Activating a CMOS Pixelated Capacitive Sensor Platform by Inkjet Printer

Hardware Group Bachelor Graduation Thesis

by

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Abstract

The manufacturing of sensors often requires the precise deposition of small volumes of liquid. In order to do this, expensive industrial equipment is often used, giving this form of manufacturing a high financial barrier to entry. As standard desktop inkjet printers operate by precisely depositing small volumes of paper onto a substrate, typically paper, the goal of the project was to modify a desktop inkjet printer, the Epson EcoTank ET-8500, to allow it to be used to deposit small droplets of fluid onto a CMOS sensor chip.

This report covers the design process of the hardware modifications that were necessary in order to allow the Epson EcoTank ET-8500 to print onto CMOS sensor chips packaged in a QFP-44 package. These modifications include a custom chip tray to safely house the chips as they go into the printer, as well as an external fluid system to allow the user to easily use ink other than the stock ink provided by Epson or to put a cleaning fluid into the system in order to clear out any residue deposited by the inks used. The results obtained indicated high levels of precision, and the system's accuracy was sufficient for the sensor chips used. The external fluid system was also tested and successfully allowed the printer to work with fluids not placed into the built-in tanks.

Preface

We would like to acknowledge and thank our supervisors, Suman Kundu and Frans Widdershoven, the former for his unrivaled guidance. He has been a great inspiration and help, without whom we may never would have reached the product we have now. He always helped us in finding solutions when we found a roadblock and stimulated us to be creative in all situations or to at least *think about it* and the latter for his continued support, delivering the CMOS chips in collaboration with NXP that were indispensable to the project as well as being a great source of information and inspiration.

Tao Shen for giving us the workshops necessary to gain the skills to properly conduct the research and give us a helping hand in some practical matters which helped us develop our final product.

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And finally the TU Delft's Open Research Hardware Stimulation Fund for funding the purchasing of any tools, components and other hardware as well as the department of Bio-electronics in special for lending us the research facilities.

Without the support of these parties, all of this research would not have been possible.

Nicky Chen & Daniel Rueda Lindemann
Delft, August 2024

Contents

1

Introduction

1.1 Inkjet Printers

Nowadays printing technology has become widespread, available to most if not all middle-class families. Despite its rather low costs, the technology is already very mature and can print to a very precise degree. The printer used for research in this thesis, the Epson ET-8500, has shown from testing that it is capable of printing with an incredible accuracy of up to a tenth of a millimeter of distance between two different droplets with ink droplets with a diameter of around 80 micrometers.

With this accuracy, a lot more can be achieved than just daily printing jobs such as high precision deposition of fluids. If one were to be able to print on CMOS chips, then it would enable both in theory and in practice the fabrication of capacitive sensors readily available for anyone to do at home. This would make sensor technology a lot more accessible as compared to before, for one needed very expensive and complicated machinery to produce them. This in turn makes the product also rather expensive.

1.2 State of the Art

The Epson ET-8500 is an inkjet printer that uses a piezoelectric printing technology. This technology is currently the most reliable in terms of drop consistency and speed. It uses piezo-driven inkjet printhead that is activated by a voltage waveform applied to a piezoelectric transducer. This in turn changes in shape when activated, generating a pressure pulse in the ink chamber, causing a droplet of the printing substance to drop[1].

Although the technology is readily available, the option for a consumer to easily print any substance on any substrate is far from accessible. This is due to a few different reasons. Two of them being the nature of the printers usually only allowing for (easy) printing on paper, thus the transition to other substrates requires significant alterations to the printer and the second is that printing software is not properly documented for the public to view and ultimately to understand.

Despite the fact that manipulating a printer to do what a consumer exactly wants is made quite difficult by the manufacturers, there have been more people who have tried to control their printer through unconventional ways. Such ways can mean both the making of significant hardware changes as well as the use of driver commands. More on this will be mentioned in section 1.3 Similar Research.

On the other hand, if one were to refer to more advanced printers, which are usually known as material printers. Though, these do cross over more in the territory of 3D printers. As mentioned before, these printers can be rather pricey, with prices starting in the ten-thousands going up to over a million euros, but they can also be rather large, smaller ones are about double the size of household printers while the larger material printers can be as large as a a medium sized room, which also depends on the kind of material that is printed by the printer.

Theoretically, these more expensive printers are also able to print on a resolution of up to 1200 dpi up to an accuracy of even 2900 dpi. According to the documentation of the Epson ET-8500, it should have a printing resolution of up to 5760 x 1440 dpi. Although, in practice, the highest practical resolution is 720 x 720 dpi. Though, taking into account the sizing of the printed dots, this is plenty for the manufacturing of capacitive CMOS sensors.

1.3 Similar Research

As previously mentioned, this project is not entirely unique in its premise of taking more or full control of a household printer.[2]

In some cases an effort was also made to print on surfaces of one's own choosing. Other research also proved that using a printer's CD printing feature is usable as a platform to jump start the development from.[3] [4] [5].

Other research was also done on the potential of CMOS pixelated capacitive sensors, the same concept this project builds on. [6][7][8]

1.4 Synopsis

Using this information and personal research, the latter of which will be reported on in this document. The printer was eventually modified to allow for cleaning with cleaning solutions altering the tubing with custom tubing, valves and extra ink tanks to store the cleaning fluid in. Next to that, direct printing on the chip using a tray for the chip, based on the tray for CDs and DVDs, together with the in-built CD and DVD printing function of the printer.

2

Project Description

2.1 Problem Definition

To alleviate the scarcity of affordable sensor fabrication options and to make it more easily available, we come to the Epson ET-8500. To achieve this some modifications need to be done, such as modifying the printer itself to allow for printing on the chips physically. Also, the digital print method needs to be changed to allow for dropping individual dots on the specified locations. Afterwards, the chips must be measured and analysed to see if the printing succeeded. These tasks are divided into three subgroups

- Hardware
- Software
- Measurements

This thesis focuses on the hardware part of the project. In the roadmap of Figure 2.1 this part of the project is outlined in red. The task to redesign some parts of the printer or entirely remove them to allow for printing on a different surface than paper, CD or DVD for which the printer was produced. Finally, full control has to be taken of the printing mechanics of this printer to control each dot that is printed to allow for full control.

This results in the problem definition:

"Can an Epson ET-8500 be both manipulated physically and taken control of digitally to print on a CMOS chip surface?"

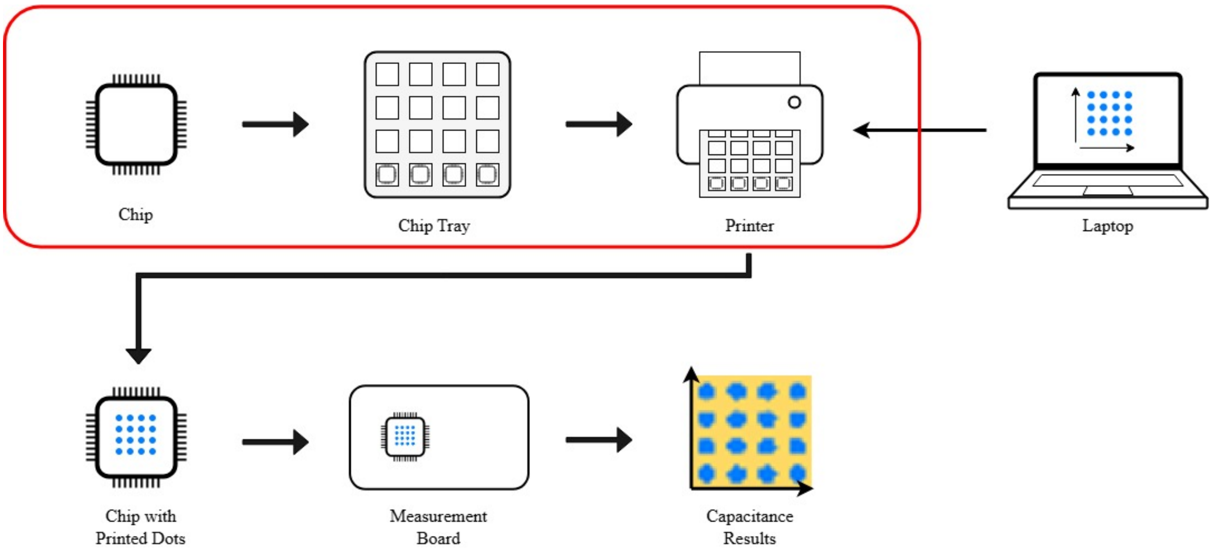


Figure 2.1: Block diagram of the whole process for printing on and measuring a CMOS chip. Outlined in red is the part that the hardware subgroup is responsible for.

2.2 System Limitations

Because of the nature of the project being based on existing technology, some limitations have been set for the project beforehand. These limitations can be considered in the context of substrate limitations, printing fluid limitations and finally hardware limitations limitations. Substrate limitations being limitations that are set for the usable printing substrates. The fluid limitations have to do with the nature of the printing fluids. The hardware limitations have to do with anything related to hardware.

Measures of Quality

Combining these factors, the goal was to achieve fluid droplets of the highest quality achievable. Here, the quality of the droplets is measured by the following properties:

1. Droplets with as little splash as possible when deposited
2. Droplets with a form that is as round as possible
3. Single droplets that are not mixed with other neighbouring droplets

Substrate Limitations

The substrate limitations mostly have to do with the tray that is used to present the CMOS chips to the printer. These are as follow:

1. The tray has to be slanted slightly at the end that is inserted first to be nudged under the rollers
2. The width of the tray has to be at most 18.7 cm
3. The tray needs to have 3 holes to allow for the printer's internal sensor to scan
4. Although the tray can be as long as the user wants it to be although
   a) The length of the printable area is 12.2 cm
   b) The width of the printable area is 13.5 cm

5. The distance between the printhead and the substrate should be ideal such that the printed droplets resemble the properties as mentioned above in section subsection 2.2.1 as much as possible

Fluid Limitations

Because of the nature of the printer, the fluid needs to adhere to a few limitations to achieve a proper product as described in section subsection 2.2.1. Those are the following limitations:

1. The printing fluid should preferably not harden or harden very slowly
2. The printing fluid should not be able to dissolve the tubing or fluid tanks of the system
3. The printing fluid should consist of (mostly) fluid components at room temperature

Hardware Limitations

Finally, the following limitations are imposed on any hardware alterations of original components or custom designed components:

1. Any alterations to the printer should not impede the normal functioning of the printer, this entails
   a) The printhead's movement should not impeded
   b) The fluid flow inside the printer should not be obstructed

2.3 Programme of Requirements

Down below you will find a list of the complete programme of requirements for the entire project in more detail. The requirements can be divided into requirements and goals. Both of which are defined to achieve the proper printing of good ink droplets as defined in subsection 2.2.1.

Requirements

The requirements are as follows:

[1] The printer must be manipulated to a minimal degree and should not expand the printer's volume by more than 20 %.

[2] The manipulations should be easily reproducible.

[3] The hardware should enable the user to print on a thin CMOS chip.

[4] The hardware should allow the user with the right software to print droplets that check the requirements 2.2.1 to a high level.

[5] The hardware should allow printing that is reproducible both in quality and accuracy.

[6] The hardware should be accessible to cater to a large audience.

[7] The hardware should allow for a wide range of fluids to be printed that is not limited to only ink.

[8] The hardware should allow for the user to easily clean the system

[9] The hardware should allow for a wide range of cleaning fluids to accompany the printing fluids.

3

Chip Tray

In order to be able to deposit ink droplets onto the chip, a tray had to be designed to hold the chips in place inside the printer. This chapter outlines the process by which the tray was designed, the way it was ultimately manufactured and various measurements related to droplet quality, repeatability across multiple insertions of the tray and accuracy when printing onto a chip.

3.1 Design Process

CD Tray and Early Prototypes

The goal when designing the first prototype tray was simply to prove whether it would even be possible to use a tray other than the stock CD tray, and what features would need to be a part of the design in order to so. The stock CD tray's dimensions were measured and copied to design the first prototype tray, whose dimensions and design can be found in Figure 3.1. Although not shown in the overhead profile in Figure 3.1, the tabs at the top of the tray are all angled to allow for easier insertion under the printer's rollers, from the thinnest point at 0.7 mm to the thickest point at 2.7 mm. As the tray's filleted edges serve a largely cosmetic purpose, the radii were not measured and were instead estimated visually. This never caused any problems.

After the tray was designed, it was 3D printed, however, before that could be done, the tray's height had to be reduced to fit within the 220 x 220 mm print area of the Creality Ender 3 V3 SE that was used to 3D print the tray, these changes are reflected in Figure 3.1. More details on the process of 3D printing the trays can be found in Section 3.2.

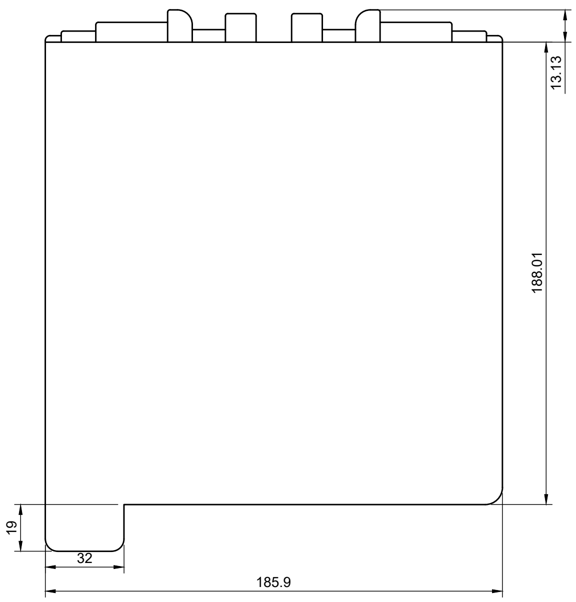


Figure 3.1: Schematic of the first prototype tray, all measurements in mm. Tray Thickness: 2.7 mm

Upon testing the first prototype tray, it was discovered that the printer wouldn't accept the tray and would return the error "CD Tray not inserted properly". As it turns out, the ET-8500 uses a photo interrupter mounted to the printhead to check the status of four holes before it will accept the tray and start printing (shown in Figure 3.2).

Figure 3.2: Stock CD tray. Holes marked in red have to be unobstructed and the hole marked in purple has to be obstructed in order for the printer to accept the tray.

In order for the printer to accept the tray without returning an error, it first checks whether the three holes circled in red in Figure 3.2 are obstructed. If any of the three holes are obstructed, the printer ejects the tray and returns the aforementioned error. In the event that all three holes are unobstructed, the hole circled in purple in Figure 3.2 is checked. This time, if the hole is unobstructed the printer once again ejects the tray and reminds the user to place a CD into the tray. This last check was not of concern, as the tray was going to be solid in that area regardless, in order to maximize the number of chips that can fit on one tray.

The final modification that was made to the blank tray was the addition of the line and arrows marking the vertical alignment point when inserting the tray into the printer. This was done by recessing a small channel and two triangles into the tray's top surface at a depth of 0.5 mm. The design and dimensions of this iteration of the tray are pictured in Figure 3.3.

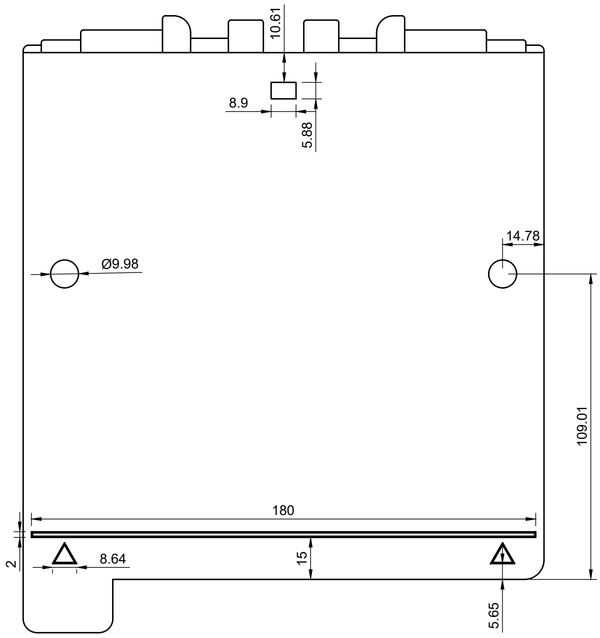


Figure 3.3: Schematic of the second prototype tray. Vertical alignment indicators recessed by 0.5 mm. All unmarked dimensions are unchanged from the previous version. All measurements in mm.

Designing the Chip Tray

Once the blank tray was proven to be functional, work was started on designing two different trays. The first and most important tray that needed to be designed was the chip tray, as without it the project could not be completed. The second tray was designed to hold microscope slides, however as this tray was not directly necessary for the completion of the project, details about its design process that weren't relevant to the design of the chip tray can be found in Appendix B.

In order to design proper cutouts for the chips, the dimensions of the QFP-44 packages were measured, with the measured dimensions being 12.1 x 12.1 x 1.36 mm. In order to account for physical tolerances of both the chip and the tray itself, as well as to make sure that the chips would not stick out of the tray when inserted, the chip cutouts were designed with the dimensions 12.3 x 12.3 x 1.5 mm.

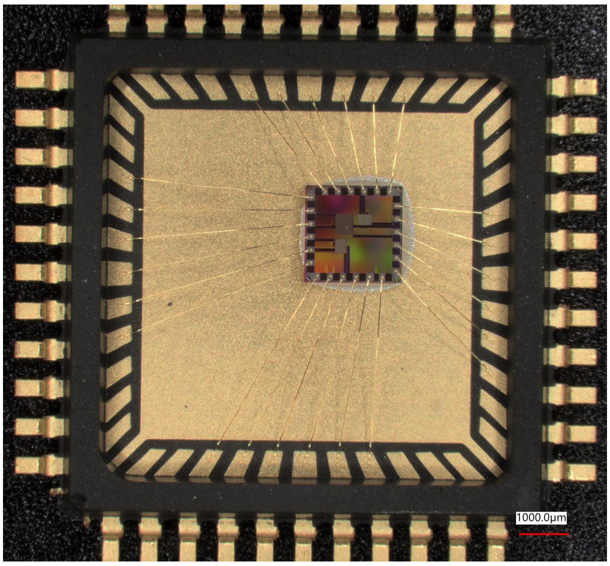


Figure 3.4: Picture of the CMOS sensor chip in a QFP-44 Package.

It was initially uncertain as to whether it would be possible to print outside of the area covered by the CD in the original CD tray, however after our software team determined that it was possible to do so, a 10 x 10 grid of chip cutouts was placed onto the top surface of the tray. Another modification that was made in this time frame was that the recessed vertical alignment indicators were deepened to go all the way through the tray to not only make them easier to see, but also to slightly increase 3D printing speed. The design of this iteration of the tray can be found in Figure 3.5.

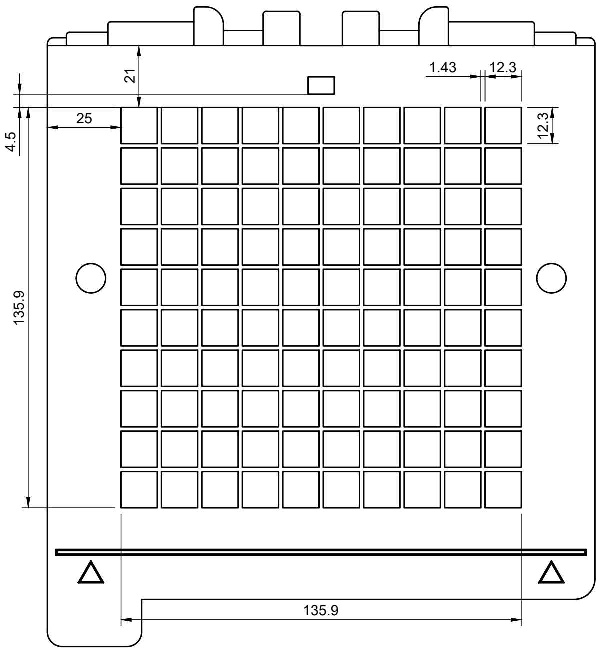
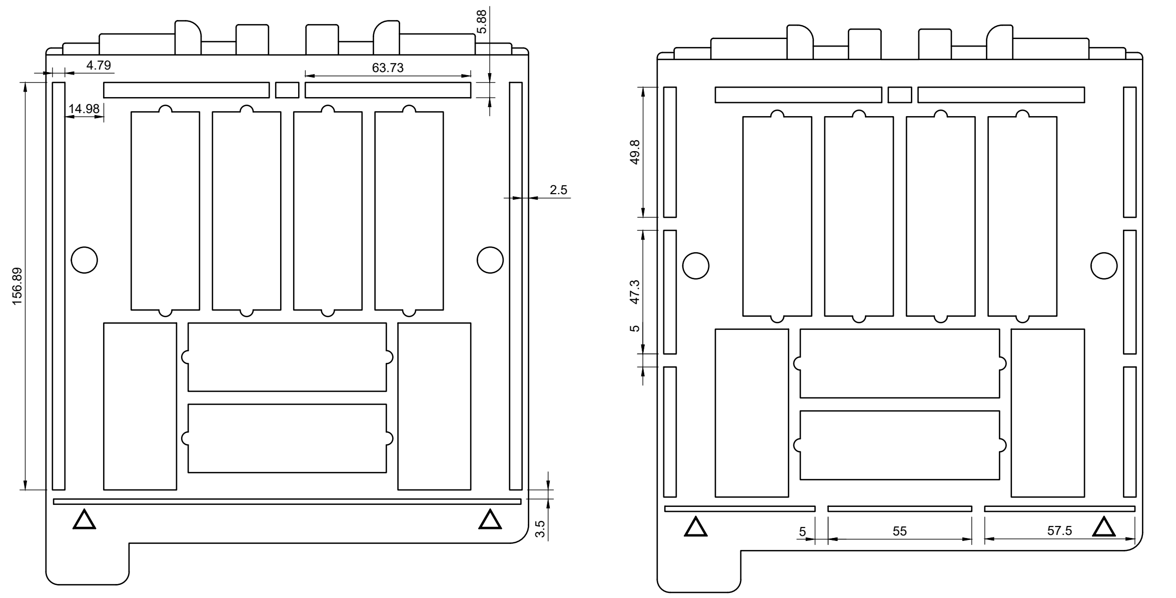


Figure 3.5: Schematic of the first chip tray. All unmarked dimensions unchanged from previous iterations. All measurements in mm.

At this point, extra holes were added into only the microscope slide tray initially to increase the tray's printing speed and to reduce the amount of filament used in the process, but these changes eventually made it into the chip tray. These holes were added outside of the print area and out of the way of the holes used to detect whether the tray is properly inserted so as to not interfere with the tray's functionality. The original design of the tray with the speed holes can be found in Figure 3.6a.

After 3D printing this iteration of the microscope slide tray, we discovered that the speed holes and the vertical alignment indicator severely compromised the tray's rigidity. As such, both lateral speed holes and the vertical alignment indicator were all divided into three smaller holes to strengthen the tray. The modified tray is pictured in Figure 3.6b.



(**a**) Microscope slide tray with the original speed holes. (**b**) Microscope slide tray with the modified speed holes.

Figure 3.6: Schematics of both iterations of the microscope slide tray with speed holes. All unmarked dimensions unchanged from previous iterations. All measurements in mm.

When incorporating the speed holes into the chip tray's design, two more holes were added in between the chip cutouts and the vertical alignment indicator. On top of this, after some tests with the original chip tray, it was determined that removing chips from the tray was more complicated than it should have been due to limited space for grabbing onto the edges of the chip. As such, in order to make the process of removing chips from the tray easier, thus reducing the chance of damaging a chip in the process, cutouts were added into the walls between chips to improve access to the chips. This iteration of the chip tray is pictured in Figure 3.7.

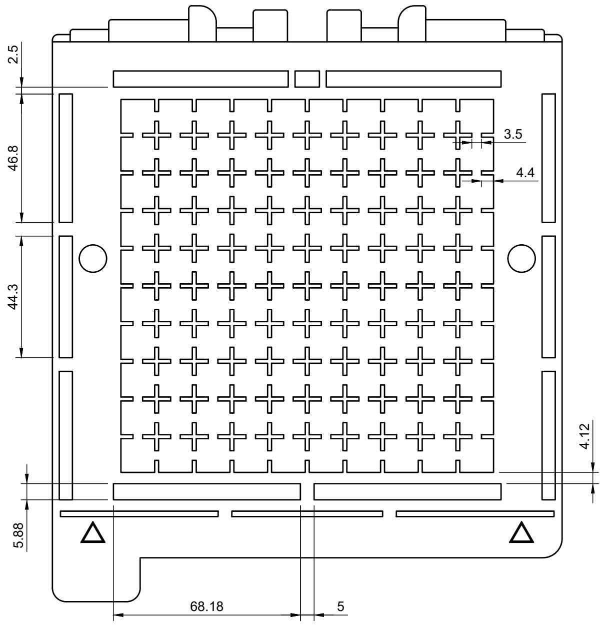


Figure 3.7: Schematic of the chip tray with speed holes and access cutouts. All unmarked dimensions unchanged from previous iterations. All measurements in mm.

Variable Depth Chip Tray

In order to test the quality of the ink droplets at various distances distances from the printhead, a modified version of the chip tray was designed with the chip cutouts in each column being at a different depth to the others. Starting from the leftmost column, which was at the same depth as the previous chip tray, namely, 1.5 mm, the cutout depth increased by 0.1 mm every column, leading to a depth of 2.4 mm in the rightmost column. On top of that, in order to allow proper access to the chips, the wall cutouts between chips were all deepened to 2.4 mm. As this iteration of the tray has the same top-down schematic as the previous iteration, refer to Figure 3.7 for its design.

After the original variable depth chip tray was tested, a few modifications were made to the design. Firstly, the bottom row of chips was removed from the tray as it was outside of the area addressable by the printing software and the printer's internal coordinates. This is further described in Section 3.2. The second modification made was that the cutouts between adjacent chips were extended into channels that ran across each row and column of the chip tray at a depth of 2.3 mm. This was done to further increase the ease of removing chips from the tray, by allowing them to be grabbed from underneath. Finally, and perhaps most importantly for the system's performance, the tray was widened by 0.8 mm to improve the consistency of drop placement closer to the tray's edges (discussed further in Section 3.3). The schematic of the final version of the variable depth chip tray can be found in Figure 3.8.

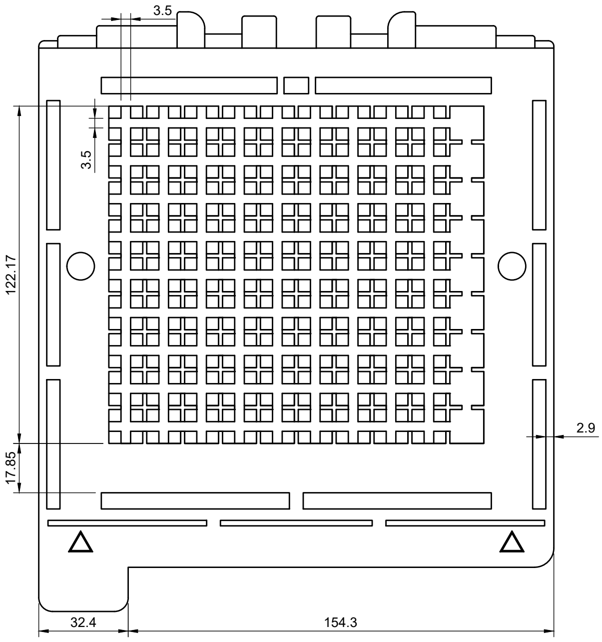


Figure 3.8: Schematic of the final variable depth chip tray with chip cutout depths varying from 1.5 mm (left) to 2.4 mm (right) in increments of 0.1 mm. Chip access channels at a depth of 2.3 mm. All unmarked dimensions unchanged from previous iterations. All measurements in mm.

Final Chip Tray

As discussed in Section 3.3, the final depth of the chip cutouts was chosen to be 1.5 mm due to its high droplet quality. The final chip tray design was heavily inspired by the final version of the variable depth chip tray. The most notable changes are as follows. Firstly, the two speed holes above the vertical alignment guide were expanded into some of the area that was formerly covered by the tray's tenth row. Secondly, the chip access channels were modified in a few ways. The first of these changes was that their depths were decreased to 2.3 mm to allow for higher quality in the final 3D printed part. Secondly, the vertical access channels were removed to allow the cutout walls to extend Vertically across the whole tray and strengthen the part; this also had the added benefit of simplifying the process of placing double-sided tape on the tray's slots as discussed in Section 3.2. Lastly, the vertical chip access channels were also widened to go into the tray's walls to allow for easier access to the chips on the edges of the tray. The inner corners of the tray's speed holes were also filleted with a radius of 2 mm for aesthetic reasons. The final tray is pictured in Figure 3.9.

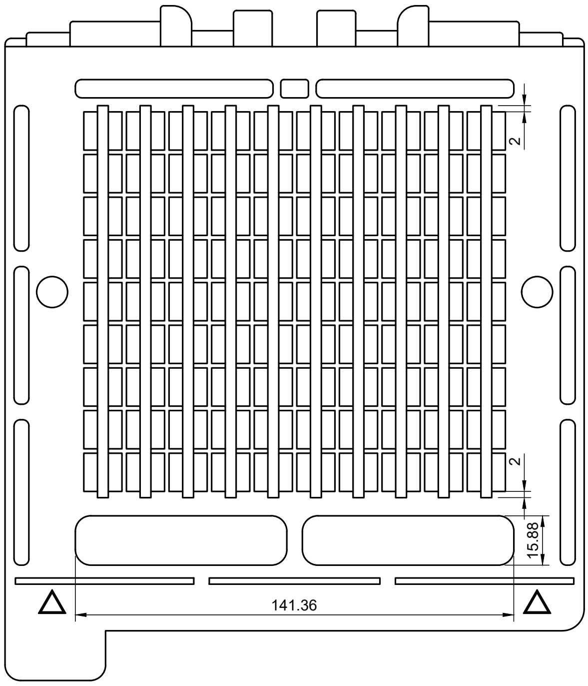


Figure 3.9: Schematic of the final chip tray. Chip cutouts at a depth of 1.8 mm. Chip access channels at a depth of 2.3 mm. All unmarked dimensions unchanged from previous iterations. All measurements in mm.

3.2 Implementation

Manufacturing the Chip Tray

In order to manufacture the trays, we decided that given the resources available to us, it would be easiest to 3D print them. All parts were printed on a Creality Ender-3 V3 SE. As the plan for the trays was not to expose them to any harsh environments, such as high temperatures or any strong solvents, Polylactic Acid (PLA) was chosen as the material for the tray due to its ease of use as a 3D printing filament. In the event that inks with stronger solvents than the water-based inks we tested were to be used, a more chemically resistant material such as Polyethylene Terephthalate Glycol (PETG), Polycarbonate or, in more extreme cases, Polypropylene would have been a more suitable material for a tray that was supposed to survive longer than the few weeks encapsulated by the span of the project.

In order to print a high-quality tray, a few settings had to be adjusted within the slicing software. Firstly and perhaps most importantly, in order to ensure dimensional accuracy along the tray's z-axis, the tray needed to be printed with a layer height such that all important surfaces were at a height that is an integer multiple of the layer height. When designing the original chip tray, we ultimately decided on a layer height of 0.1 mm as it not only allowed for the 1.2 mm height of the chip cutouts and the 2.7 mm height of the tray to be printed accurately, but it also made sure that the angled surfaces of the upper tabs would print at a sufficiently high quality while not extending the printing time beyond an unreasonable point. Once the layer height was chosen, it also made the decision to increment the depths of the variable depth chip tray by 0.1 mm incredibly easy, however it meant that the surfaces at a depth of 2.4 mm were only three layers thick, meaning that there were a few small holes on those surfaces where the printer wasn't quite able to fill up all of the gaps. This and other notable print settings can be found in Table 3.1.

Table 3.1: Relevant 3D Print Settings for Manufacturing the Trays.

Print Setting	**Value**
Nozzle Temperature	218 °C
Bed Temperature	60 °C
Layer Height	0.10 mm
Perimeters	3
Top Solid Layers	5
Bottom Solid Layers	4
Fill Gaps	True
Perimeter Generator	Arachne
Fan Speed	90%
Infill Density	25%
Infill Pattern	Adaptive Cubic
Infill/ Perimeters Overlap	23%
Infill Speed	170 mm/s
Perimeter Speed	75 mm/s
External Perimeter Speed	85%
Solid Infill Speed	100 mm/s
Top Solid Infill Speed	85%
First Layer Speed	20 mm/s
Bridge Speed	25 mm/s
Travel Speed	200 mm/s
Perimeter Line Width	0.44 mm
External Perimeter Line Width	0.40 mm
Infill Line Width	0.45 mm
Solid Infill Line Width	0.45 mm
Top Solid Infill Line Width	0.50 mm

Finally, after the tray was 3D printed, small pieces of thin double-sided tape were placed into the chip cutouts in order to keep the chips firmly adhered to the tray. This was important, because a chip managed to escape the tray and got stuck inside the printer during one of our earlier tests, although with that being said, we weren't able to replicate the behavior in any of our other tests. Although ideally all chip slots would be prepared with double-sided tape, in the interest of time, only the slots we intended to use in our testing were prepared.

Using the settings mentioned in Table 3.1, the following estimated print time was achieved:

Table 3.2: Breakdown of the printing time for the final chip tray. Time format: h:mm.

Line Type	Print Time
Perimeter	1:19
External Perimeter	0:57
Internal Infill	0:30
Solid Infill	2:16
Top Solid Infill	0:27
Bridge Infill	0:35
Travel	0:22
Total	7:10

Figure 3.10: Final 3D Printed Chip Tray

Setting up the Experiments

In order to test the quality of the system, a few tests were designed using the ESC/P2 client designed by our group's software team. Going forward, specific cutouts on the chip tray will be referred to in the same way as they are denoted in the ESC/P2 client, namely with each column being denoted by a letter in the range A-J and each row being denoted by a number in the range 1-9. For more details on the layout, see Figure 3.11.

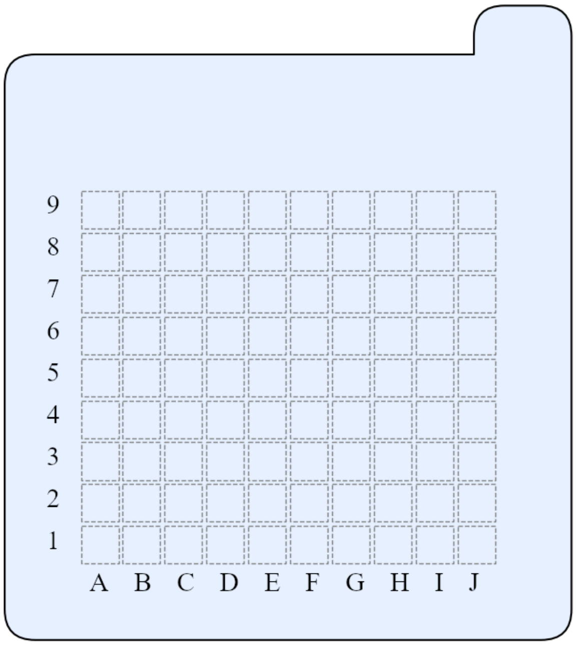


Figure 3.11: Naming guide for cutouts on the chip tray.

The first test designed was to check which depth of the chip cutout provided the greatest ink droplet quality. A test pattern was designed at a resolution of 360 dpi consisting of 28 dots horizontally and vertically, and was placed onto each cutout in row 5. All settings were kept at their default values except for "DotSize", which was changed to "VSD3 2bit", as the group's software team assured us that would result in the smallest drop size. The resolution of 180 dpi was selected to ensure there would be no merging of adjacent dots, allowing for a good measurement of dot diameter and circularity.

The second test was designed to verify whether the printer's rollers touched the surface of the glass slides upon repeated insertions. For this, a 35x100 grid at a resolution of 180 dpi was printed twice, with the pattern being inspected afterwards for any signs of smudging, which would indicate that the droplets were touched while inside the printer. The purpose of this test was to make sure no part of the printer dropped below the surface of the tray, as this could damage the wire bonds connecting the chip to the pins on the package, ultimately breaking the chip.

The third test was designed to test how accurately the printer could deposit an ink droplet at the same spot across multiple insertions. The test pattern had a horizontal resolution of 90 dpi and a vertical resolution of 60 dpi. A low resolution was selected in order to ensure that all of the ink droplets corresponding to one coordinate would be clearly distinguishable from each other. This pattern was then printed five times with two minutes in between insertions to allow the droplets to dry and minimize the degree to which dots would combine with each other. The first run of this test was conducted on all slots in row 5 in order to test whether repeatability was influenced by the depth of the cutout, however after it was found that repeatability was more dependent on the position within the tray rather than the depth of the cutout, the experiment was conducted again with the wider variable depth chip tray and slots A1, A9, E5, J1 and J9 were tested to measure the repeatability at the tray's extremes and its center.

Finally, we tested how accurately we'd be able to print onto a chip inserted into the tray. This was done in two steps. Firstly, the same 28x28 grid as the first experiment was printed, after which it was offset by 3 mm both horizontally and vertically in order to match the placement of the chip die on the QFP-44 package. Once it was verified that all, or at the very least a vast majority, of the droplets landed on the chip's die, a second pattern was designed to target specifically the sensor arrays on the chip. This pattern is pictured below:

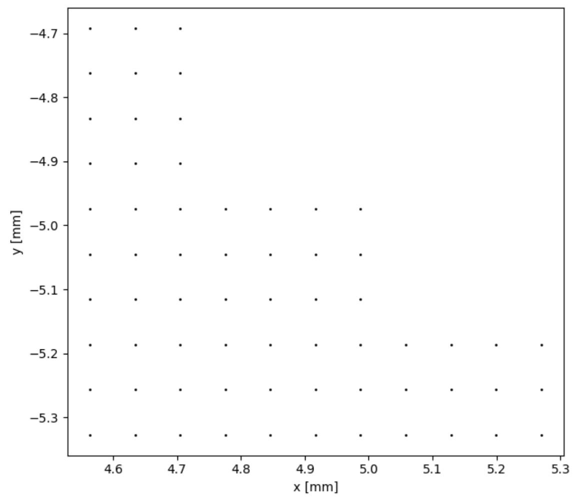


Figure 3.12: Second test pattern designed to target only the sensor arrays on the chip die. Pattern resolution is 360 dpi.

Part of the way through the project, our software team discovered that the position of the ET-8500's coordinate system's origin on the chip tray, particularly its vertical position, was within the row 10 of the chip tray. As it was not possible to send the printer a negative coordinate, row 10 was rendered unusable and was thus removed from the tray. The position of the ET-8500's origin relative to the chip tray is shown in Figure 3.13.

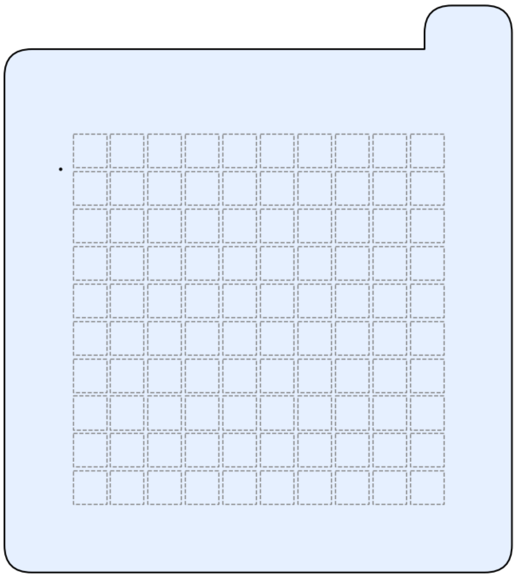
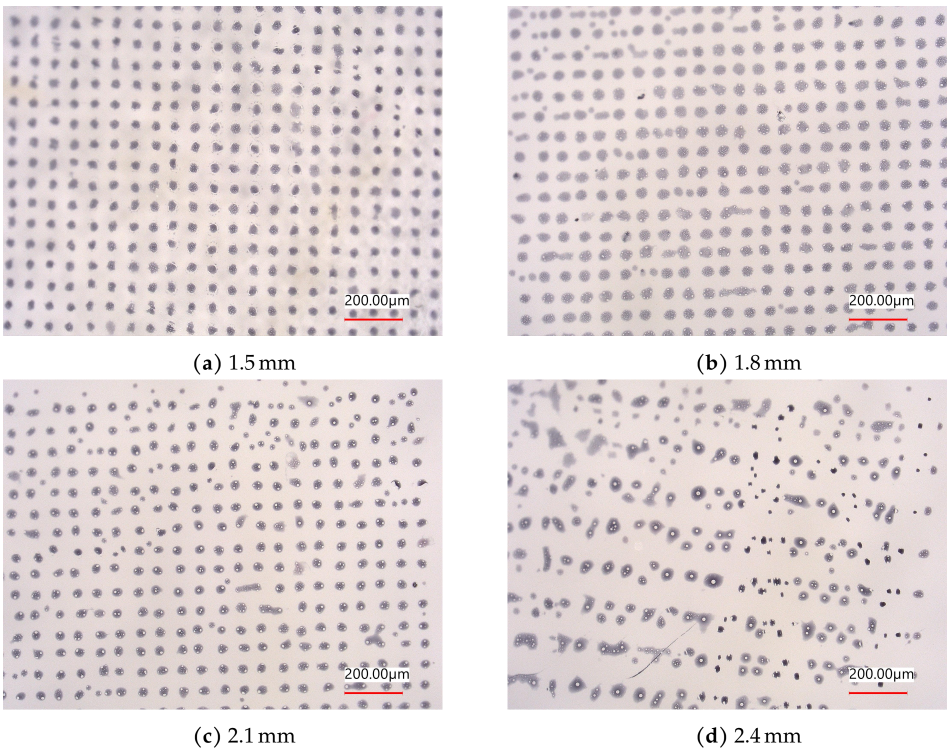


Figure 3.13: Black dot indicates the position of the origin of the ET-8500's coordinate system on the chip tray.

3.3 Results

Ink Droplet Quality

Using the methodology described in Section 3.2, a test pattern was printed onto a microscope slide cut to fit within the chip cutouts on the variable depth chip tray. The results of the experiment at cutout depths of 1.5 mm, 1.8 mm, 2.1 mm and 2.4 mm are pictured in Figure 3.14. The purpose of this experiment was to investigate the quality of the droplets at various cutout depths according to the criteria outlined in Section 2.2.1 in order to determine the optimal cutout depth.



(**a**) 1.5 mm (**b**) 1.8 mm
(**c**) 2.1 mm (**d**) 2.4 mm

Figure 3.14: Ink droplet quality at various cutout depths. Grid printed at a resolution of 360 dpi.

Based off of the results of the experiment, when increasing the cutout depth from 1.5 mm to 2.4 mm, the quality of the droplets decreases. As shown in Figure 3.14b, at a depth of 1.8 mm, most drops are still of acceptable quality, however some splitting and splattering of the dots can be seen, particularly in the upper left corner, and a few of the dots have also merged with each other. At 2.1 mm, most of the dots are once again of acceptable quality, however, there is notably more splattering when compared to the results at 1.8 mm, and once again, a few of the dots have merged. At 2.4 mm, the results are significantly worse, with the grid being almost unrecognizable as a result of the splitting, splattering and merging exhibited by most, if not all, of the dots.

As the droplet quality was visibly better for a cutout depth of 1.5 mm, measurements regarding the dot quality were only conducted for the dots printed at 1.5 mm. The circularity, C, of a dot is defined in Equation 3.1, with A being the dot's area and p being the dot's perimeter.

$$C = \frac{4\pi A}{p^2} \tag{3.1}$$

The average drop area, circularity, horizontal spacing and vertical spacing, as well as the standard deviation of the sampled dots for the cutout depth of 1.5 mm were measured with the "imageProcessing2.py" script included within the ESC/P2 client repository. The results of these measurements can be found below in Table 3.3.

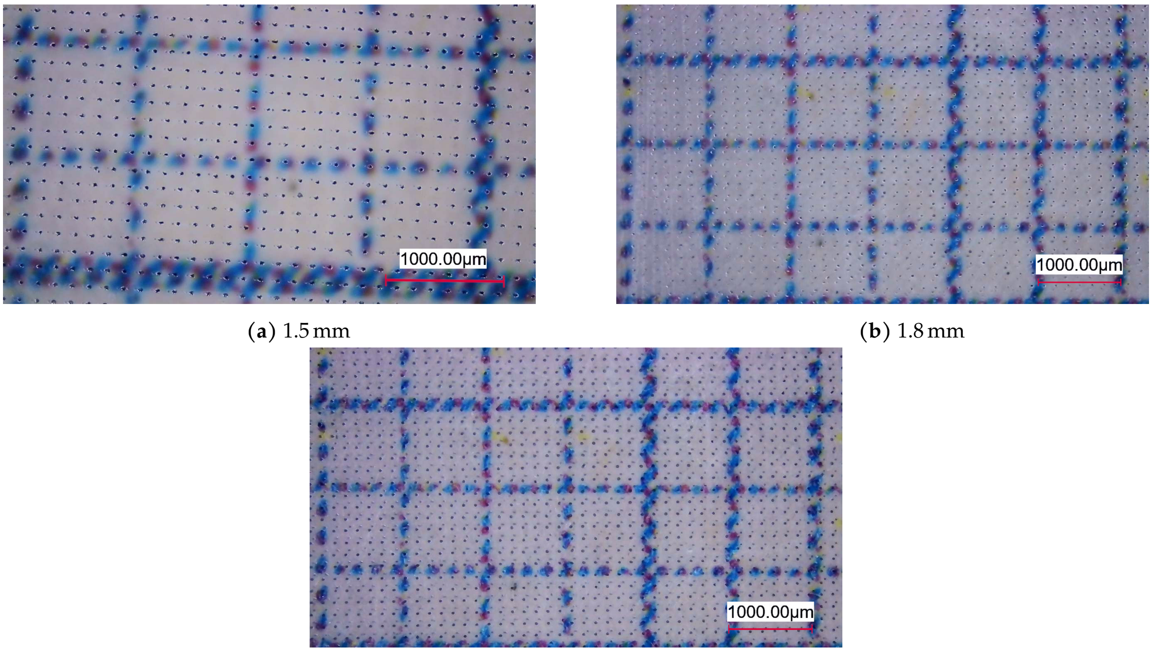
Table 3.3: Ink droplet quality at 1.5 mm height.

	Average	**Standard Deviation**
Area	587.94 μm^2	97.10 μm^2
Circularity	0.82	0.07
Horizontal Spacing	71.00 μm	2.49 μm
Vertical Spacing	69.10 μm	2.95 μm

Based off of the data in Table 3.3, we determined that the dots produced were of sufficient quality, with the average circularity of the dots being greater than that of a square, easily calculated to be $\frac{\pi}{4} \approx 0.785$ and slightly lower than that of a regular pentagon, $\frac{\pi\sqrt{5(5+2\sqrt{5})}}{25} \approx 0.865$. This measurement was likely also affected by the air bubbles inside the dots, as the pixels making up the air bubbles were not taken into account for the dot area, resulting in a lower circularity. As for the spacing, the results obtained are close enough to the expected spacing of 70.612 μm to consider the results to be sufficiently high quality.

Smudging Test

The second test that was conducted was to determine whether the printer's rollers would come into contact with the surface of a glass slide, smudging previously deposited ink droplets, thus indicating that they could come into contact with the chip's package and potentially damage it. Testing was conducted using the methodology previously described in Section 3.2 and in the interest of saving space on results that aren't particularly interesting, only the results for cutout depths of 1.5 mm (slot J5), 1.8 mm (slot G5) and 2.1 mm (slot D5) are shown in Figure 3.15.



(a) 1.5 mm (b) 1.8 mm

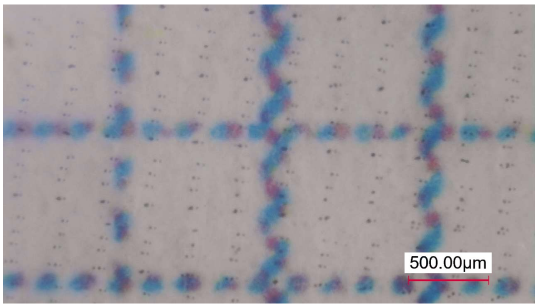
(c) 2.1 mm

Figure 3.15: Results of the ink smudging test at three different cutout depths. Grid was printed twice at a resolution of 180 dpi on glass slides at various cutout depths.

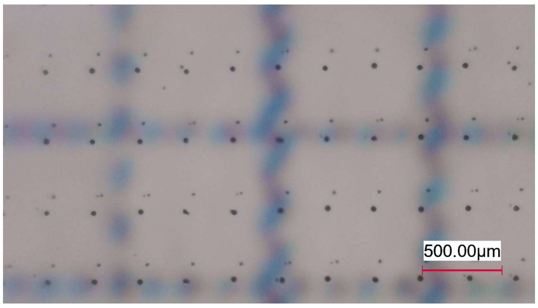
Ultimately, as can be seen in Figure 3.15, it was determined that the rollers did not come into contact with the surface of the glass slides, meaning that we were good to continue without making any other modifications.

Ink Droplet Consistency and Repeatability

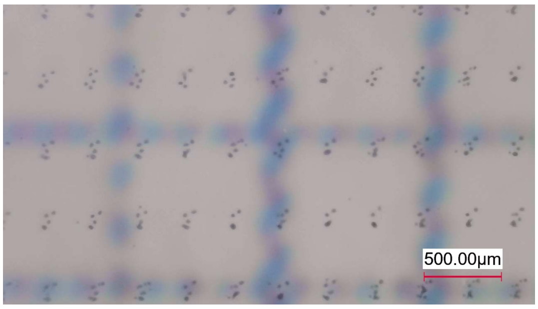
The final test conducted on glass slides rather than the packaged chip itself was to check the repeatability of the droplet placement across multiple insertions. The results for cutout depths of 1.5 mm, 2.0 mm and 2.4 mm for the first iteration of the test as outlined in Section 3.2 are pictured in Figure 3.16.



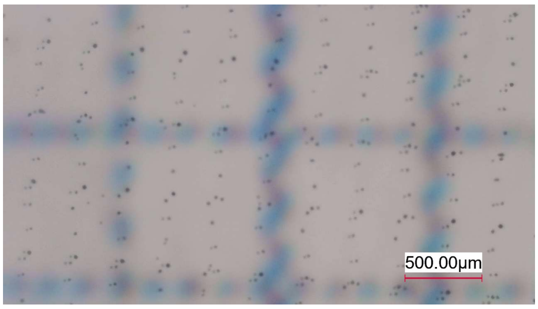
(**a**) 1.5 mm



(**b**) 1.9 mm



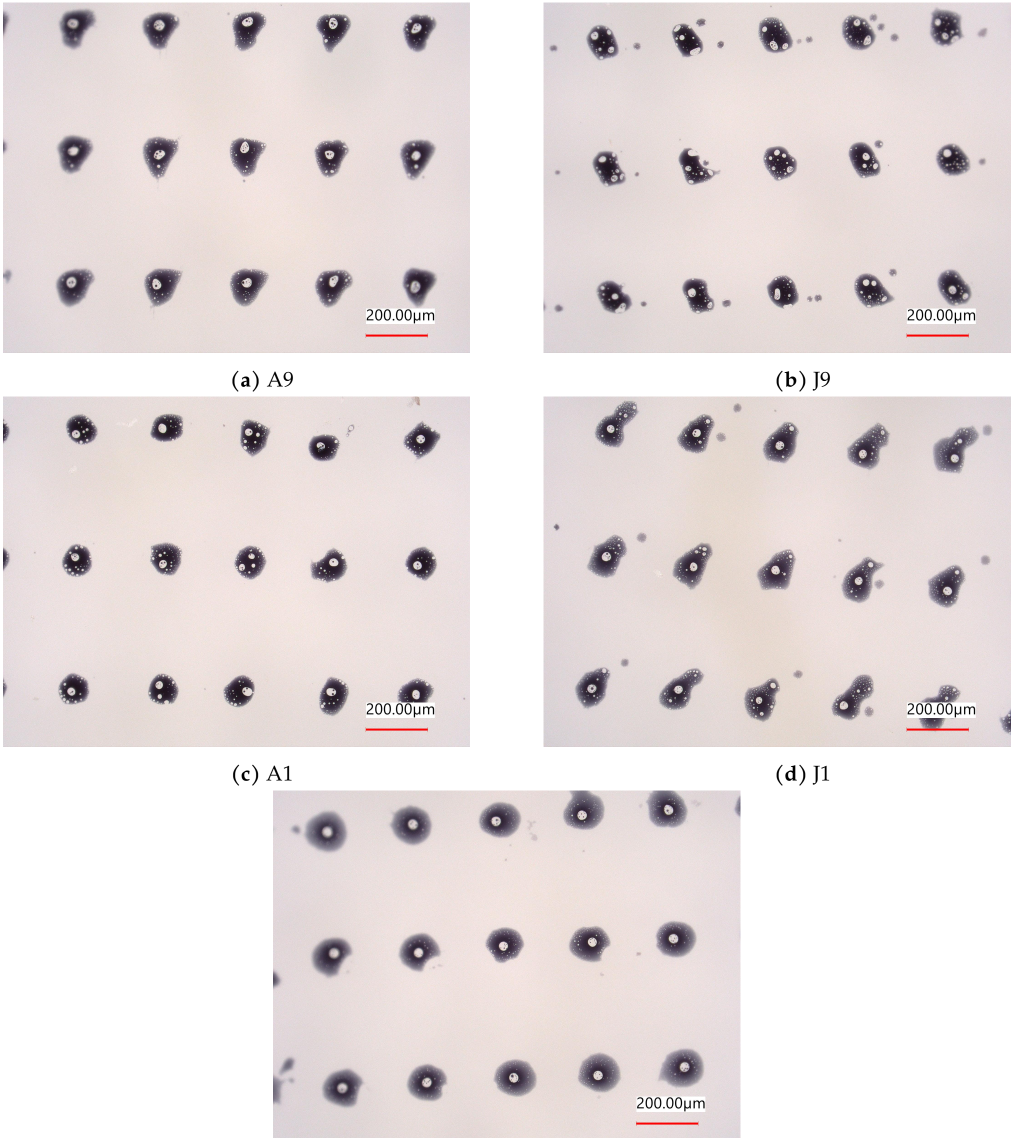
(**c**) 2.0 mm



(**d**) 2.4 mm

Figure 3.16: Results of the original repeatability test at three different chip cutout depths. Grid was printed 5 times, with 2 minutes of drying time in between prints, at a resolution of 90x60 dpi

Upon analyzing the results of the first iteration of the repeatability test, it was quickly realized that the spread of the dots appeared to be less dependent on the depth of the chip cutout and more so on the distance the slot was from the center of the tray, with depths of 1.9 mm (3.16b) and 2.0 mm (3.16c) giving the best results and 1.5 mm (3.16a) and 2.4 mm (3.16d) giving the worst. The cause of this was determined to be the gap between the edges of the chip tray and the edges of the insertion port, which allowed for the tray to be inserted at a great enough angle such that it would greatly diminish the repeatability of the results along the edges of the tray. In order to remedy this, the tray was widened by 0.8 mm to reduce the gap and decrease the maximum angle at which the tray could be inserted into the printer. After these modifications had been made, the results depicted in Figure 3.17 were obtained.



(**a**) A9 (**b**) J9 (**c**) A1 (**d**) J1 (**e**) E5

Figure 3.17: Results of the second repeatability test across five different chip cutouts. Grid was printed 5 times, with 2 minutes of drying time in between prints, at a resolution of 90x60 dpi

Figure 3.17 shows that for the areas depicted, all dots were deposited closely enough to each other for the dots to merge. As such, we deemed that the system's precision was sufficient in order to satisfy requirement [5] in Section 2.3.

Printing Test Patterns Onto Chips

The final test conducted was to print a test pattern onto a packaged chip and once that was done, to attempt to print onto only the sensor arrays. Once the 28 x 28 grid at a resolution of 360 dpi was designed, its position was adjusted in software until it was printed to almost cover the whole chip (Shown in Figure 3.18).

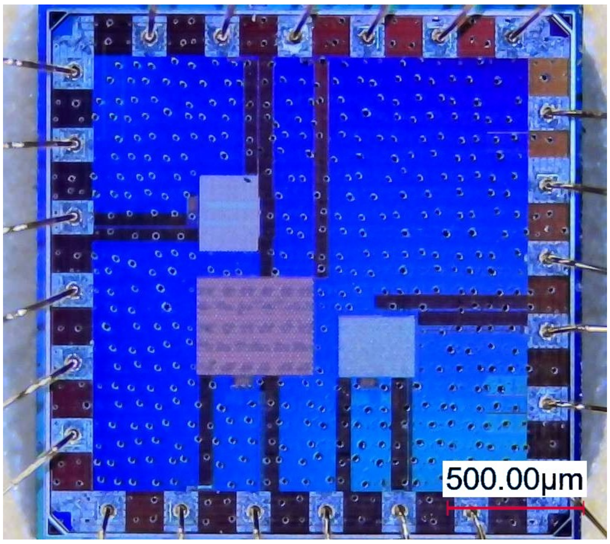


Figure 3.18: Chip fully covered by 28 x 28 droplet array.

After this was done, the printed array was modified into the array shown previously in Figure 3.12, keeping the coordinate offset the same and only changing which dots are printed. The results of this experiment, conducted on two different chips, are shown in Figure 3.19.

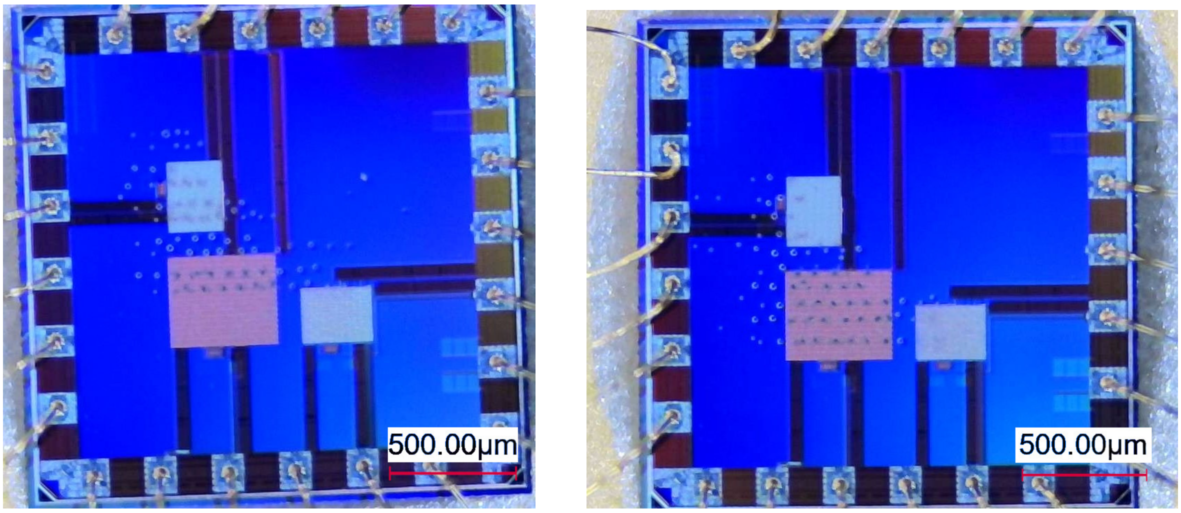


Figure 3.19: Final test pattern printed onto two different chips using the same alignment offset as in Figure 3.18.

What quickly became apparent after conducting this experiment was that the physical tolerances in the chip's placement on the package would have to be taken into account when designing patterns to print onto the chip. As there was no official documentation available on the die placement tolerances, a sample of five chips was measured in order to gain some insight into the tolerance so that they could be taken into account when designing future test patterns (which we ultimately didn't have the time to design and test). The results of the tolerance measurements can be found in Table 3.4.

Table 3.4: Horizontal and Vertical distance between the inner edge of the package's plastic edge and the edge of the die.

	Horizontal Distance	**Vertical Distance**
Chip 1	2.22 mm	2.18 mm
Chip 2	2.10 mm	2.08 mm
Chip 3	2.19 mm	2.16 mm
Chip 4	2.41 mm	2.15 mm
Chip 5	2.28 mm	2.23 mm
Average ± Std. Dev.	2.24± 0.115 mm	2.16 ± 0.054 mm

4

External Fluid System

One of the main goals of this project is to be able to print materials not originally meant to be used as printing fluids for this printer. To be able to keep the printer in as pristine a condition as possible regardless of this fact, a proper cleaning method had to be developed. The idea behind the cleaning system is rather simple, by making use of the ET-8500's built in cleaning capabilities, one only has to substitute the printing fluids for the cleaning fluids by a simple turn of a few valves when running the cleaning routine. In this chapter, we shall walk through the system by means of first describing the design process to eventually present the implementation and results that followed.

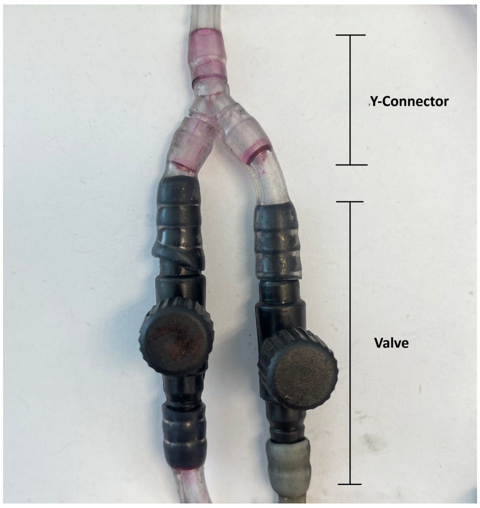
4.1 Design Process

The Cleaning system design can be divided into two parts; the first part revolves around the redesigning of the tubing to allow for extra tanks for the cleaning fluids. The second part is required as a direct result from the redesigning of the tubing system, namely the modifications of the chassis. Although not strictly necessary, it improves greatly upon the tube management and the overall structural integrity of the printer. Each subject will be touched upon hereafter respectively.

Tubing

Taking inspiration from the original tubing of the printer and taking the program of requirements as well as the extra goals. The elongation of the original tubes was the first step in the development as a proof of concept for the redesigning of the tubing. This was especially important because of the necessity of Y-connectors for the reorganisation of the tubing and allow for the simple switching between the printing fluid and the cleaning fluid. The reason this elongation is necessary to reach these goals is due to a lack of space inside the printer.

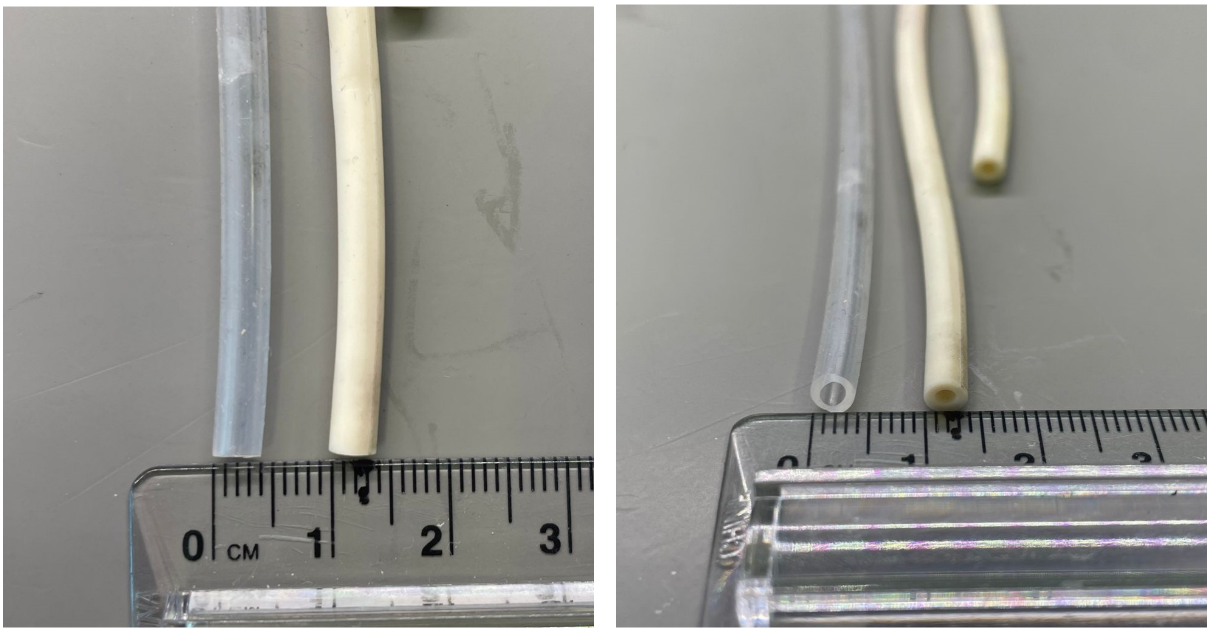
Although the proof of concept showed that the idea of Y-connectors have a great promise (figure 4.1a) it was also immediately obvious that the space next to the printhead did not provide much room for the additional Y-connectors to remain inside the original printer's housing. Although it could suffice to keep the system as is, it was clear that due to constant contact between the printhead and the tubing during printing that it is not ideal. The conclusion follows that the system is more reliable if the tubing were to be extended outside of the printer chassis such. For this, it was necessary to opt for using tubes different from the original ones. As a result, the removal of the Y-connection system from the printer's chassis would result in a more reliable system, without the printhead scraping the tubes during each printing run.



(a) The Y-connector setup with Valves connected

(b) The room for tubing within the printer chassis as pictured from the right-hand side of the printer

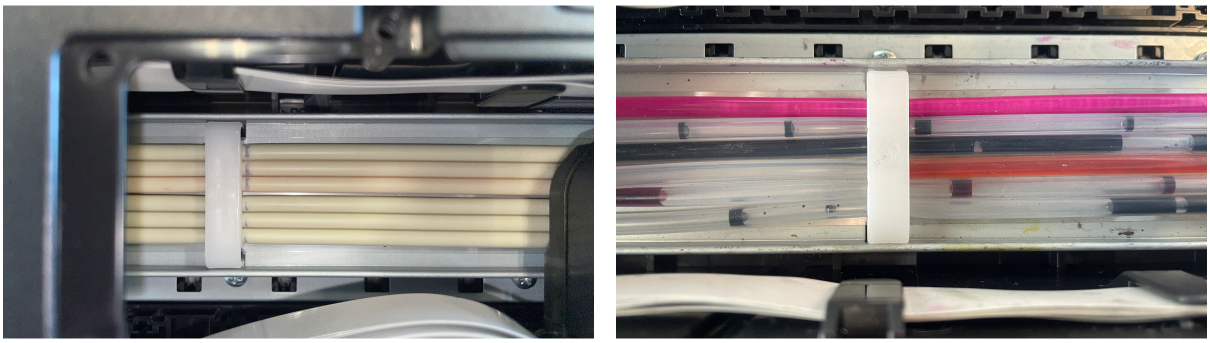
To gain the additional tubing length necessary which was lacking in the previous design, one could either opt for using connectors to extend the tubes or to entirely substitute the original tubing with new longer tubes. Although it is easily stated, it was not entirely certain that changing the tubing to non-factory standard tubes is possible due to differences in the toughness, the size as well as the chemical makeup of the two different tubes. The new tubes have an slightly larger cross diameter compared to the factory issued tube, being slightly under 2 mm inner diameter and slightly under 4 mm outer diameter. The new tubes have a cross section with an inner diameter slightly larger than 2 mm and about 4.1 mm out diameter, both tubes are shown in figure 4.2 Through testing by prototyping it was revealed that the new tubes were similarly reactive as the factory issued tubes to a solvent based (1-ethoxy-2-(2-methoxyethoxy)ethane) printing fluids [9].



(**a**) Topview of both new and original tubes (**b**) Sideview of both new and original tubes

Figure 4.2: Views of the tubes at different angles

Despite the first prototype showing that using non-original tubing works for the printer as long as the tubes were cut to a sufficient length, the toughness of the new tubing did pose a challenge in terms of fitting the new tubes in the original clamps as is shown in figure 4.3. Though eventually, the new longer tubes did allow for an extension of the Y-connector and valves to remain outside of the printer chassis.

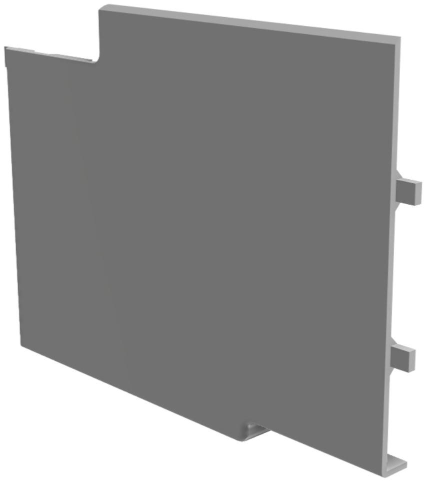


(**a**) The original tubes in the tube clamps (**b**) The new tubes in the tube clamps

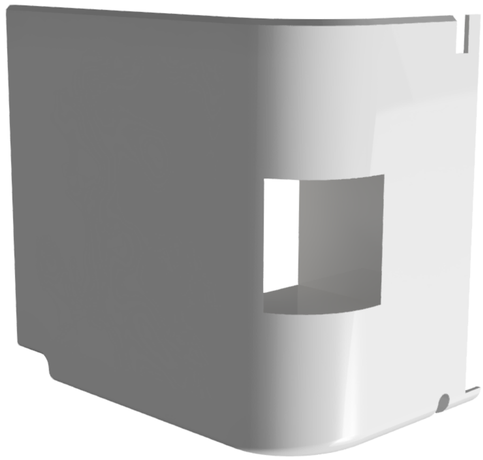
Figure 4.3: The clamps with the different tubes

Chassis

Like mentioned before, the main reason for the manipulation of the chassis of the printer is to allow for proper housing of the tubing. As such, the side panel has gone through a few iterations to first allow for tubes to exit the printer and secondly to attach the external fluid tanks to the entire printer. First, the side panel was modeled in two separate parts due to limits of the printing size that the 3D printer allowed for (figure 4.4).



(**a**) First version of the front of the side panel



(**b**) First version of the back of the side panel

Figure 4.4: The two parts of the first version side panels modeled in Fusion

Having proven the fit of the model, next the model was edited to allow for tubing to exit en re-enter the printer. Despite the hassle that assembly and disassembly pose for the design of two separate holes, the improved tube management was deemed more important (Figure 4.5).

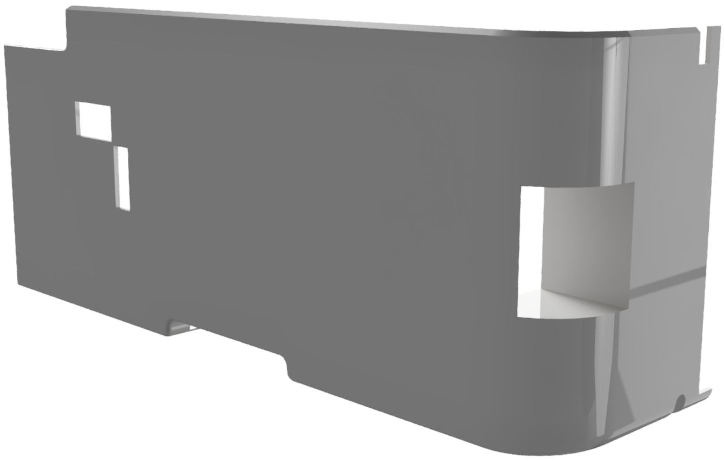


Figure 4.5: Both parts of the second version of the side panels modeled together in Fusion

As is evident from Figure 4.5, the two parts of the side panel models can be attached to each other. This is made possible with the addition of the clips as are slightly visible on the side of Figure 4.4a. Figure 4.6 shows these clips outlined in red. Furthermore, there are some clips outlined in blue. These clips are modeled after the original side panel's clips which clip onto the printer's inner components.

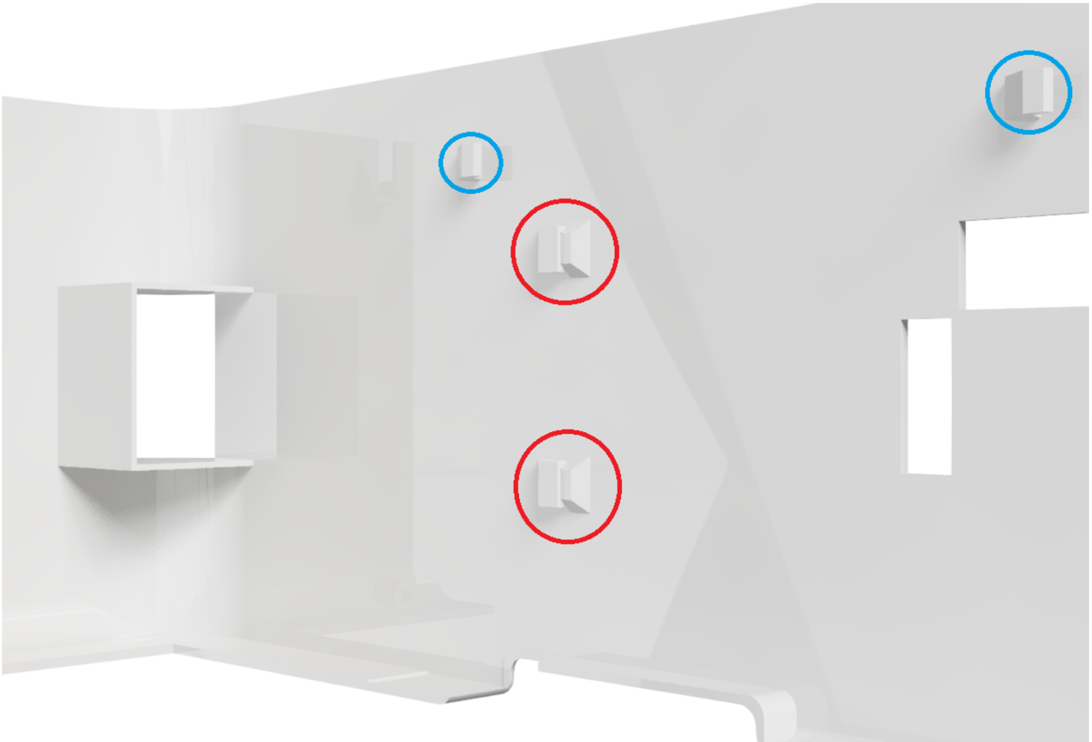
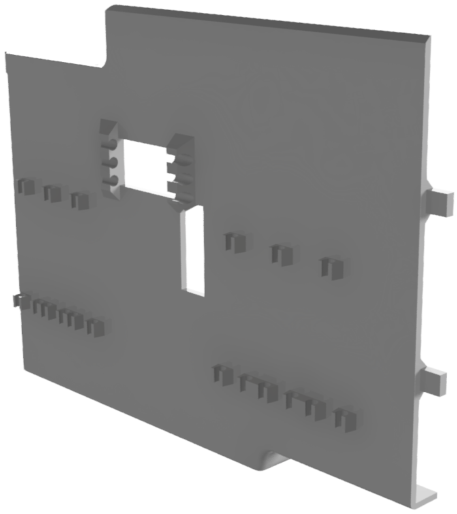
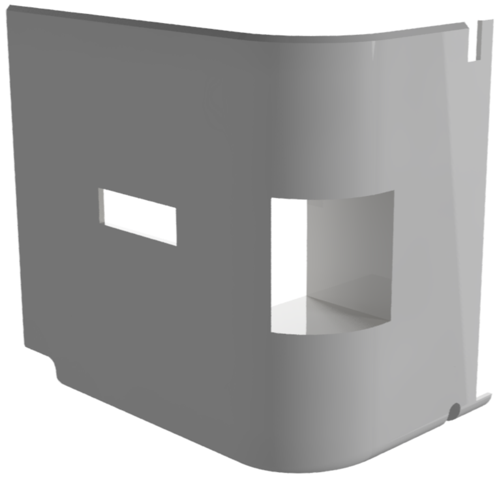


Figure 4.6: All Clips on the Side Panels

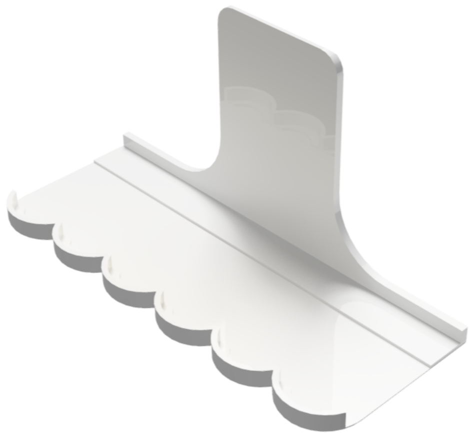
Finally, with the designing of an ink tank holder, the backside of the side panel was modified with a hole to allow for attaching the tank holder to. The tank holder was made to fit the size of the purchased ink tanks exactly tightly to make sure that the parts will not vibrate more than the printer does during printing. To also allow for proper tube management with the addition of these external tanks, additional clips to maintain the additional tubes were designed. These clips are visible in figure 4.7a.



(a) Third version of the front of the side panel with the tubing clips



(b) Third version of the back of the side panel with the hole for the ink tank bracket



(c) The ink tank holder

Figure 4.7: The two parts of the third version of the side panels and the ink tank holder modeled in Fusion

4.2 Implementation

Similarly to the chip tray and its variations as mentioned in Section 3.2, the side panels were 3D-printed using PLA. Although the original chassis of the printer is made out of acrylonitrile butadiene styrene (ABS), for the purpose of this research, PLA was used as the filament to produce the substitutional side panels. This is because PLA is rather easy to work with, the printing would take a significantly shorter time to print than other materials such as PETG. Besides that the printed products would not be exposed to any extreme environment or situations, thus a more resistant material was not needed.

To print a side panel of sufficient quality, the slicing software had to be adjusted accordingly. These settings can be found in Table 4.1

Table 4.1: Relevant 3D Print Settings for Manufacturing the Trays.

Print Setting	Value
Printing Temperature	217 °C
Build Plate Temperature	55 °C
Layer Height	0.10 mm
Wall Line Count	2
Top/ Bottom Layers	4
Enable Ironing	False
Fan Speed	70%
Infill Density	16%
Infill Pattern	Gyroid
Infill Speed	190 mm/s
Wall Speed	90 mm/s
Top/ Bottom Speed	120 mm/s
Wall Line Width	0.48 mm
Top/ Bottom Line Width	0.56 mm
Infill Line Width	0.48 mm
Generate Support	True
Support Placement	Everywhere
Support Overhang Angle	55 °

Using the settings as noted in Table 4.1, the following estimated print times were achieved for each component:

Table 4.2: Breakdown of the printing time for the final version of the front of the side panel. Time format: h:mm.

Line Type	Print Time
Outer Wall	0:17
Inner Wall	0:14
Skin	1:18
Infill	0:12
Travel	0:14
Retraction	0:39
Skirt	0:10
Support	0:49
Support Interface	0:16
Total	4:10

Table 4.3: Breakdown of the printing time for the final version of the back of the side panel. Time format: h:mm.

Line Type	**Print Time**
Outer Wall	0:45
Inner Wall	0:43
Skin	1:29
Infill	0:15
Travel	0:24
Retraction	1:12
Skirt	0:03
Support	0:41
Support Interface	0:06
Total	5:43

Table 4.4: Breakdown of the printing time for the final chip tray. Time format: h:mm:ss.

Line Type	**Print Time**
Outer Wall	0:21
Inner Wall	0:21
Skin	0:46
Infill	0:14
Travel	0:24
Retraction	0:19
Skirt	0:01
Support	0:29
Support Interface	0:00
Total	2:59

4.3 Results

Unlike the chip tray, the results that the cleaning mechanism provide are mainly cosmetic and organisational. Unfortunately the effectiveness of the cleaning mechanism could not be tested properly due to the printer breaking suddenly during the testing phase of the project. Nevertheless, the final version of the altered side panel is shown in Figure 4.8.

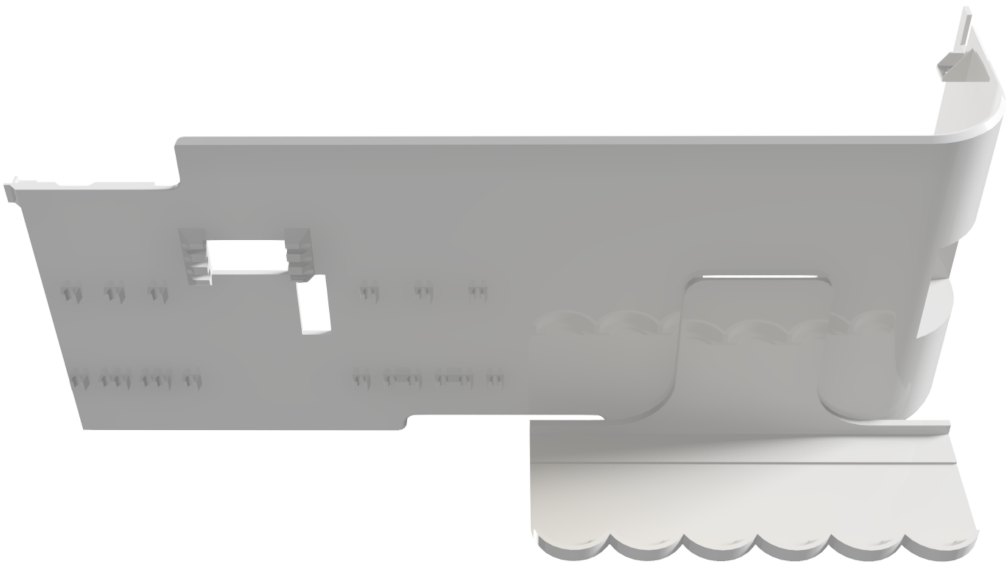


Figure 4.8: The entire cleaning system from side view

The tanks designed together with the cleaning mechanism can potentially serve a second purpose in which it can be used as a tank for customised inks. Due to the practical issues that occurred during the testing phase. Without any clear reason as to why these errors, it was decided that an alternative method of connecting the fluid tubes that does not require the redoing the tubing of the entire printer was most promising. This method of tubing has a similar tubing length between the print head and the external tanks, omitting the standard tubing routing. This means that the external tanks can not be used to clean the standard tubing, but it can be used for extra ink storage to store additional (custom) inks suiting the user's needs.

Following these limitations, successful prints were achieved both using custom inks as well as external ink tanks. These were achieved using syringes to fill the tubes right before they are to be connected to the printheads. The results of the prints as mentioned here are shown in Figure 4.9 and Figure 4.10. Although the results show the potential of external tanks, it should be noted that the use of the syringe to fill the tubes is rather time consuming and at times also unreliable in the sense that it does not fill the tube sufficiently to the top or properly leaving air bubbles, both of which may degrade the quality of the print results.

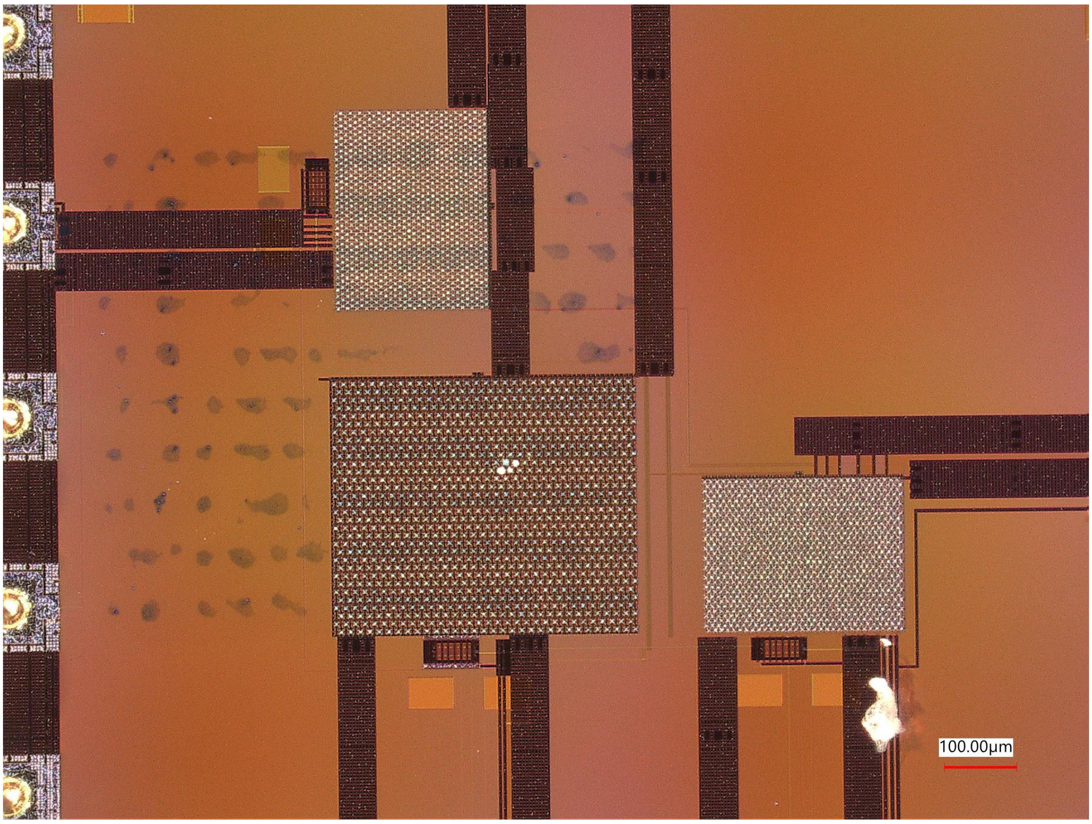


Figure 4.9: Wide view of the print using a customised ink containing SnO_2

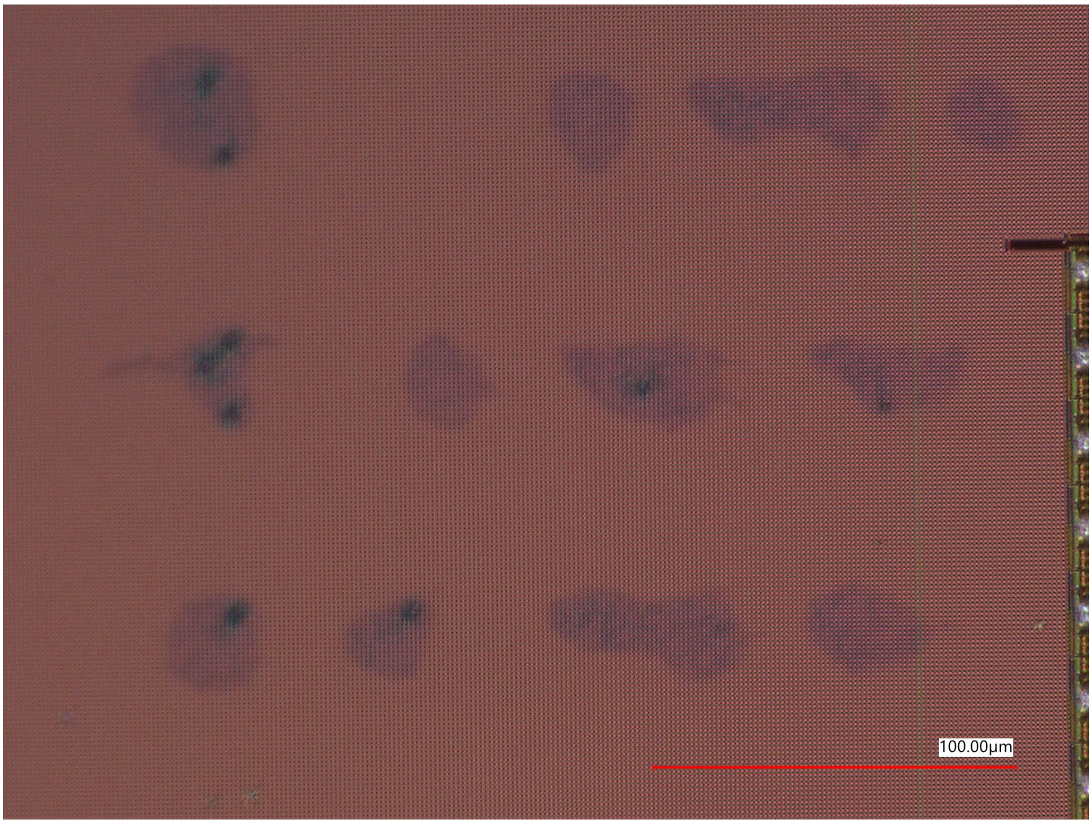


Figure 4.10: Close up of the print using a customised ink containing SnO_2

5 Conclusion

The primary goal of the project was to design a system such that the Epson ET-8500 could be used in the manufacturing process of CMOS sensor chips by depositing small droplets of fluid onto the chip's surface. In order to do this, two main systems needed to be designed. Firstly, an alternative tray to replace the printer's CD tray was designed to hold the chips and allow them to be inserted into the printer for the purpose of printing various patterns onto them. Secondly, an external fluid system was designed to allow for the user to easily use their own ink, as well as giving the user the opportunity to load in cleaning fluids in order to unclog the print head and printer tubes..

In order to evaluate the project's success, we turn back to Section 2.3, the Programme of Requirements. Requirements [1], [3], [4] and [6] with the decrease in the financial barrier to entry for high-quality 3D prints being a clear contributor to the accessibility of the system. As for the ease of manipulation described by requirement [2], the original system designed clearly put the printer at risk of being damaged, likely as a result of the replacement of the ink supply tubes. That being said, we still consider the requirement satisfied, as we were able to devise an installation method that didn't show signs of damaging the printer. The quality and reproducibility as outlined by requirement [5] are described in Section 3.3. As most droplets were deposited onto the glass slides closely enough for them to recombine upon testing the repeatability and reasonably circular drops with a radius of approximately 10.4μm, this requirement is deemed satisfied. Although we conducted some tests with the Epson T890A white ink and deemed it unsafe to use with the system seeing as it could react with many of the plastics found within the printer, all of the tests we conducted with water-based inks were successful. Although we haven't experimentally verified this, we also believe that inks based on solvents that don't react with the printer's plastics should cause no problems. As such, we believe that requirement **??** is satisfied. As for requirement [8], given that we didn't explicitly test the external fluid system's performance as a cleaning system, we cannot consider it satisfied. Finally, for requirement [9], we once again consider it not fully satisfied, as it wasn't explicitly tested, but based on the tests conducted with the T890A white ink, we expect that any cleaning fluid that doesn't react with the printer's plastics would be safe to use.

5.1 Recommendations and Future Work

While the results of the project are largely satisfactory, there are still avenues by which to further improve upon the project. Firstly and most importantly, the cleaning system would have to be tested in order to fully satisfy requirements [8] and [9]. After this is done, however, some work could be done to design a system that allows for the ink within the external ink tanks to be stirred. This could be important as many fluids that could be used as an alternative for the original ink could contain particles that have a tendency to deposit sediment at the bottom of the tank. As an ink tank that's firmly connected to a printer can't be shaken as easily as a bottle of ink in order to get the particles back into the liquid such that they can be printed, a stirring system would be required to do so. On top of this, to ensure that larger particles don't make it through the tubes and clog up the nozzles, the installation of filters within the fluid lines could prevent this. As for the chip tray, further work could be done into investigating ways to improve the accuracy of droplet placement, perhaps by designing an external machine vision system to calculate the software offsets required to accurately print patterns onto a chip's sensor arrays.

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A

Software Used

Table A.1: Software used throughout the project

Software	Usage
FreeCAD	Used to design the first two prototypes of the chip tray, once the design needed to be further complicated, we deemed it inadequate.
Autodesk Fusion	Used to design all parts after the first two chip trays.
Creality Print	Used to slice all trays except the final ones for 3D printing.
Ultimaker Cura	Used to slice all parts except the trays after Creality Print inexplicably created various blobs and other artifacts in more complex parts.
PrusaSlicer	Used to slice the final trays for 3D printing.
ESC/P2 Client	Used for designing and sending test patterns to the ET-8500 as well as measuring the circularity of ink droplets

B

Designing the Microscope Slide Tray

This Appendix covers the design process and some of the design flaws of the microscope slide tray that was designed to allow the printer to print onto microscope slides in order to be able to rapidly test different print patterns.

B.1 Design Process

The earliest iteration of the microscope slide was built off of the second prototype tray, pictured in Figure 3.3. The dimensions of the microscope slides used were 26 x 76 x 1 mm, and the cutouts for the slides were given 0.3 mm of clearance on all edges to ensure that the slides would fit within the tray and not stick out at all. On top of that, small circular indents were added to the edges of the slide cutouts with a radius of 2.5 mm to allow for the slides to be removed easier. The schematic for the final microscope slide tray is pictured in Figure B.1.

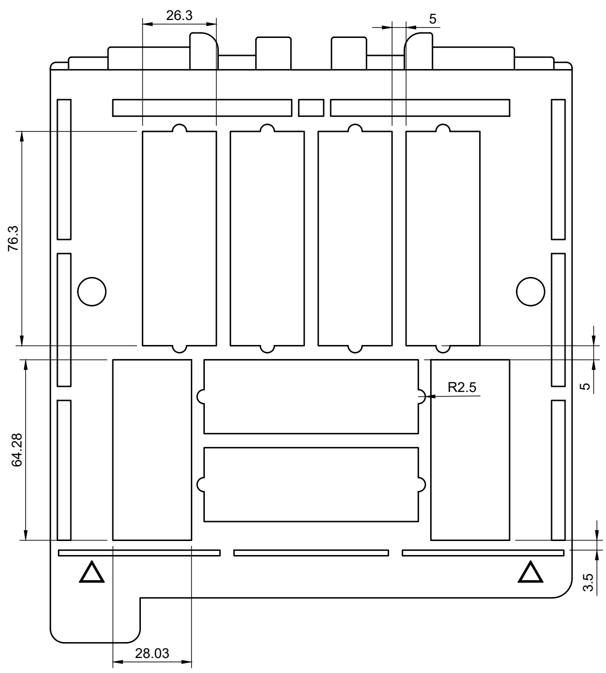

Figure B.1: Schematic of the final microscope slide tray. All unmarked dimensions are the same as Figure 3.6b. Slide cutout depth of 1.3 mm. All measurements in mm.

B.2 Design Flaws

The microscope slide tray had two fundamental flaws, but as it was not crucial for the completion of the project, they were never fixed. Firstly, the cutouts on the edges of the slide cutouts were too small to be able to properly grab the edges of the slides with your fingers, meaning that the best way to extract the slides was to pry the slide out of the tray or another small prying tool. The bigger flaw, however, was related to the printer's construction, namely, that the printer's rollers don't move up and down as a single unit, but rather that the rollers are connected to each other in pairs that can move up and down independently. Because of this, the surfaces of the leftmost and rightmost slides come into contact with the edge of one of the rollers, smudging a thin vertical line on all prints done on those slides.