaning apparatus/ device is needed to clean the tip of the thermode after curing a set amount of solder paste.

Take aways from this test:

- Slow feed rate needed to get the solder paste to cure.
- Thermode doesn’t touch the printed plastic part and also doesn’t scar the plastic part.
- The PTFE tape on the tip reduced sticking solder paste considerably.

Table A.6: Settings in the G-code for thermode test 3

Test sample No	Line 1	Line 2	Line 3
#1 (PLA x3)	165C F10	165C F10	165C F10
#2 (PLA x3)	165C F10	165C F10	165C F10

figure A.26: Tip of the thermode with PTFE cover (white) after printing

A.8 Thermode test 4

In this test the PTFE coating is again used to see if the solder paste can be cured without too much sticking to the tip of the thermode. However during the previous test the solder paste did not cure fully. To improve the curing of the solder paste the feed rate was lowered for this test (see table FIXME).

Table A.7: Setting of thermode test 4

Test sample No	Line 1	Line 2	Line 3
#1 (PLA x3)	165C F9	165C F8	165C F7

In figure FIXME the results of sample #1 can be seen. The solder paste has not fully cured in either of the three lines, and at the end of each line a pool of flux can be seen. An explanation for the solder paste not fully curing could be that there is no contact with air when the solder paste is heated up by the thermode and thus there is no space for the flux to evaporate into the air. The solder paste did not stick to the tip of the thermode as can be seen in figure FIXME. This was a major problem in thermode test 2. This solution seems to have resolved the problem sufficiently.

Take aways from this test:

- No air contact when the solder paste is heated might block the flux from evaporating.
- The PTFE tape on the tip reduced sticking solder paste considerably.

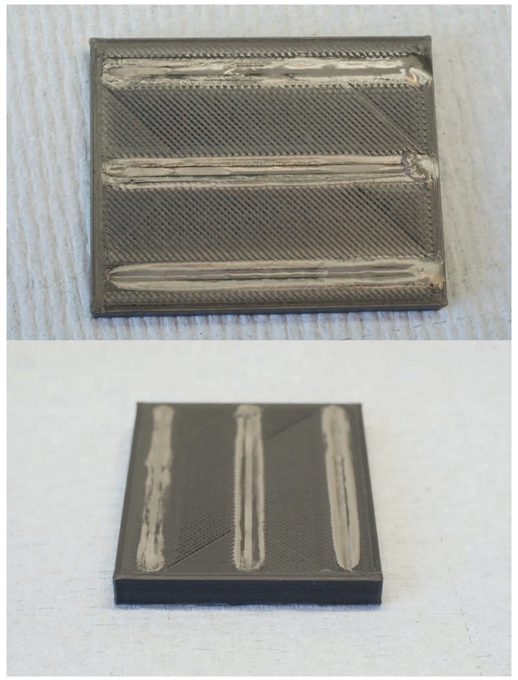
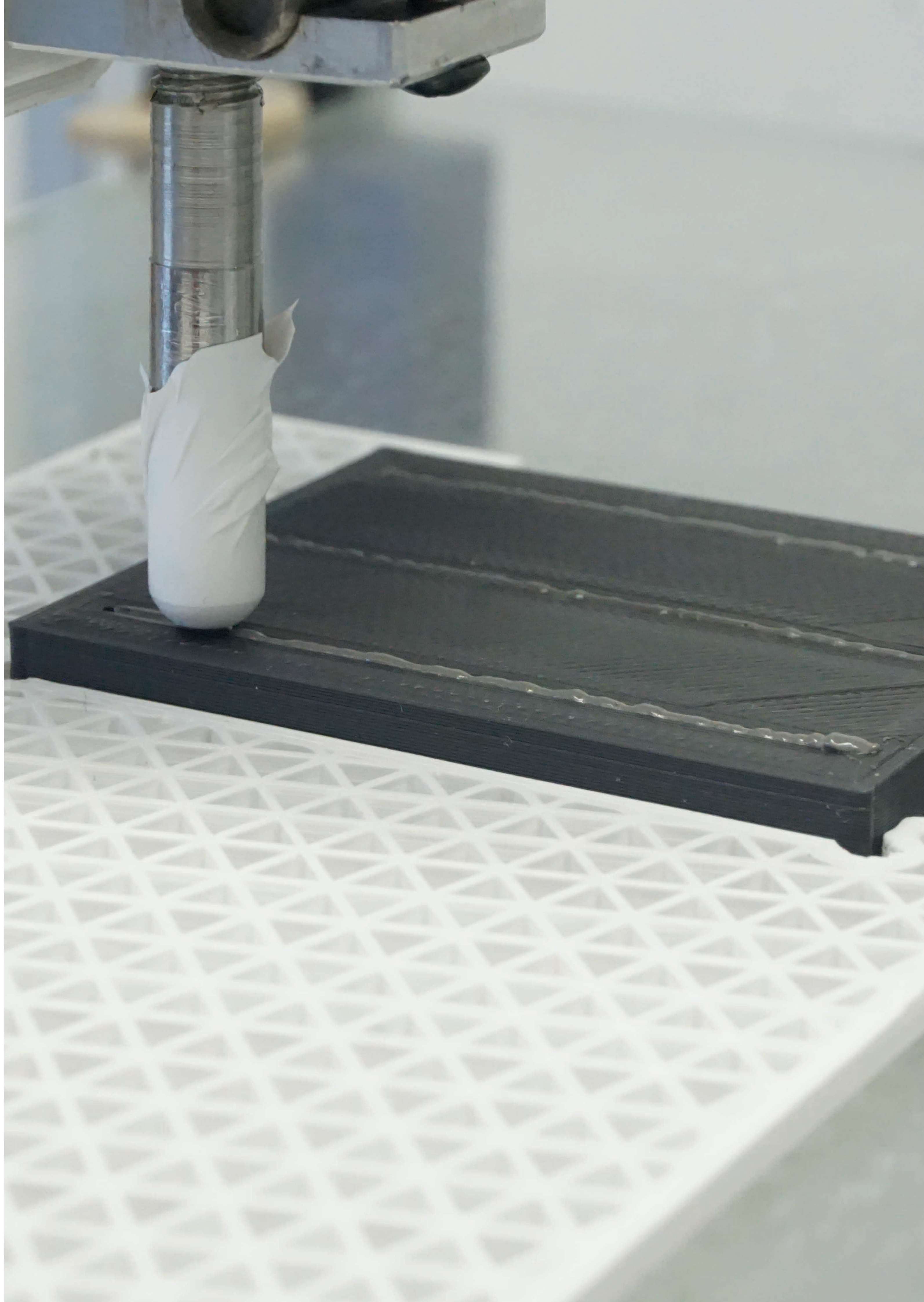


figure A.27: Results of sample #1, line 1 to 3 from bottom to top (left image) and right to left (right image) respectively.

figure A.28: Tip of the thermode with PTFE cover (white) with little to no solder paste sticking to it.



A.9 Laser test 1

The goal of this test was to find out what power setting of the laser was needed to reflow the solder paste. The power of the laser was increased from 40/255 to 210/255, the results can be seen in figure FIXME.

Take aways from this test:

- Laser power too low.
- Or feed rate/ movement too high.

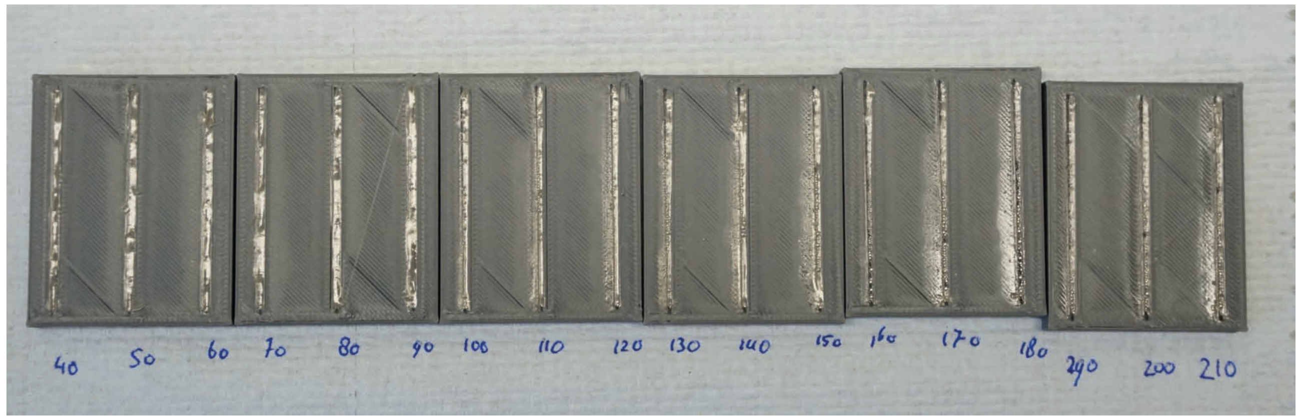


figure A.29: The results of the first laser test.

Table A.8: Setting of laser test 1

Test sample No	Line 1	Line 2	Line 3
1.1 (PLA x3)	S40 F100	S50 F100	S60 F100
1.2 (PLA x3)	S70 F100	S80 F100	S90 F100
1.3 (PLA x3)	S100 F100	S110 F100	S120 F100
1.4 (PLA x3)	S130 F100	S140 F100	S150 F100
1.5 (PLA x3)	S160 F100	S170 F100	S180 F100
1.6 (PLA x3)	S190 F100	S200 F100	S210 F100

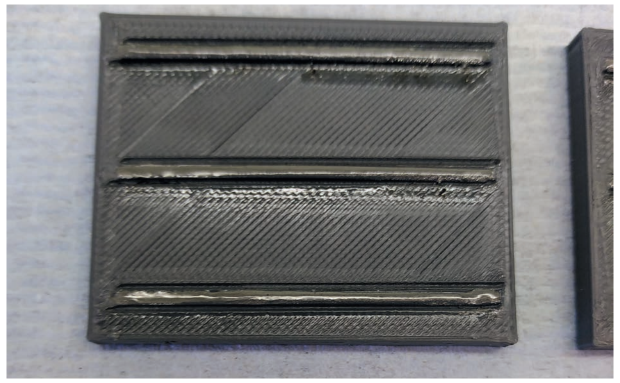


figure A.30: Sample 2.1 (Line 1 t/m 3 for bottom to top)

figure A.31: Sample 2.2 (Line 1 t/m 3 for bottom to top)

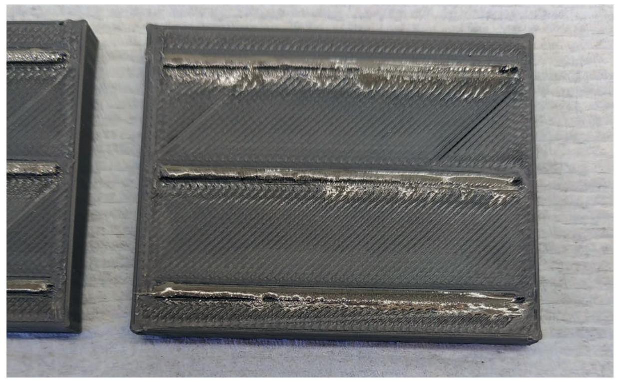


figure A.32: Sample 2.3 (Line 1 t/m 3 for bottom to top)

A.10 Laser test 2

The goal of this test was to better align the sample to see if the solder paste line could be perfectly followed. The laser burned a line in the sample when not being aligned correctly. The plastic sample did not catch fire however which is a good thing.

Take aways from this test:

- Focal area too small
- Small focal area makes aligning sample difficult

Table A.9: Setting of laser test 2

Test sample No	Line 1	Line 2	Line 3
2.1 (PLA x3)	S100 F100	S150 F100	S200 F100
2.2 (PLA x3)	S100 F100	S150 F100	S200 F100
2.3 (PLA x3)	S100 F100	S150 F100	S200 F100

A.11 Laser test 3

The goal of this test was to see if defocussing the laser would improve the curing of the solder paste which is test 3.1 See figure FIXME below. The solder paste did no cure which can be explained by the less energy per area because the laser was defocussed.

The defocussed laser did not cure the solder paste with the setting from sample 1. The lower energy per area of the defocussed laser means that the laser feed rate needed to be slowed down to heat up the solder paste the same. The results of the lowered feed rate can be seen below. The top line #3 is fully cured but not in a solid line/ trace.

As can be seen in figure FIXME above the solder paste cured in little balls like a pearl necklace. The next sample will be heated with a the slowest feed rate from the previous test F40 but the power of the laser will be lowered in steps. The result can be seen in figure FIXME below.

Take aways from this test:

- Solder paste cures consistent but still forms balls, Lower curing temperature needed.
- S150 F40 seems to cure the solder paste fully
- The defocussed beam is not a circle but rather a oval shape

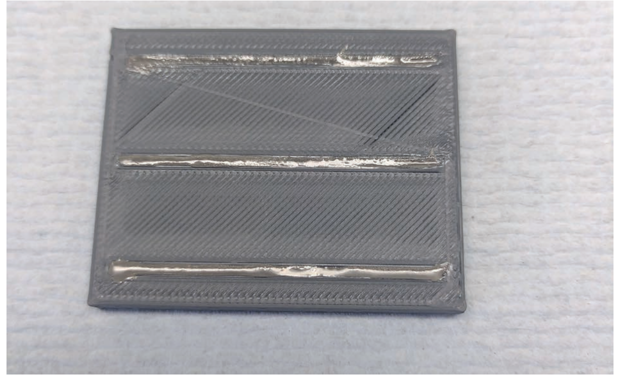


figure A.33: Sample 3.1 (Line 1 t/m 3 for bottom to top)

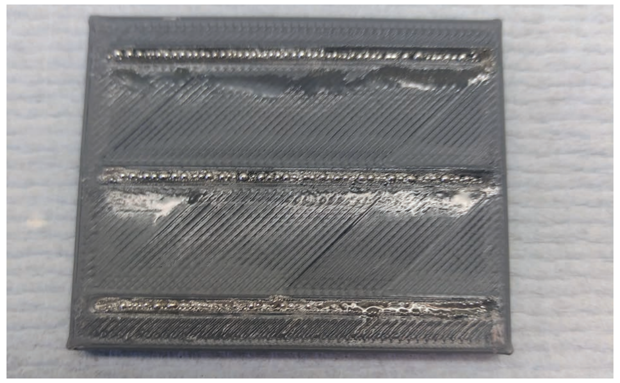


figure A.34: Sample 3.2 (Line 1 t/m 3 for bottom to top)

figure A.35: Sample 3.3 (Line 1 t/m 3 for bottom to top)

Table A.10: Settings of laser test 3

Test sample No	Line 1	Line 2	Line 3
3.1 (PLA x3)	S100 F100	S150 F100	S200 F100
3.2 (PLA x3)	S200 F80	S200 F60	S200 F40
3.3 (PLA x3)	S150 F40	S125 F40	S100 F40

Table A.11: Settings of laser test 5

Test Sample No	Line 1	Line 2	Line 3
5.1 (PLA x3)	S150 F40	S125 F33	S100 F27
5.2 (PLA x3)	S150 F30	S125 F25	S100 F20

A.12 Laser test 5

In this test the goal was to see if adding flakes (cut up pieces of copper flex wire core) into the solder paste would cure the solder paste balls together creating a continuous line which is conductive. The test was done with longer stands of copper wire (~20mm), small bits of copper wire (~3-6mm) and a control sample without copper for comparison.

In figure FIXME below the results of test 5.1 can be seen. The settings of this test were varied slightly line one is at S150 power and F 40 feedrate. The others are lower in power but also lower in feed rate to compensate, reaching the same power output more or less.

The second round in this test is done with a higher total energy output, i.e the same laser power but lower feedrate. The results can be seen in the figures below.

Take aways from this test:

- Adding copper flakes increases the energy needed to heat up the solder paste.
- Copper flakes or copper wire did not improve curing.

figure A.36: Laser test 5.1 from left to right: without copper, with copper flakes and with copper strands

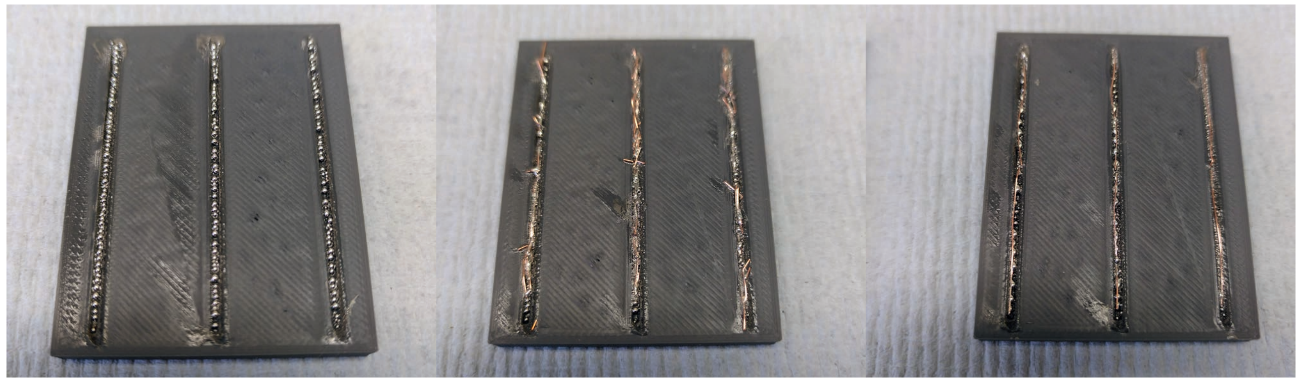


figure A.37: Laser test 5.2 from left to right: without copper, with copper flakes and with copper strands

A.13 Laser test 6

The goal of this test is to see if the solder paste still cures in balls if it is heated slower. Slower heating means a lower feed rate combined with lower laser power output. If the laser power is divided by the feed rate a value is found that can be used to compare combinations.

Test 6.1 and 6.2 are done with the same ratio, the results can be seen in figure FIXME. It can be seen from the results that the lower the feed rate got less of the solder paste is being cured. A reason for this could be that more heat is flowing away through the material when moving slower.

Test 6.3 and 6.4 are therefore done with the same low feed rate but with a higher ratio meaning more energy input.

The results of test 6.3 an 6.4 can be seen in figure FIXME below. It can be seen that more solder balls form but also uncured solder paste remains in the channel. Achieving a uniformly cured trace is not possible with these settings.

Take aways from this test:

- Laser is not useful for curing solder paste in 3d printed parts!

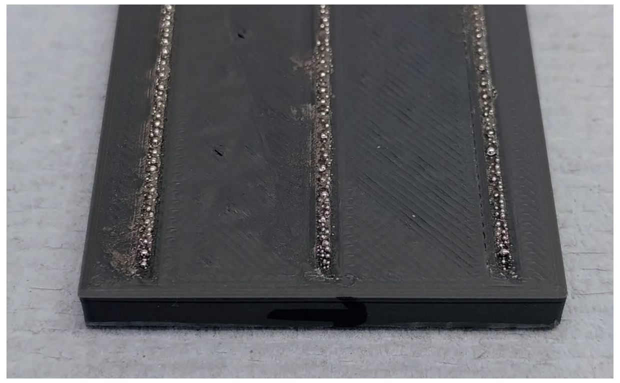


figure A.38: Sample 6.1

figure A.39: Sample 6.3

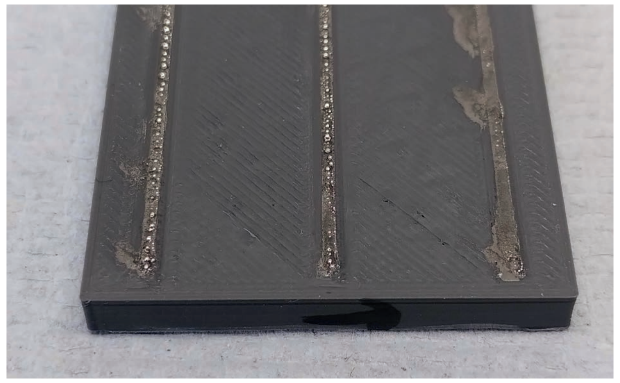


figure A.41: Sample 6.2

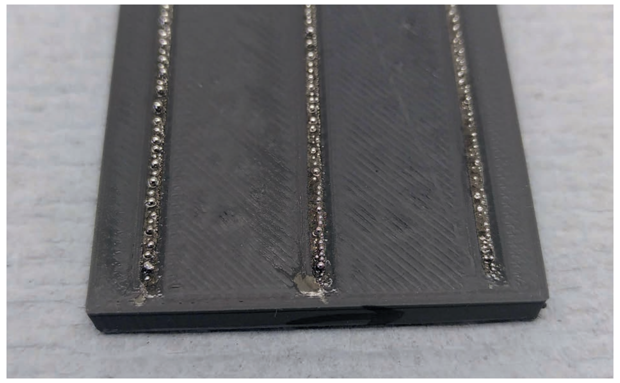
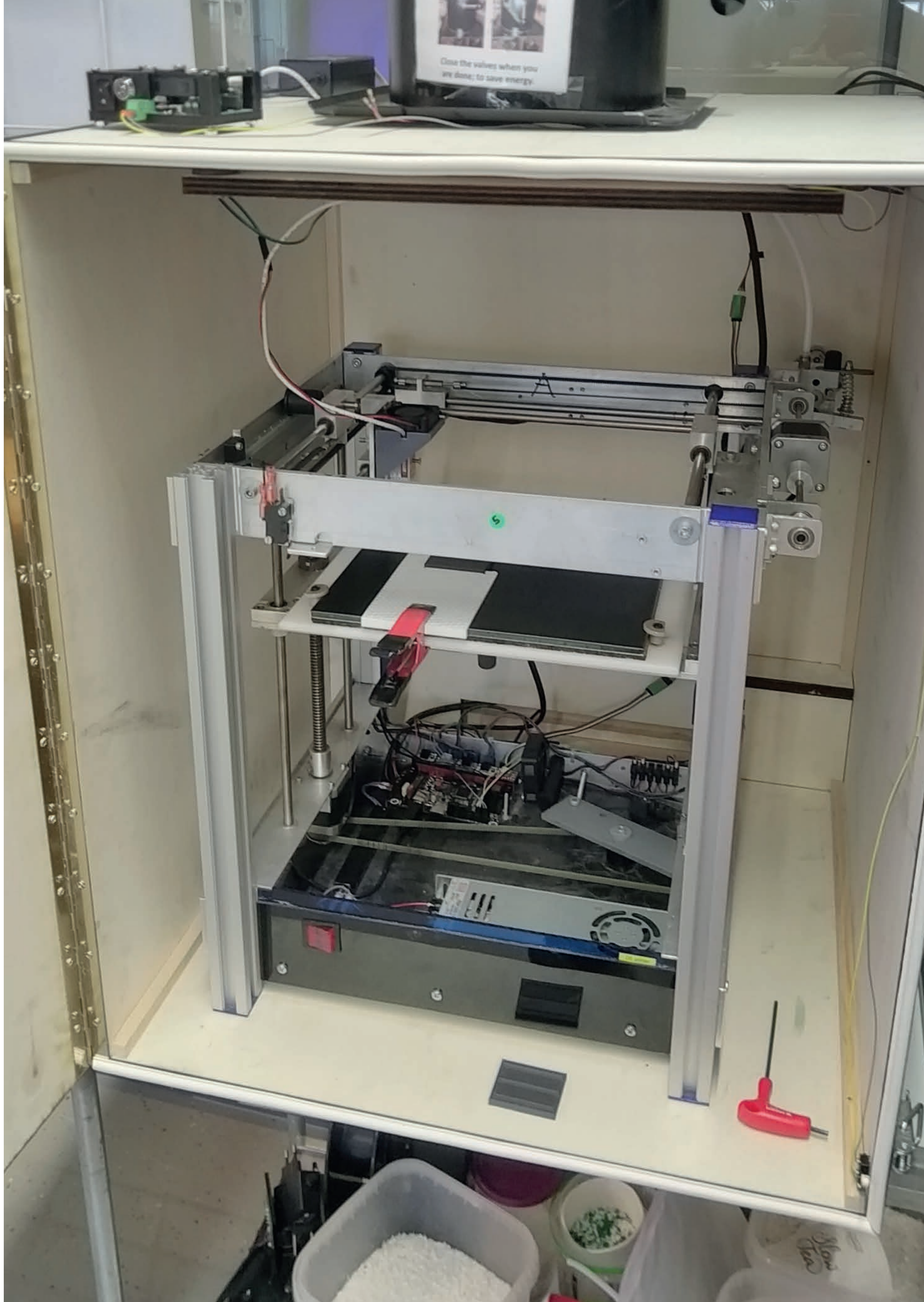


figure A.40: Sample 6.4

Table A.12: Settings of laser test 6

Test Sample No	Ratio	Line 1	Line 2	Line 3
6.1 (PLA x3)	3	S150 F50	S120 F40	S90 F30
6.2 (PLA x3)	3	S75 F25	S60 F20	S45 F15
6.3 (PLA x3)	3.5	S87 F25	S70 F20	S52 F15
6.4 (PLA x3)	4	S100 F25	S80 F20	S60 F15



3962

DESIGN FOR our future

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: Eekhout

initials: K.T. given name: Kasper

student number: 4228715

street & no.:

zipcode & city:

country: Netherlands

phone:

email:

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: Ir. Minnoye, A.L.M. (Sander) dept. / section: SDE / M&M

** mentor: Dr. Song, Yu (Wolf) dept. / section: SDE / M&M

2nd mentor:

organisation:

city: country:

comments (optional): Both chair and mentor belong to the same department, however, with different focus. Wolf will focus on the (testing of) structural electronics . 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.

TU Delft

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

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

chair: Ir. Minnoye, A.L.M. (Sander) date: 05-03-2020 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: 30 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:

(✓) YES all 1st year master courses passed

( ) NO missing 1st year master courses are:

name: date: 10-3-2020 signature: CB

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

comments: Approved, but abbreviation in title must be written in full

name: Manon Borgstijn date: 02-04-2020 signature: MB

Initials & Name: K.T. Eekhout Student number: 4228715

Title of Project: Design and prototype of a large scale electronics FDM 3D printer

Design and prototype of a large scale electronics FDM 3D 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 17 - 02 - 2020 — 24 - 07 - 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, ...).

Rapid prototyping has become a indispensable part of product design and development. The development of 3D printing has greatly reduced the time needed to make prototypes of physical products and decreasing development time.

Relatively new in the field of 3D printing is printing with conductive filaments to create passive electronic circuits. Printing circuits directly into prototypes or product yields some interesting opportunities, namely ; 1) it offers designers more freedom in their designs; 2) it promotes miniaturization of design; 3) it accelerates the design and manufacturing process; 4) it is able to improve the efficiency of producing customized/ personalized mechatronic/electronic products and 5) it improves the sustainability in the product design and manufacturing process (Song et al., 2017).

Currently there are several "3D printers" on the market which can produce electronics, one group uses inkjet technology (Aerosol jet 5X, Nano dimension dragonfly) but these machine are very expensive (>$100.000) and large in dimensions and thus not suitable for a wide group of users. The second group are desktop printers (Voltera, Botfactory SV2) which are able to print silver ink on several substrates creating multilayer PCB's. These desktop machines are relatively low in price (~$4000) but still produce 2D parts. The last group (Voxel8, eForge) are 3D FDM printers able to print silver ink or conductive filament which makes it able to produce 3 dimensional parts with integrated circuits. The Voxel8 is not on the market anymore, and the eForge still has to be released to the market so no comments on performance can be made yet. These machines (Voxel8, eForge) are still relatively low in price (~$8000) although higher than the previous machines (Voltera, Botfactory SV2).

This shows that there is still need for a 3D FDM printer which is small (desktop size), relatively cheap and easy to use by designers. Currently there is a 3D FDM printer being developed in the applied labs using solder paste as conductive material. Solder paste is a cheaper alternative for silver ink and can greatly reduce the cost of consumables for this 3D printer.

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.

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introduction (continued): space for images

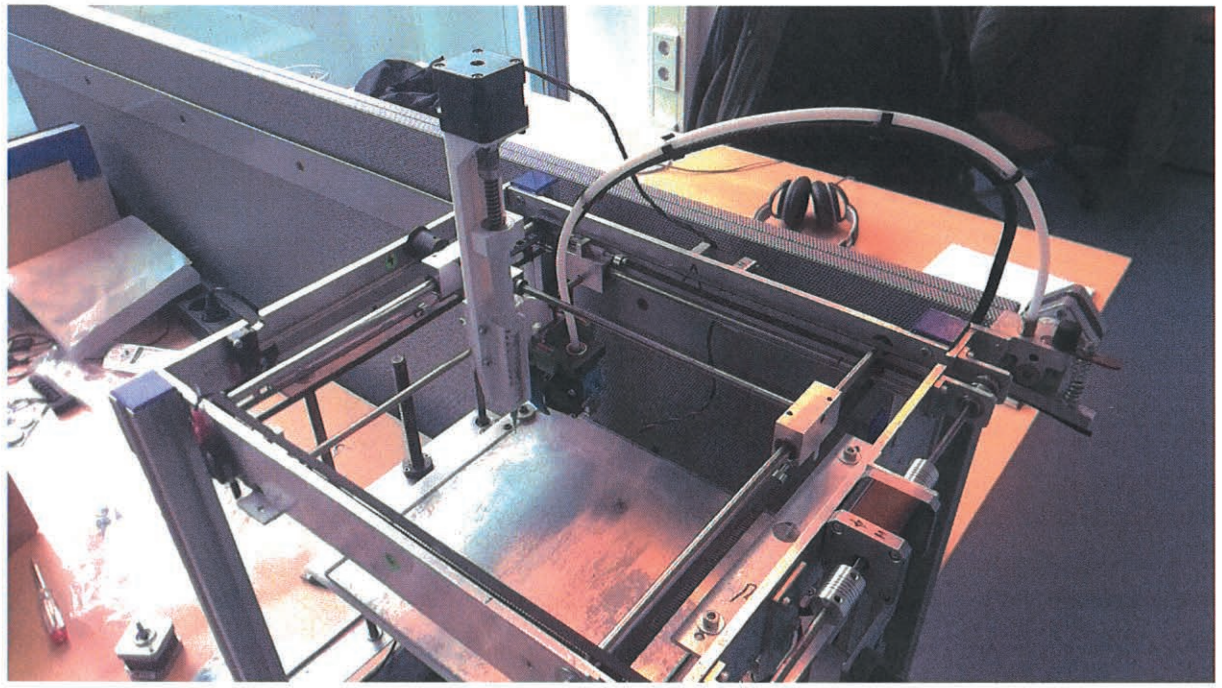


image / figure 1: The current printer in the applied labs

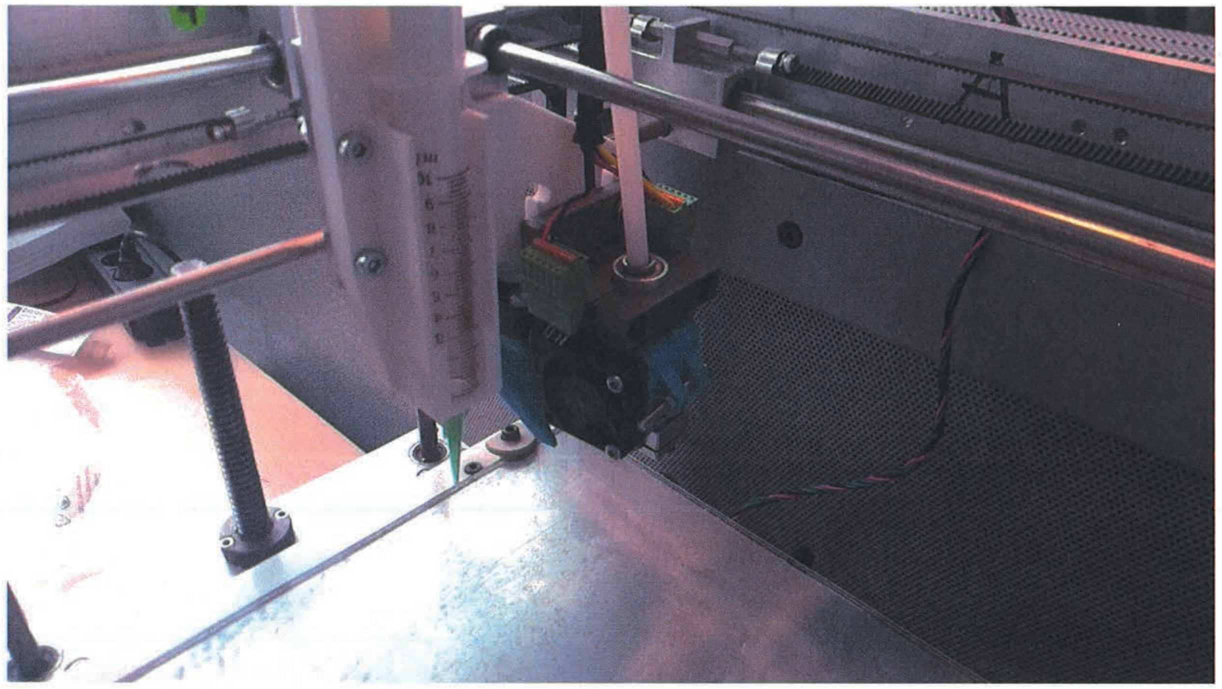


image / figure 2: Close-up of the print head with solder paste syringe (left) and thermoplastic extruder (right)

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.

The main problem is that there is no affordable option to use 3D printing to create physical prototypes with integrated structural electronics. The Voxel8 is affordable (~$8000) but uses silver ink paste as conductive material which is expensive. Considering the fact that multiple prototypes are usually made before the final prototype is finished a more affordable material is desirable.

The printer being prototyped in the applied labs at the IDE faculty is able to print 2D circuits with solder paste as a conductive material and temperature resistant PLA as the substrate in the current state of the project. After printing the solder paste has to be cured in an external oven.

To utilize this technology to its full potential the printer should work in 3D. To achieve this multiple layers of thermoplastic and conductive material should be printed on top of each other, creating 3 dimensional designs with conducting paths. Curing the solder paste after each layer in an external oven poses problems in aligning for further printing and greatly increases production time which is not desirable. The first step in achieving 3D prototypes with integrated circuits is to cure the solder paste in the printer itself during printing (on-site curing), either simultaneously or after every layer. This would enable printing multiple layers of thermoplastic and conductive material making 3D printed circuits in 3D designs.

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.

Test and prototype on-site curing of solder paste on a 3D printed substrate to enable the 3D printing of structural electronics in prototypes using an FDM 3D printer. On-site curing of solder paste would enabling multiple layers of thermoplastic and conducting material being printed on top of each other. Making it possible to print 3D designswith integrated structural electronics.

The main goal of the assignment is researching which technology will be most suitable for on-site curing the solder paste in the printer and showing a proof of concept.

If on-site curing is viable and feasible the printing of multiple layers can be tested. Testing how the stacking of multiple layers of solder paste affects conductivity and structural integrity of the 3D printed structural electronics.

If these steps are successful the new technology can be integrated into the printing head of the 3D FDM printer, optimizing the design of the printer head to maximize the usable space on the bed of the printer.

The goal is to design a demo product to as a proof of concept of on-site curing the printed structural electronics either in 3D (or 2D).

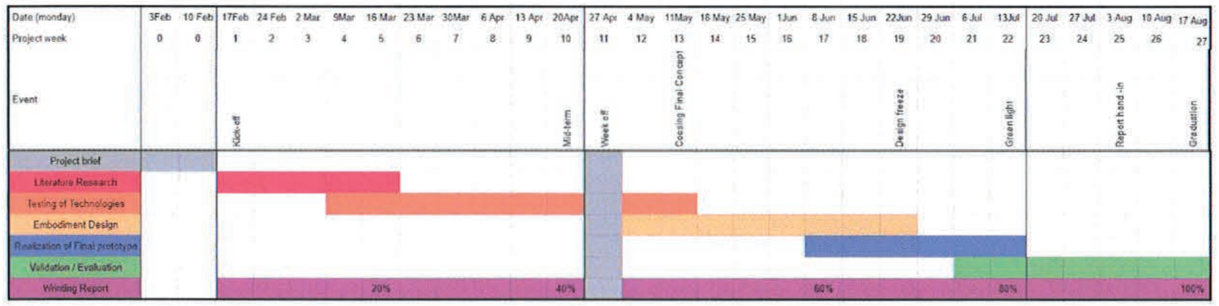
Personal Project Brief - IDE Master Graduation

TUDelft

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 17 - 2 - 2020 24 - 7 - 2020 end date



Because of working 1.5 days a week I will graduate 4 days a week which amounts to 33.6 hours a week (42 hours is 5 days). Due to 5 national holidays and 1 week off, the planning is 25+1+1= 27 weeks.

Literature Research: During this phase I want to become better acquainted with the current state of the project and the state-of-the-art. During this phase preparations are made for the testing of different technologies for live curing solder paste.
Testing of Technologies: Different promising technologies from the literature research are tested to see which is the most promising, if tests runs smoothly and a suitable technology is identified early on further testing with stacking multiple layers can be done. I want to present a suitable technology during the midterm evaluation.

Embodiment Design: The most suitable technology must be integrated into the printing head of the 3D printer to enable testing in a real environment. Testing and prototyping are to be done during this phase to develop a final design.
Realization of Final Prototype: This is a phase in which the final prototype will be built for validation / evaluation and demonstrating purposes.

Validation / Evaluation: Evaluating the final design in a realistic environment using the final prototype.
Writing Report: I want to start writing my report from the start to keep track of what has been done. Different progress marks of written down to remind me of where I should be.

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.

My main passion in my master study at IDE is the embodiment phase of the design process. Making prototypes and physical (scale) models is a useful part of the embodiment design phase and 3D printing is a very useful tool for making prototypes quickly (rapid prototyping). Making physical models and 3D printing have become a hobby of mine over the last several years.

Although making models has been something I like to do for a while, integrating electronics into prototypes is something I am not yet very familiar with, and I would like to learn more about this. Electronics are in more and more products and the amount keeps growing thus showing the importance of prototyping physical products with electronics.

Another ambition is learning more about the physical en electronics design of a 3D printer itself, until now I only used the printer to make models but I never worked on improving the actual design of the printer. Working for a company developing and designing 3D printer is one om goals after graduation.

FINAL COMMENTS

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