

Embedding Conductive Paths into 3D Objects by Coupling Fused Filament Deposition and Conductive Ink Piezo-Jetting

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Short abstract

This work investigates the integration of fused filament fabrication (FFF) 3D printing and piezo-jetting of conductive silver ink using a 6-axis industrial robot, with the aim of embedding functional electronic circuits directly into 3D-printed polymer objects. Planar substrates made from four thermoplastic materials: acrylonitrile-butadiene-styrene (ABS), polylactic acid (PLA), polyethylene terephthalate glycol (PETG), and high-performance PLA (PLA-HT), were characterized with a high-speed laser profilometer to assess the influence of layer height and extruder multiplier on surface roughness. A U-shaped channel design with a small interconnect hole was adopted to route conductive ink between vertically stacked layers. Silver ink (Henkel Loctite Edag 418SS) was deposited by the robot-mounted piezo-jetting printhead into the channels and onto the cover-layer surfaces. Electrical resistance measurements confirmed track conductivity and the effects of channel geometry, layer count, and filament orientation on ink connectivity were systematically investigated. A layer height of 0.15 mm and an extruder multiplier of 103–105 % yield the best surface quality for ABS and PLA. Ink deposited in channels with 0.2 mm layer height gave resistance per unit length of 0.43–0.48 Ohm/cm, in good agreement with theory. Electrical continuity between substrate and cover layers was maintained for stacks of up to four cover layers using a three-pass jetting strategy over the interlayer connecting hole thus demonstrating that the developed approach could be viable for the fabrication of multilayer circuits.

Keywords: fused filament fabrication, conductive ink, piezo-jetting, 6-axis robot, printed electronics

1. Introduction and Background

Among direct-writing techniques compatible with polymer substrates (Macdonald et al., 2014; Kamysny and Magdassi, 2019), piezo-jetting of conductive inks is particularly attractive owing to its non-contact deposition mode, compatibility with high-viscosity silver pastes, and high placement accuracy (Espera et al. 2019; Delfaut et al. 2022; Borghetti et al. 2024).

Most early demonstrations of 3D printed electronics relied on Cartesian gantry robots, which restrict printing to planar or near-planar surfaces. The use of poly-articulated 6-axis robots overcomes this limitation by enabling freeform trajectory following and controlled tool orientation on curved substrates (Yoshida et al. 2017; Li et al., 2018; Bao et al. 2023).

Despite these advances, the integration of FFF-printed structural layers with robotically jetted conductive paths, including the routing of ink between layers through small interconnect holes, has not been systematically studied. The surface quality of FFF substrates, which strongly affects ink spreading and resistance, also requires dedicated optimisation for each polymer material. The present work addresses these gaps by investigating: (i) the influence of layer height, ironing, and extruder multiplier on the surface roughness of FFF substrates for four thermoplastics; (ii) the electrical resistance of silver ink deposited inside U-shaped channels and on flat substrates; and (iii) the conditions enabling reliable ink interconnection between vertically stacked FFF layers through sub-millimetre holes.

2. Materials and Methods

2.1 Experimental setup

The experimental setup (Figure 1) consisted of a commercial FFF 3D printer (Artillery Sidewinder X2, Shenzhen Yuntuchuangzhi Technology Co., Shenzhen, China) operated alongside a 6-axis industrial robot (Stäubli TX2, 60, Stäubli International AG, Pfäffikon, Switzerland), having a 670 mm range with 0.02 mm repeatability, equipped with a piezo-jetting dispensing valve (Vermes MDS 3200A, Vermes Microdispensing GmbH, 83607 Holzkirchen, Germany) with a 100 μm nozzle, and a high-speed laser profilometer (Keyence LJ-V7080, Keyence, Osaka, Japan). Robot trajectory generation and offline programming were implemented in RhinoCeros 3D with the Grasshopper and RhinoRobot plugins (<https://www.rhino3d.com>) (Beneventi et al., 2023). FFF toolpaths were sliced using Simplify3D software (<https://www.simplify3d.com>). The two machines share the same working volume, allowing the substrate to be printed by the FFF printer, scanned by the robot profilometer, and overprinted with conductive ink by the robot-mounted jetting head without manual repositioning.

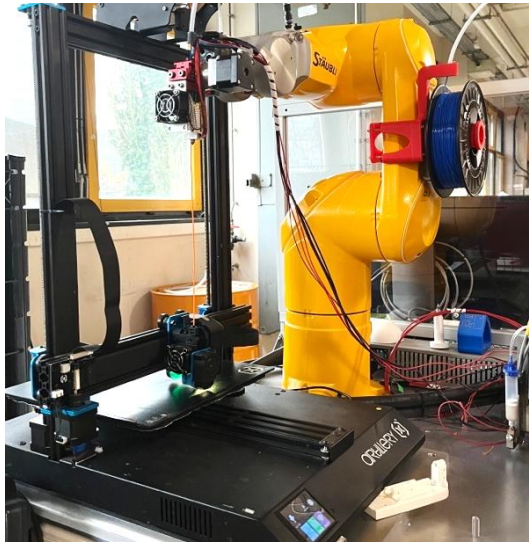


Figure 1. Experimental setup: 6-axis robot (Stäubli TX2 60, yellow) and FFF 3D printer (Artillery Sidewinder X2) sharing the same working volume.

2.2 Materials

Four commercial FFF filament materials were used as substrates: PLA, ABS, PETG, and PLA-HT. Bed and nozzle temperatures were set per manufacturer recommendations (Table 1).

Table 1: FFF printing conditions for the four substrate materials. All samples were printed at room temperature (i.e. 25-30°C).

Material (Manufacturer)	Filament diameter (mm)	Nozzle diameter (mm)	Printing speed (mm/s)	Nozzle temperature (°C)	Bed temperature (°C)
PLA (Polymaker)	1.75	0.4	40-50	200	65
ABS (Machines3D)	1.75	0.4	40-50	255	95
PETG (Polymaker)	1.75	0.4	40-50	230	80
PLA-HT (Polymaker)	1.75	0.4	40-50	210	70

The conductive ink was a silver microparticle screen-printing paste (Henkel, Loctite Edag 418SS, Henkel Adhesives Technologies, 40589 Düsseldorf, Germany) having a nominal resistivity $\leq 7.5 \times 10^{-7} \text{ Ohm}\cdot\text{m}$; dry content 66.6 wt%; used as received. After jetting, the ink was cured in an air-circulation oven for 30 min at 100 °C.

2.3 Sample design and FFF printing

A 25 mm × 25 mm planar substrate incorporating a U-shaped channel (depth 0.5 mm, width 1.5 mm) topped by a thin plate with a 1 mm × 1 mm square interconnect hole was designed (Figure 2). This geometry allows ink jetted into the channel to bridge vertically through the hole to the cover surface, forming a conductive interconnect between layers. Layer heights of 0.15 mm and 0.25 mm were used for channel samples. To study substrate surface quality, additional flat 25 mm × 25 mm × 0.5 mm specimens were printed with extruder multipliers (defined as the ratio between the effective and the nominal polymer flow) from 100 % to 110 %. The effect of ironing, a post-layer nozzle pass at minimal extrusion that partially remelts the top surface (Sardinha et al., 2022), was also investigated for grey and white ABS at layer heights from 0.075 to 0.25 mm.

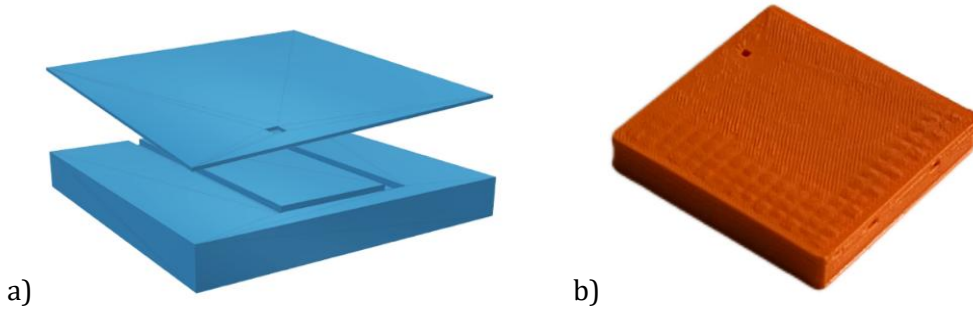


Figure 2: Substrate design: a) 3D CAD model showing U-shaped channel and 1 mm × 1 mm interconnect hole; b) FFF-printed ABS sample.

2.4 Surface characterisation

Surface defects were evaluated using a high-speed laser profilometer. The 3D-printed specimen was scanned with an accuracy of 0.05 mm, and a surface profile was extracted by intersecting the reconstructed surface with a plane normal to the scanned surface and perpendicular to the filament deposition direction. Periodic defects generated during FDM 3D printing were quantified as the peak-to-peak distance between successive surface antinodes along the extracted. Ten measurements were averaged per sample. For the generation of silver ink printing trajectories, the 3D surface was exported as .txt file, meshed on Rhino 3D using rectangular cells, and noise was reduced with the Paul Bourke iterative smoothing algorithm (<https://paulbourke.net/geometry/polygonmesh/>) (Beneventi et al., 2023). Surface texture was additionally characterised with a portable USB microscope.

2.5 Conductive ink jetting and electrical characterisation

The piezo-jetting printhead was operated at 1.4 bar dispensing pressure. Jetting frequency and printhead speed were synchronised following the semi-empirical model of Furia et al. (2021), itself building on the direct ink writing characterisation of Tricot et al. (2018), to control drop coverage ratio and line width. For interconnect holes, the program was modified to execute the pristine trajectory plus three parallel passes in an S pattern to ensure adequate ink volume. Electrical resistance was measured with a digital multimeter (Fluke 113) at the ends of each track and normalised by track length. Theoretical resistance was calculated as:

$$R = \rho \cdot L / A \quad [1]$$

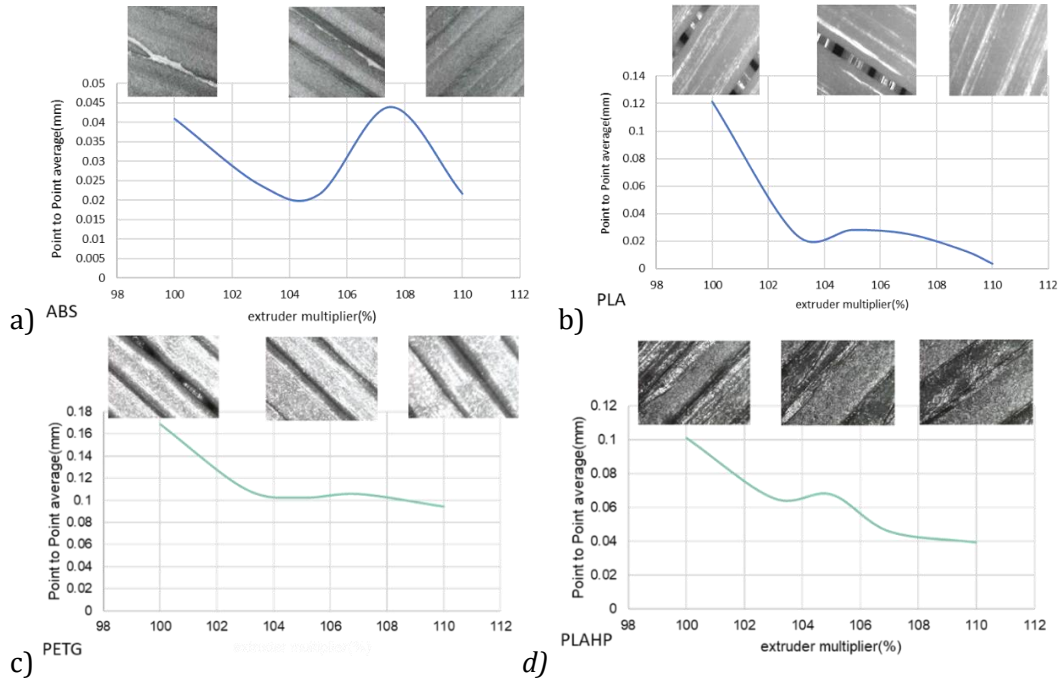


Figure 4: Effect of extruder multiplier on peak-to-peak distance for a) ABS, b) PLA, c) PETG and d) PLA-HT.

ABS reaches minimum roughness near 105 %, PLA between 103 % and 105 %, while PETG and PLA-HT benefit from higher values up to 110 %. The roughness plateau between 103 % and 105 % for most materials reflects the onset of adequate inter-filament bonding. These results indicate that individual extruder calibration is necessary before ink deposition to ensure a smooth, well-consolidated substrate surface.

3.3 Electrical resistance of ink in channels and on flat substrates

Table 2 reports measured and theoretical resistance for silver ink deposited in 1.5 mm-wide U-shaped channels on white ABS substrates (0.15 mm layer height). Measured resistance per unit length ranges from 0.39 to 0.48 Ohm/cm, in reasonable agreement with the theoretical prediction of ≤ 0.56 Ohm/cm from Eq. [1]. The slight overestimation of theoretical values reflects the use of average ink dimensions; variability in actual cross-section contributes to the spread. The dry ink thickness after curing is approximately 0.1 mm and the width 0.7–1.0 mm, with a shrinkage of 0.03–0.08 mm in height upon solvent evaporation. On flat grey ABS substrates, resistance per unit length was 0.25–0.50 Ohm/cm, confirming that channel confinement has only a modest effect on track conductivity compared to flat printing. Figure 5 shows profilometer cross-sections of the U-shaped channel before and after dry ink deposition, showing that neither channel wall shadowing of the laser beam nor channel floor irregularities can provide the scan accuracy necessary to quantify the ink film thickness.

Table 2: Measured and theoretical resistance R for silver ink in U-shaped channel (white ABS, 0.15 mm layer height).

Sample	Measured R (Ohm)	Track length (cm)	R/length (Ohm/cm)	Theoretical R (Ohm)
0	1.94	5.0	0.39	≤ 0.56
1	1.82	3.4	0.48	≤ 0.38
2	2.20	4.8	0.46	≤ 0.54
3	2.07	4.7	0.44	≤ 0.53

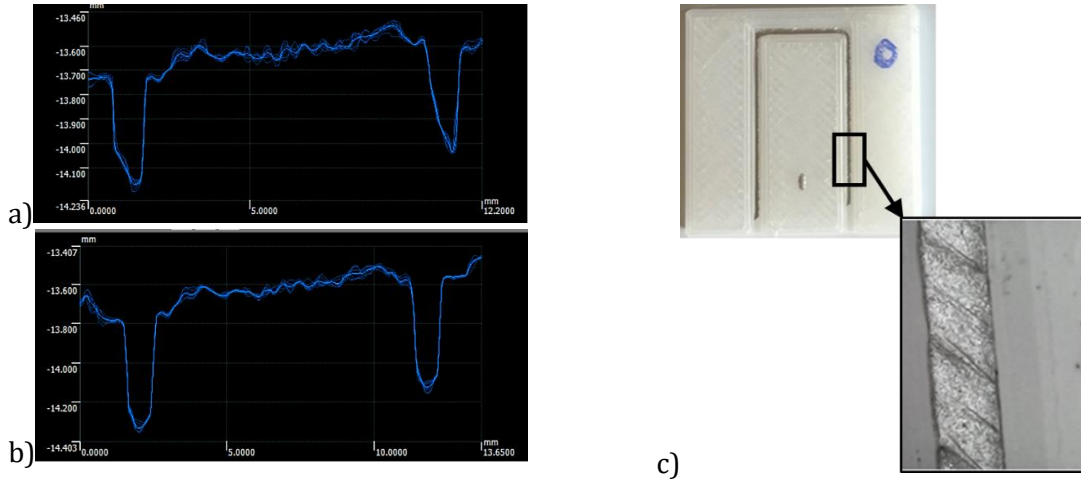


Figure 5: Profilometer cross-sections of the U-shaped ABS channel: a) before ink deposition; b) after drying of silver ink, c) image of the whole printed channel and magnification showing FFF printing defects on the channel floor.

3.4 Effect of layer height on ink resistance

Table 3 compares ink resistance for grey ABS channels printed at 0.2 mm and 0.25 mm layer height. At 0.2 mm, resistance per unit length averaged 0.51 Ohm/cm; at 0.25 mm it averaged 1.0 Ohm/cm, nearly double. The rougher surface at 0.25 mm causes irregular ink spreading and reduces the effective conductive cross-section, increasing resistance. This result confirms that the 0.15–0.20 mm layer height range is optimal for low-resistance printed tracks.

Table 3. Effect of substrate layer height on silver ink resistance (grey ABS, 1.5 mm-wide channel).

Sample	Layer height (mm)	Measured R (Ohm)	Length (cm)	R/length (Ohm/cm)	Theor. R (Ohm)
1	0.25	5.0	6.2	0.81	≤ 0.70
2	0.20	2.7	6.2	0.44	≤ 0.70
3	0.20	2.6	6.1	0.43	≤ 0.68
4	0.20	2.7	6.2	0.44	≤ 0.70
5	0.20	2.0	4.9	0.41	≤ 0.55
6	0.20	3.7	3.4	0.84	≤ 0.38
7	0.25	6.8	5.6	1.21	≤ 0.63

3.5 Ink interconnection between stacked FFF layers

A fundamental requirement for multi-layer embedded circuits is maintaining electrical continuity between ink deposited in a substrate channel and ink on the overlying cover surface, connected through the $1\text{ mm} \times 1\text{ mm}$ hole. Initial single-pass experiments showed systematic disconnection at the left edge of the hole, caused by the angular approach trajectory of the robot printhead. The three-pass left-right-left strategy (Figure 6) ensured adequate ink volume at the hole edges and improved connectivity.

Table 4 summarises the stacking experiments. With 0.15 mm layer height, minimum substrate height of 0.45 mm, and minimum cover height of 0.30 mm, electrical continuity (top-to-top resistance 1.7–4.7 Ohm) was maintained for stacks of up to four substrate and four cover plates (total height 3.15 mm). Beyond this, ink paths through the holes were disrupted. Importantly, the direction of the FFF filament relative to the channel (parallel or perpendicular) had no significant effect on ink resistance: all five samples tested gave 1.6–1.9 Ohm for a 6 cm track, consistent with the small layer thickness that ensures a stable ink-filament contact area in both orientations.

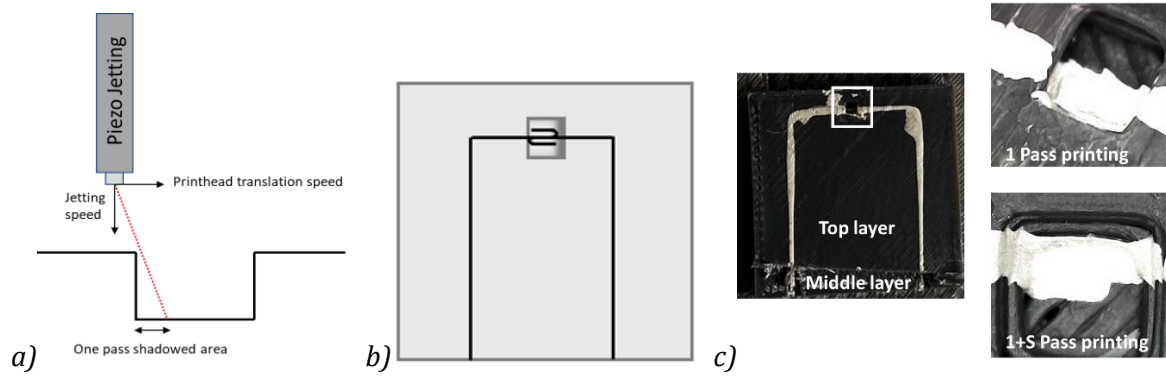


Figure 6: Three-pass jetting scheme for interconnect hole coverage: a) side view of printhead motion direction and generation of a shadowed area with a single pass; b) top-view layout of the four parallel ink paths (one straight plus an S shaped pass); c) image of the printed circuit (full view with scratched top layer to show the mid layer and magnifications showing the open-circuit one pass printing and closed-circuit 1+S passes printing) (Wang, 2024).

Table 4: Effect of substrate and cover plate stacking on top-to-top resistance (grey ABS, 3-pass interconnect jetting).

No. substrates	Substrate ht. (mm)	No. covers	Cover ht. (mm)	Total ht. (mm)	R top-top (Ohm)
2	0.45	2	0.40	1.70	1.7
3	0.45	3	0.40	2.55	1.7
4	$0.45 (\times 3) + 0.50 (\times 1)$	4	$0.40 (\times 1) + 0.30 (\times 3)$	3.15	4.7

4. Conclusions

This study demonstrated the feasibility of embedding functional electronic circuits into FFF-printed polymer objects by coupling fused filament deposition with robotic piezo-jetting of conductive silver ink.

The main conclusions are:

- 1) Surface quality is material- and parameter-dependent. A layer height of 0.15 mm and an extruder multiplier of 103–105 % provide the smoothest substrates for ABS and PLA. Ironing further reduces roughness but should be avoided at very small layer heights.
 - 2) Silver ink jetted into 1.5 mm-wide channels on 0.20 mm-layer-height ABS substrates achieves resistance per unit length of 0.43–0.48 Ohm/cm, consistent with the nominal ink conductivity and in good agreement with the semi-elliptical cross-section model.
 - 3) Electrical interconnection between vertically stacked FFF layers is achievable through 1 mm × 1 mm holes using a three-pass jetting strategy. Continuous conductive paths were confirmed for stacks of up to four substrate and four cover layers (total height ≈ 3.15 mm), a geometry compatible with practical multi-layer electronic packaging.
 - 4) Filament orientation relative to the channel (parallel vs. perpendicular) has no measurable effect on track resistance, simplifying the structural design of the FFF substrate.
- These results provide a foundation for multi-layer 3D-printed objects with embedded functional circuits. Future work will focus on extending the approach to curved substrates, reducing interconnect hole size, and integrating surface-mount electronic components onto the printed circuit layers.

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