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Multi-nozzle inkjet 3D printing with CNC motion

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Abstract

3D printing with current multi-nozzle drop on demand print heads is lacking in terms of surface quality (without post treatment) or printing of overhanging structures without support material in contrast to single nozzle inkjet 3D printing (where the part perimeters are printed with a CNC motion), which in turn is lacking in terms of volume throughput (and therefore only used for the fabrication of small parts) as everything has to be printed with one nozzle. In order to print with enhanced surface quality and overhanging structures - free of support material – as well as reasonable productivity for the production of larger 3D parts, a printing process for industrial multi nozzle printheads with CNC printing motion was developed. First 3D parts printed with paraffin wax were produced and characterized to estimate the potential of this process.

Introduction

When 3D printing with inkjet technology and lateral resolutions that are a fraction of the size of a drop, parts with mirror-like surfaces or overhanging structures can be printed without support material and post processing. Industrial drop on demand (DoD) 3D printers use multi nozzle inkjet printheads with a limited native resolution. Independent of the 3D printing technology used (such as powder bed systems, UV & phase change direct printing), due to the limited printing resolutions used with multi nozzle 3D inkjet printers, the theoretical highest surface quality cannot be achieved. Printing parts with 2x the resolution, increases the printing time by over 4x-8x, whereas depending on the print process, resolutions of 10x-20x higher than the current XHD or QHD resolutions of IJ 3D printers (e.g. 3D Systems ProJet or Flashforge Waxjet Series) would be required for a significant improvement in the surface quality of printed parts. Apart from impractical production times, as inkjet drops are not arbitrarily small, when increasing the dot density per unit square, the vertical resolution decreases. Current single nozzle inkjet 3D printers (e.g. Solidscape S-series) are lacking in mechanical precision and volumetric printing speed but have no limitation on the lateral print resolution as in 2D, any dot can be placed freely.

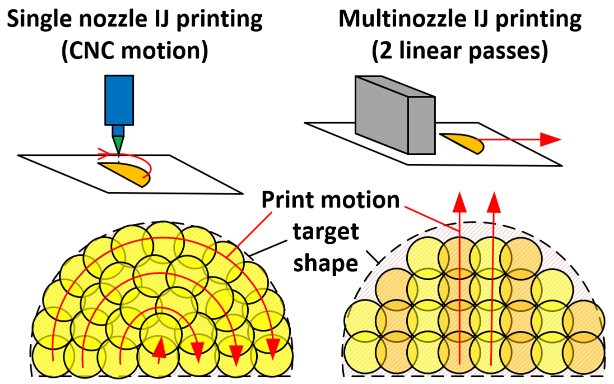

Figure 1: Single- and multi-nozzle Inkjet printing process

By printing the perimeter of each layer with a precise CNC motion and the infill with multi-nozzle printing, higher surface qualities in contrast to pixel inkjet printing and higher productivities in contrast to single nozzle printing can be achieved. The infill can either be printed with CNC motion or with pixel infill as depicted in Figure 2. In order to avoid defects in the printed surface, overfill in the border between perimeter and infill needs to be avoided. CNC infill allows for higher uniformity between perimeter and infill but requires complex transformation of the print data to jet at the correct location during the trajectory. In theory, CNC infill would allow for significantly shorter printing times as the infill can be printed simultaneously to the perimeter, but as current single pass printheads have insufficient resolution in a single line of nozzles, multiple passes are required. Pixel infill allows for increased homogeneity of the infill but the border between perimeter and infill is significantly less homogeneous than with CNC infill. If the flowability of the printed fluid before solidification is low, many gaps between surface and internal volume are printed.

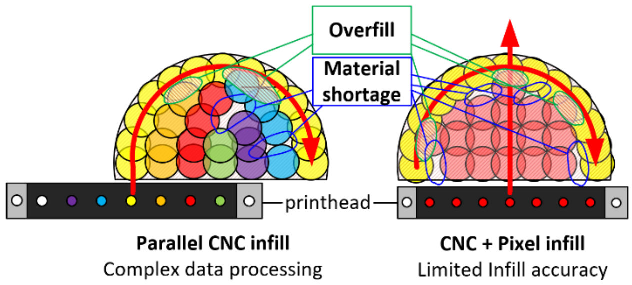

Figure 2: Multinozzle CNC printing with parallel or pixel infill

In this study, multi-nozzle inkjet 3D printing with CNC motion and pixel infill is investigated.

Materials and methods

The test platform used for the study (see Figure 3) was developed by iPrint. It has precision linear drives for the X and Y axes (JennyScience Lxs F60 with 1 µm glass encoder) and a compact linear drive for the Z axis (JennyScience Lxc F40). The axes are controlled via the TCP interface or the RS422 step/direction input of the controllers (JennyScience Xvi75V8).

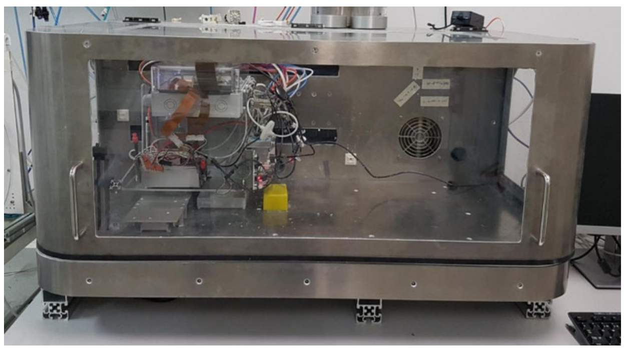

Figure 3. Test platform developed by iPrint used for the study

Figure 4 shows the schematic of the test setup. The printhead is mounted on the Z-axis which is in turn mounted on the Y-axis, whereas the X-axis is only moving the heated substrate plate. CNC motion and printing is controlled by an open-source motion controller (Arduino DUE with modified Firmware based on Marlin 2.1.2) via a step direction interface with 1 µm step resolution. The printhead (Ricoh MH2810F or MH2910F) is controlled by print drive electronics from global inkjet systems (PMB-C2 w. HIB-RH384). The hot melt recirculation ink supply (up to 130°C, accuracy +/- 0.5°C) and pressure controller (accuracy +/-0.05 kPa) used are custom developments of iPrint. All samples were printed with pure paraffin wax (Exagon 12200; melting temperature ~55°C) at a jetting temperature of 65°C. All samples were printed on glass substrates. Samples printed with the MH2810F were printed at a substrate temperature of 42°C and samples with the MH2910F at room temperature.

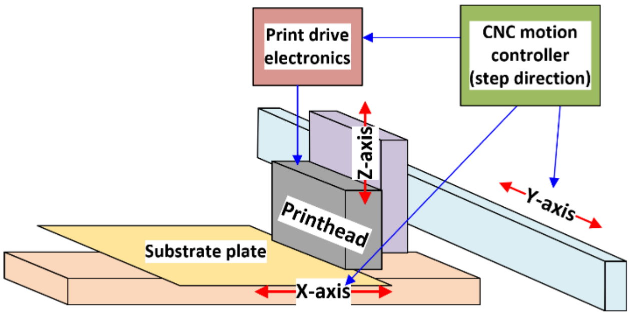

Figure 4. Schematic of the test setup

Figure 5 depicts the steps used for data generation of multi-nozzle inkjet printing with CNC perimeters and pixel infill. CNC and pixel print data was generated out of STL files with a freeware Z-level slicer (Freesteelpy to generate SVG and bitmap files) and Matlab code developed by iPrint to translate SVG files to G-code and CNC print data as well as process bitmap files to infill print data. CNC data is generated from SVG files with arc approximation (G2, G3) if a geometric tolerance of 2 µm can be kept, otherwise the raw SVG coordinates are used with linear motion (G1). For CNC print start and -end tangential points with a distance corresponding to the set acceleration and deceleration way are added.

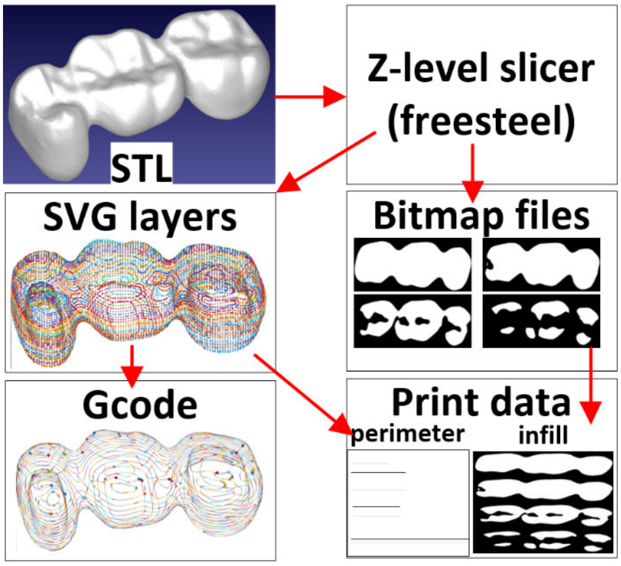

Figure 5. Generation of CNC print data with pixel infill

CNC print data for perimeters is generated as lines to print with a single pre-selected nozzle. For each perimeter, a line with the exact length of the circumference in pixels is generated, whereas the print resolution, which is the equidistant dot spacing on the CNC trajectory, of each perimeter is rounded to have the same distance between any connected dot on the perimeter. This slight individual adjustment of the print resolution is negligible concerning the perimeter height but avoids gaps or overlaps between the first and last printed drop in a loop. Pixel print data is generated as bitmap (.bmp) files with an offset of one printed line width to have the infill touch but not overprint the perimeter. The print resolution was adjusted to print homogeneous lines for infill and perimeter which was for the MH2810F (drop size adjusted to ~16 pL) about 600x600dpi at a layer height of 9.1 µm and for the MH2910F (drop size adjusted to ~40pL) about 1300x450dpi at a layer height of 35 micrometer. The print speed for CNC motion was set to 5 mm/s and for printing infill to 50 mm/s. Infill is printed with a random start nozzle layer by layer and one pixel shift per pass. Printed samples were characterized by optical microscopy with a 3D scanning microscope (Keyence VHX-6000) or a 3D laser confocal scanning microscope (Keyence VK-X3000).

Results

During initial tests, the print speed and acceleration for CNC printing motion was determined to achieve a maximum trajectory deviation of 10 µm when printing circles with a radius of 0.3 mm. With the test printer, this was achieved at print speeds of less than or equal to 5 mm/s which equates to a maximum axis acceleration of about 500 mm/s^2. For CNC printing motion, the target print speed was set to 5 mm/s and for trajectory radii smaller than 0.3 mm reduced to maintain a maximum acceleration axis acceleration of 500 mm/s^2. To align the CNC printed perimeter with the pixel infill, a single layer disc was printed and the infill aligned with a microscope. Figure 6 shows the printed perimeter and infill after alignment.

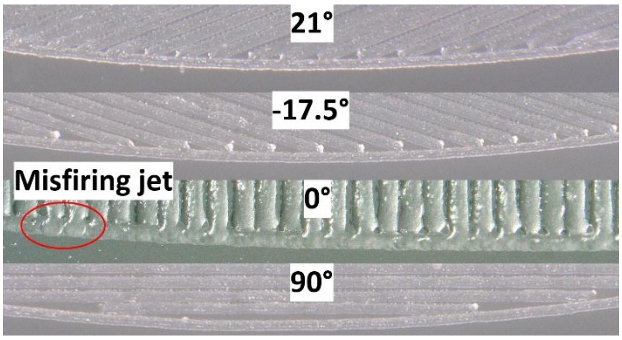

Figure 6. Border between CNC perimeter and pixel infill at different print angles on a printed disc (d=20mm) - MH2910F

The alignment between the CNC perimeter and the pixel infill can be considered proper as, with the exception of one misfiring jet, the ends of the infill fuse with the previously printed perimeter, but don't change the height of the perimeter. For defect free printing, jet straightness errors as visible in the "0°" picture of Figure 6 need to be compensated or lead to defects in the printed surface.

For printed 3D parts like the inverted cone shown in Figure 7, defects due to jets overprinting the perimeter appear as “bumps” in the surface but also affect the printed height of the perimeter which, without compensation leads to dimensional inaccuracy of the printed part.

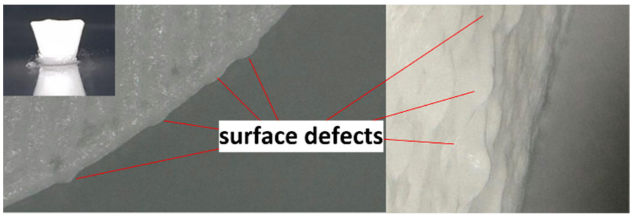

Figure 7.Surface defects due to misfiring jets on a printed inverted cone with 14° overhang - top and side view (right) - MH2910F

The maximum printable overhang with the chosen print parameters was tested by printing structures with overhanging faces with the MH2810F in steps of 1 micrometer perimeter offset. As shown in Figure 8, with the chosen configuration, an overhang of up to 26° (or 5 micrometers offset per layer) could be printed whereas an average surface roughness between 1.2 µm – 2.6 µm over a length of 1mm was measured in vertical direction. With a different print configuration, faster solidification and less flowability of drops, it is assumed that higher angles of overhang can be printed which would however result in increased roughness of the printed surface.

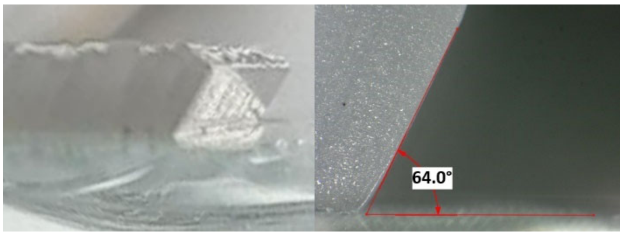

Figure 8. Maximum printed overhang with the MH2810F

Figure 9 shows a comparison of 3D printed dental parts (dimensions 25x11x2.5mm) with and without CNC printed surface. Upon visual inspection, the CNC printed surface does look smoother and reproduces the source geometry better. Due to the lack of jet straightness compensation, there are however many surface defects in the CNC printed surface.

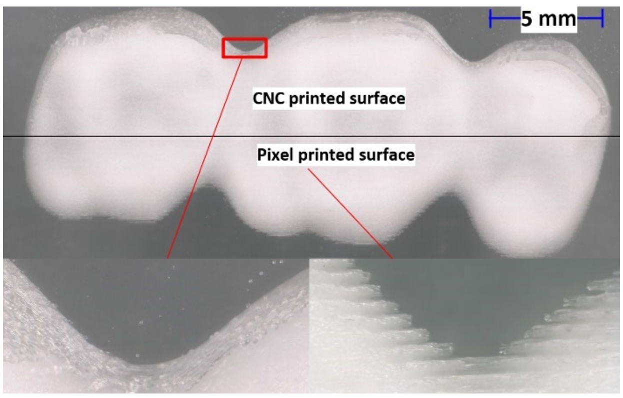

Figure 9. 3D printed dental bridge with and without CNC printed surface - MH2910F

Without pixel printing and the same print parameters, the discretization steps of the pixel printed layers in vertical and planar orientation are visible with the naked eye.
The average surface roughness was evaluated with an averaging filter over 150 µm at areas with low steepness (measurement length of ~6mm, slope angular range 0° to 30°; where 0° is horizontal and 90° is vertical) and high steepness (measurement length of ~1mm, slope angular range 60° to 80°) as shown in Figure 10.

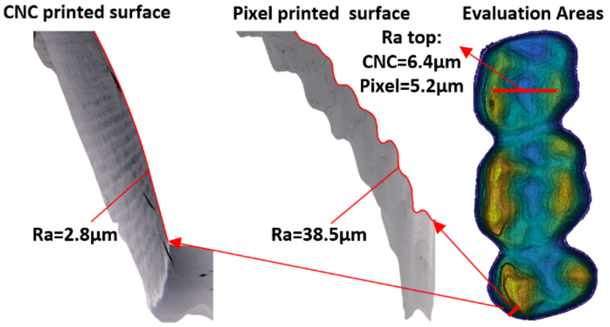

Figure 10: Evaluation of average roughness values with higher and lower surface steepness – MH2910F

On the evaluation area with higher steepness (see small red line in Figure 10 on the bottom – right), the measured average roughness of the CNC printed surface is with 2.8 µm significantly lower (over 13x) compared to when printed with pixels. For the area with lower steepness, the measured average roughness for the pixel printed surface is with 5.2 µm slightly lower than the roughness of CNC printed surface with 6.4 µm, but in about the same order of magnitude. The printing time for the CNC perimeter of the dental part with 25x11x2.5mm dimensions and a circumference length of about 70 mm was about 14.5 seconds, what is in good approximation equivalent to the circumference divided by the CNC print speed of 5 mm/s. The time needed to print the pixel infill with three linear printing passes was about 2.5 seconds which leads to a time of 17s per layer and a buildup speed of about 81 minutes per centimeter for the CNC process with pixel infill or 10.7 minutes per centimeter for the pixel printing process whereas in the latter case many different parts could printed in parallel. Printing all of the part volume with the used CNC print speed and a single nozzle would result in a buildup speed of about 54.7 hours per centimeter.

Discussion

Multi-nozzle inkjet 3D printing with CNC motion can be utilized for a variety of fluids and inkjet 3D print processes. In this study, paraffin wax was chosen as part material for tests. Paraffin wax is mainly used in inkjet 3D printing fluids for lost wax casting or as support material where, apart from sufficient green strength, only the accuracy and quality of the 3D printed part surface matters. For a CNC printing process with pixel infill and hot melt jetting fluids, it is however challenging to have no gaps between the surface and the infill. As gaps between CNC surface and infill can be tolerated, internal part volume could also be printed hollow, allowing for a reduction of required jetting fluid. Energy curing or solvent based jetting fluids with reasonable wettability are expected to allow for the production of dense parts without gaps between surface and internal part volume, but may pose different challenges when 3D printing overhanging structures challenging without support material. For powder-based inkjet 3D printing, a CNC printed surface would also positively affect part accuracy. In the case of a solvent on granules 3D printing process [2] where layers are cross linked with a solvent that evaporates afterwards, a multi-nozzle inkjet 3D printing process with CNC motion would be most easy to integrate, as in contrast to binder jetting, there is no issue with overfilling CNC printed perimeters.

The surface roughness is directly related to drop spreading and contact angle of the jetted fluid on the previous layer. A planar top surface of a part, printed with CNC surface and pixel infill does have the infill exposed on the top and, with the exception of the perimeter, has the same appearance compared to when printed in a pixel process. By adjusting ambient and substrate temperature, the flowability of the paraffin wax can be adjusted to achieve lower roughness values. Parts printed with UV curable polymer in a pixel process and a similar drop size can achieve significantly lower roughness values (down to ~0.5 um) with low surface steepness [1].

While the test setup can be considered to be suitable for a multi-nozzle inkjet 3D printing process with CNC motion, there is a lot of room for improvement. The printheads used in this study were chosen for practical reasons as they were already available on the test platform, but have a relatively low nozzle density 75 npi (nozzles per inch) per row and relatively large minimum droplet sizes (nominally 27pL for the MH2810F and 50pL for the MH2910F). For inkjet 3D printed parts, the maximum achievable part resolution is directly proportional to the pixel volume within a layer. For increased surface quality and part accuracy it is therefore beneficial to print with smaller drops. Current single pass printheads with high npi (nozzles per inch) values in a single row (for piezo DoD up to 300 npi produced by Epson & Toshiba Tec and for thermal inkjet up to 800 npi produced by Memjet) would allow for parallel printing of infill while reducing printing time.

One major drawback of multi-nozzle inkjet printing with CNC motion is the increased printing time which was for the relatively small dental test parts already about 6 times longer than the printing time needed with a pixel printing process. Compared to when printing the full part volume with CNC motion at the same print speed as used for the perimeter and a single nozzle however, the multi-nozzle CNC process would have been over 45 times faster.

Fast production times of 3D parts was not a goal of this study. A printer optimized for a printing process with fast CNC motion would allow for the same drop placement error at significantly higher trajectory acceleration and CNC printing speeds. Although test platform used in this study was not designed for an inkjet process with CNC motion, it would also allow for faster production times. For the tests, the CNC print speed was limited to have sufficient accuracy when printing the smallest radius of interest. The CNC print speed, without compromising dot placement accuracy, could have been set much higher for parts of the trajectory with lower curvature. When accelerating or decelerating in print direction during jetting however, the drop flight angle [3] changes, which impacts the dot pitch would require timing compensation. As varying drop flight trajectories were not taken into account, a fixed print speed for all layers was chosen. Considering the dental 3D part printed, with a maximum axis acceleration of 500mm/s^2 layers with lower curvature on the perimeter could have been printed with fixed CNC print speeds up to 17 mm/s. Only 15% of the printed layers had minimum CNC printing curve radii of less or equal to 0.3 mm.

For successful implementation of a multi-nozzle inkjet 3D printing process with CNC motion, it is required that dot placement is sufficiently accurate. Maintained accurate dot placement sets demands on reliability to the complete print system. The highest relative dot placement accuracy for the CNC printed surface with a multi-nozzle printhead can be achieved when using only one fixed nozzle as its unique jet straightness angle is most reproducible [4], but it can only be maintained with suitable printhead maintenance (e.g. contact free cleaning) or printhead calibration to compensate changing jet straightness may be required in frequent intervals.

Conclusion

In this study, a novel 3D multi-nozzle inkjet printing process with CNC motion was introduced. Sample parts out of paraffin wax were printed with the introduced CNC multi-nozzle process and in by conventional pixel printing and printed samples were characterized and compared. With a drop size of 16 pL and a layer thickness of about 9.1 µm an overhang of up to 26° could be printed with an average surface roughness Ra in vertical direction of down to 1.2 µm and a subpixel displacement of 5 µm per layer. With a drop size of 40 pL and a layer thickness of 35 µm, freeform geometries were printed and characterized. With CNC printed surface, the printed part dimensions represent the source geometry better than with pixel printing and the surface appears to be smoother. For higher printed slope angles of 60° to 80° an average surface roughness Ra of 2.8 µm was measured with the proposed multi-nozzle inkjet printing process with CNC motion whereas, with the same drop size and layer height and conventional inkjet pixel 3D printing, an average surface roughness Ra of 38.5 µm was achieved. On surface areas with low slope angles from 0 to 30° the average surface roughness measured with the multi-nozzle inkjet CNC process was with an Ra of 6.4 µm similar to the pixel printed surface with an Ra of 5.2 µm. The buildup speed for the dental part printed with an average perimeter length of ~70mm and an area of 25x11mm is with 81 minutes / cm for the CNC multi-nozzle process significantly slower than with pixel printing (10.7 minutes/cm) but also significantly faster compared to when printing the full part volume with a single nozzle in CNC motion at the same print speed (~54.7 hours/cm). With a 3D printer optimized for accurate dynamic CNC motion, or a single pass printhead with high nozzle densities printing and buildup speeds can be significantly increased.

Multi-nozzle inkjet 3D printing with CNC motion requires accurate dot placement (sub-dot diameter precision) for successful implementation. It is not expected to be a good choice for 3D printing of liquids prone to nozzle plate wetting and jet outs. The proposed 3D printing process can be applied to many pixel inkjet 3D printing processes (e.g. solvent based, UV curable, powder based,...) , and may improve part accuracy and surface quality of printed parts.

References

[1] Vidakis, N., Petousis, M., Vaxevanidis, N., Kechagias, J., "Surface Roughness Investigation of Poly-Jet 3D Printing" (*Mathematics* 2020), *8*, pg. 1758

[2] Carreno-Morelli, E., "A comparative study of cemented carbide parts produced by solvent on granules 3D-printing (SG-3DP) versus press and sinter" (International Journal of Refractory Metal and Hard Materials June 2021), 97

[3] Renner, J. & Von Arx, R., "Selective coating of PCBs with paraffin wax" (The Inkjet Conference, Düsseldorf 2019)

[4] Renner, J., Bircher, F. & Schlegel, G. Reproducibility of Inkjet Printing Systems (Advances in Print and Media Technology / Iarigai 2011), 38, pg. 79-85

Author Biography

Johannes Renner obtained a master's degree in engineering at the Bern University of Applied Sciences in 2012, where he worked from 2007 as scientific collaborator at the Institute of Print Technology until joining the iPrint institute (at the HEIA-FR) in 2013 as scientific adjunct. With over 15 years of experience in applied inkjet research related to IJ print process development (3D additive manufacturing, direct to shape, coatings, printing for electronics, bioprinting,…), development IJ inkjet related devices (printers, complex ink supplies, system components, drop watchers, drive electronics, PIV for drop air flow analysis …) and dispensing systems (microvalves, micro extrusion), Johannes is active in development, consulting, and management in inkjet related projects as well as teaching in iPrint's inkjet education program.

Vincent Nidegger obtained a bachelor's degree in electrical engineering with a focus on electronics at the School of Engineering and Architecture in Fribourg in 2018 where he worked for two years as scientific collaborator at the iSIS institute for intelligent and secure systems. In 2022 he joined the iPrint institute as R&D engineer and is active in 3D printing (direct to shape & additive manufacturing), printing for electronics and platform development.