Supplementary Information

Understanding and improving FDM 3D printing to fabricate high-resolution and optically transparent microfluidic devices

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1. Assembly and configuration of the FDM-based 3D printer

1.1 Printer assembly

The assembly diagram is depicted in Figure S1. The printer consisted of four main parts: 1) extruder, 2) LCD display, 3) build plate, and 4) filament support, as shown in Figure S1A. The extruder comprised a double extrusion system controlled by a controller board with a 32-bit chip with open-source firmware. The extrusion system was assembled using seven main parts: stepper motors, extruder support, mounting block, PTFE tube, heater block, and adapted nozzle, as shown in Figure S1B. The assembled frame is shown in Figure S1C. The completely assembled 3D printer and the controller board are depicted in Figures S1D and S2, respectively.

Figure S1: Assembled FDM-based 3D-printer. (A) Main components, (B) Extrusion system assembling, (C) Open cabinet (D) Enclosed cabinet and final 3D-printer

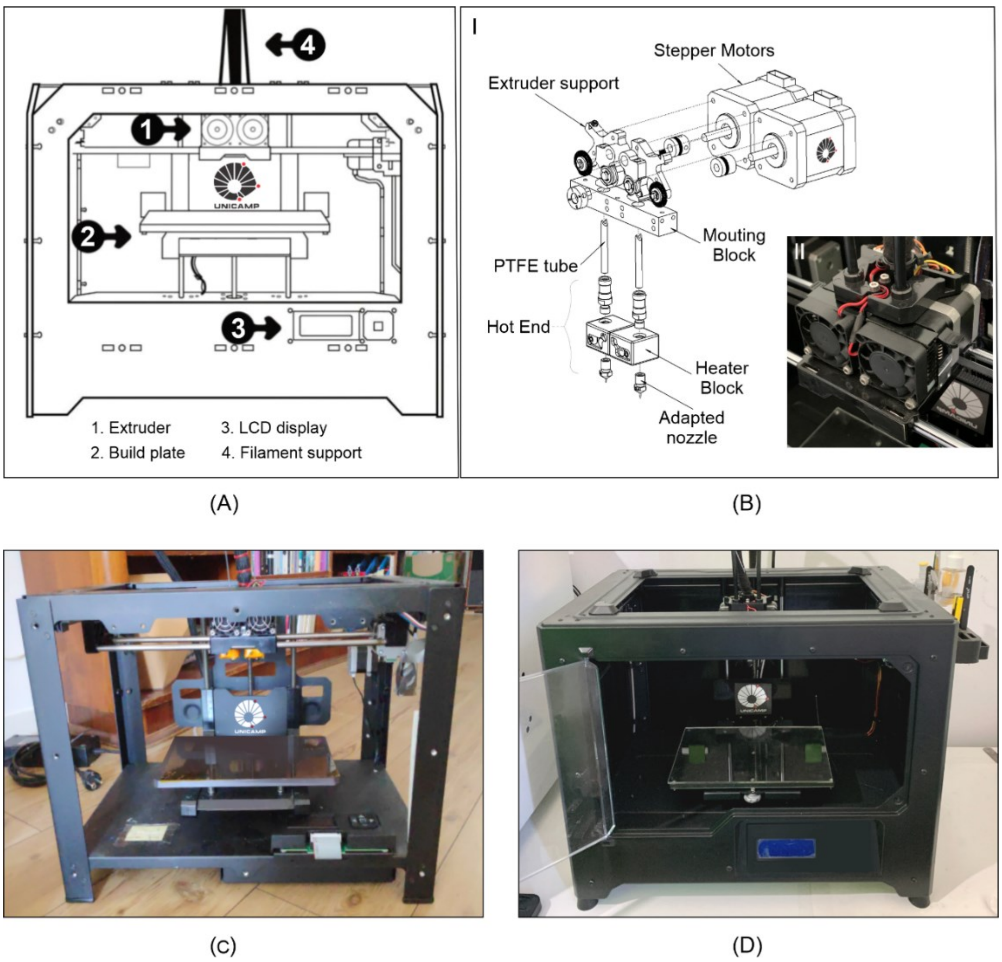
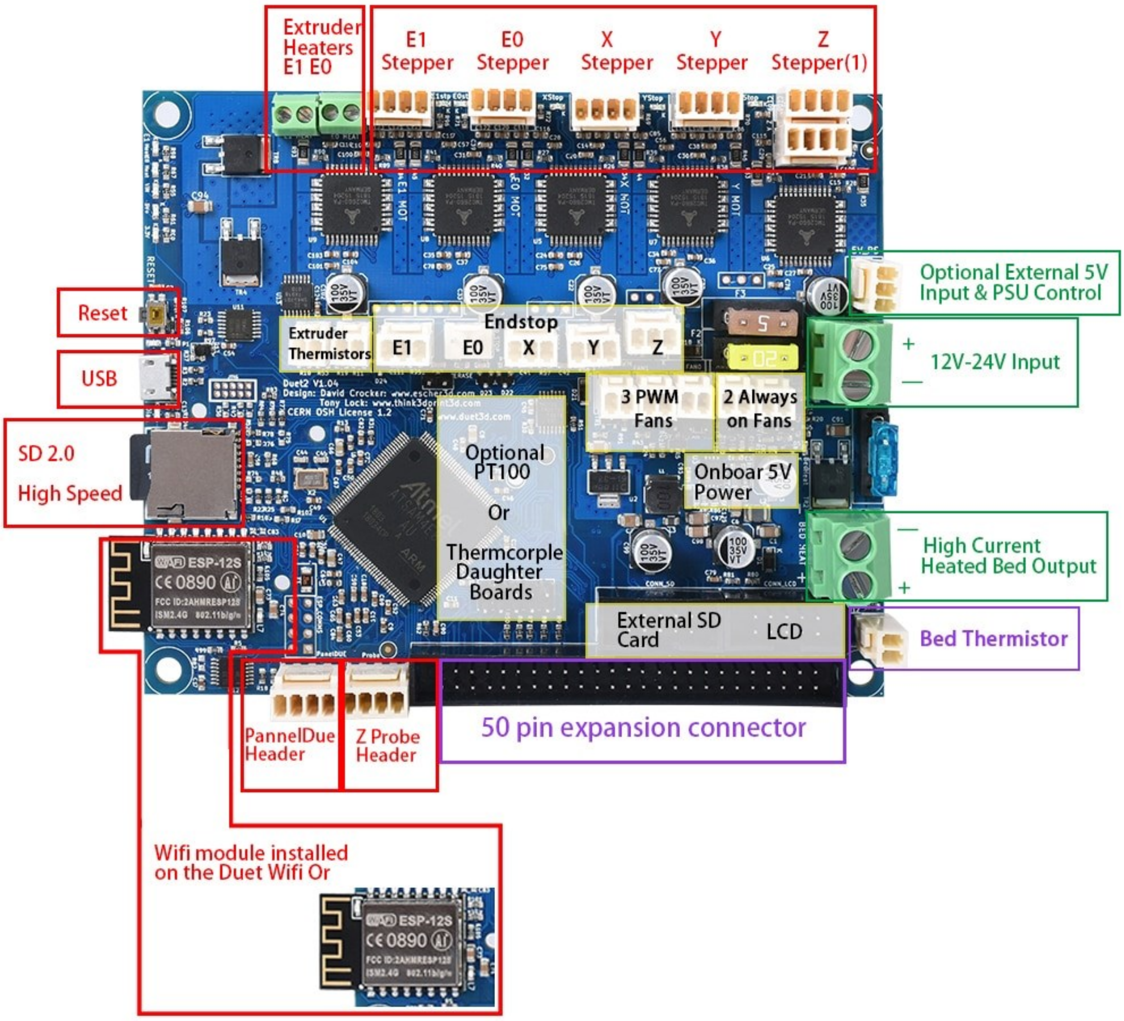


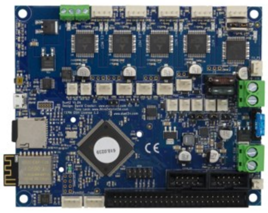
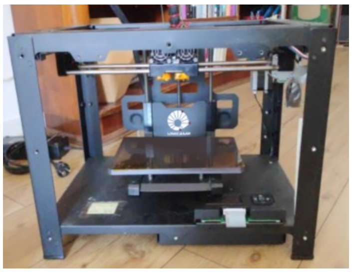
Figure S2: Details for Controller Board assembly.



The borosilicate and quartz glass used on the heating bed was purchased at Vidrak (São Paulo, Brazil; www.vidrak.com.br). The rigid frame and the metallic closed cabinet were designed based on an open-source prototype and machined from Gama (Campinas, Brazil; www.usinadagama.com.br).

All the components used to assemble the printer and the file configurations are listed in Table S1.

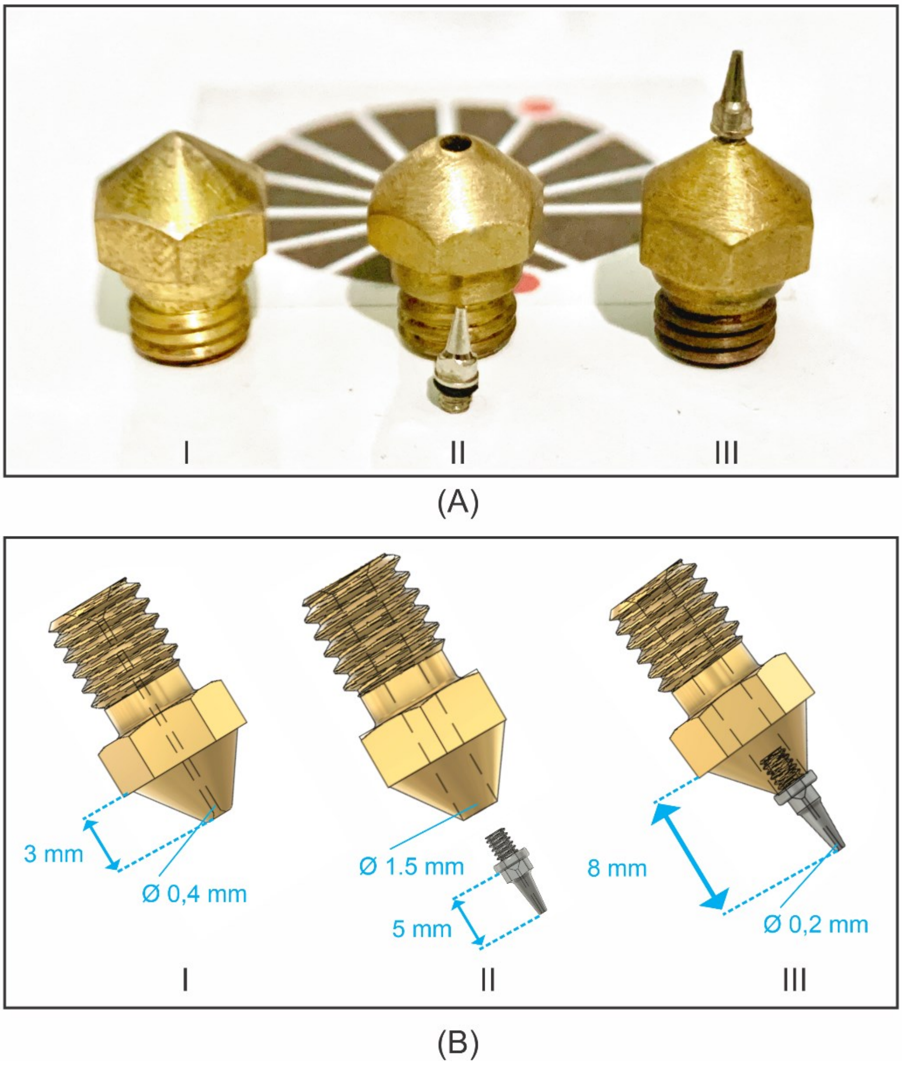
Table S1: Components used to assemble FDM 3D-printer

Picture	Item	Quantity
	**Printer Controller Board** Duet 2 Wifi ARM 32 bits Built-in drivers TMC2660 Microcontroller Atmel SAM4E8E	1
	**LCD touch screen** PanelDue color touch screen controller Screen size 5" Resolution 800×480 pixels	1
	**Direct drive extruder** Extruder retrofit kit for dual-extruder direct-drive machines	1
	**X, Y, and Z axis motor** Twotrees Nema17 Stepper Motor 4 Lead Stepper Torque 42 N.cm (60 oz.in)	4
	**Heating Platform** Printing area: 220 x 160 x 3mm Aluminum Plate Maximum temperature: 120 °C 24V working voltage and 240W power.	1
	**Metal Framing** Metal frame structure with Acrylic covers Build volume is 220 x 160 x 150 mm Aluminum thickness: 20 mm Acrylic thickness: 6 mm	1

1.2 Adaptation of the nozzle

A commercial brass nozzle was purchased at a local store (Campinas, Brazil) to be adapted as depicted in Figure S3A-I. Using a 1.4 mm grinding drill and a 1.6 male thread, the commercial nozzle was perforated, as shown in Figure S3A-II. Then, an airbrush tip of stainless steel with 0.2 mm precision (the same used for tattoos) was purchased at Steula (São Paulo, Brazil; www.steula.com.br), and it was coupled to the initial commercial nozzle. Thus, a final adapted nozzle was obtained, as shown in Figure S3A-III. The standard nozzle with a nominal diameter of 0.4 mm and 3 mm of distance from the printing base (Figure S3B-I) was coupled to an airbrush tip of 5 mm (Figure S3B-II) and finally, a new nozzle with a final distance from the printing base of 8 mm and 0.2 mm of diameter was reached, as shown in Figure S3B-III.

Figure S3: (A) I. Standard nozzle. II. nozzle perforated. III. Final nozzle adaptation. (B) I. Distance from the base of the nozzle to the tip, with a diameter of 4 mm. II. Nozzle extension by coupling the airbrush tip. III. Nozzle adapted with a distance from the printing base of 8 mm and a diameter of 0.2 mm.



2. Printing parameters

Printing parameters of each device are presented in Table S2. Other parameters are listed below:

Additional parameters:

- ✓ Filament material: modified *polyethylene-terephthalate*-glycol (PETG)
- ✓ Material Density: 1.27 g cm^{-3}.
- ✓ Drawing software: Autodesk Fusion 360, version 2020.
- ✓ Slicing software: Simplify3D, version 7.1.
- ✓ File format for printing: STL (available for download in **LINK**)

- ✓ File format for modeling: DWG (available for download in **LINK**)
- ✓ *Other items and all files for assembly and configuration are available in:* **LINK**

The modeling, slicing, and printing files (open) of each device are available for download in Table S2.

Table S2: Open files of the devices

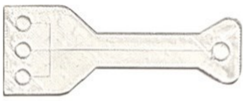
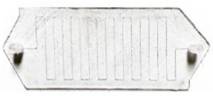
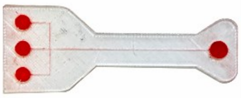
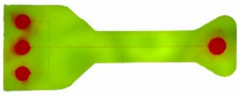
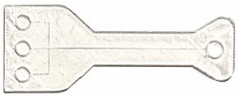
Device	Modeling DWG file	Slicing STL file
	DOWNLOAD	DOWNLOAD
	DOWNLOAD	DOWNLOAD
	DOWNLOAD	DOWNLOAD
	DOWNLOAD	DOWNLOAD
	DOWNLOAD	DOWNLOAD
	DOWNLOAD	DOWNLOAD
	DOWNLOAD	DOWNLOAD

Table S3: Printing parameters of the devices.

Device	Material	Nozzle/Bed temperature (ºC)	Time printing (min)	Layer height (mm)	Extrusion width (mm)	Extra multiplier (%)
	ABS	235/100	12	0,10	0,20	100
	TPU	225/80	12	0,10	0,20	100
	PLA	205/70	12	0,10	0,20	100
	PETG	230/90	12	0,08*	0,18*	104*
	PETG	230/90	26	0,10	0,20	100
	PETG	230/90	10	0,10	0,20	100
	PETG	230/90	18	0,10	0,20	100
	PETG	230/90	19	0,10	0,20	100
	PETG	230/90	22	0,10	0,20	100
	PETG	230/90	34	0,10	0,20	100

**optimized parameters with experimental planning.*

3. Characterization and tests performed

Thermal and vibrational tests

The vibration tests were carried out by assembling an open-source system using a piezoelectric-based accelerometer on a sensor module with an Arduino UNO controller. A sampling frequency of 1 kHz was used, and the data were recorded every 7 seconds with an accuracy of around 1%. The diagram of the connection of the piezoelectric sensor with the Arduino is shown in Figure S4, while the generic code used to configure the sensor is presented in Figure S5.

Figure S4:Diagram of connection of the piezoelectric sensor with the Arduino.

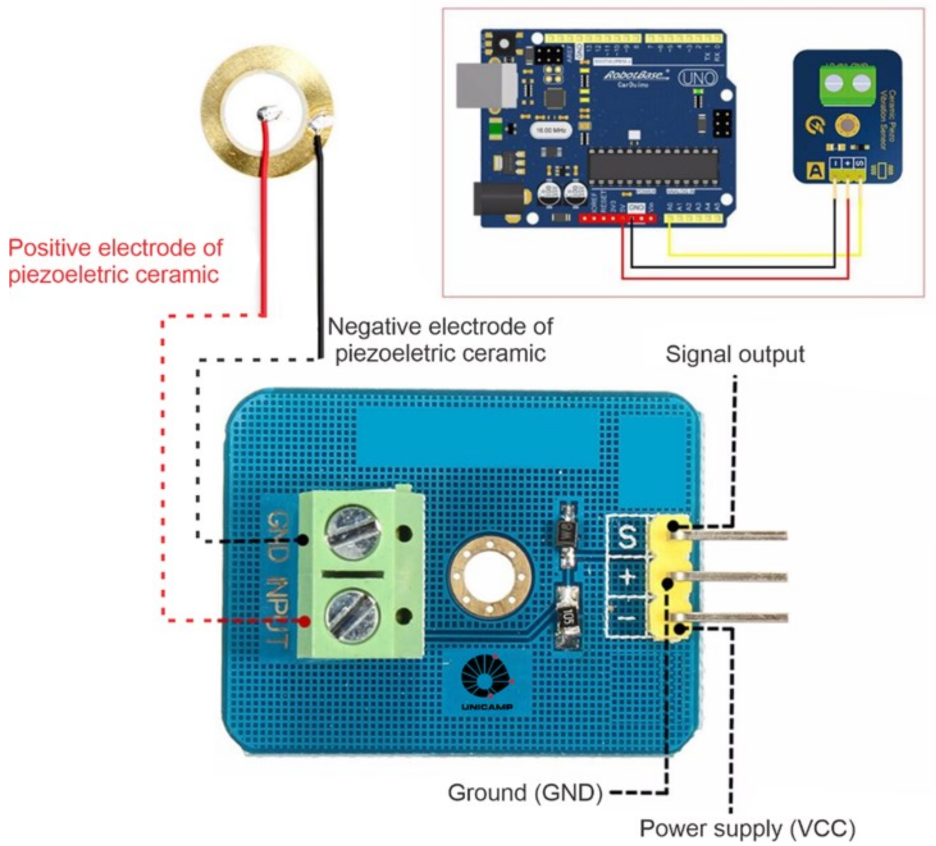


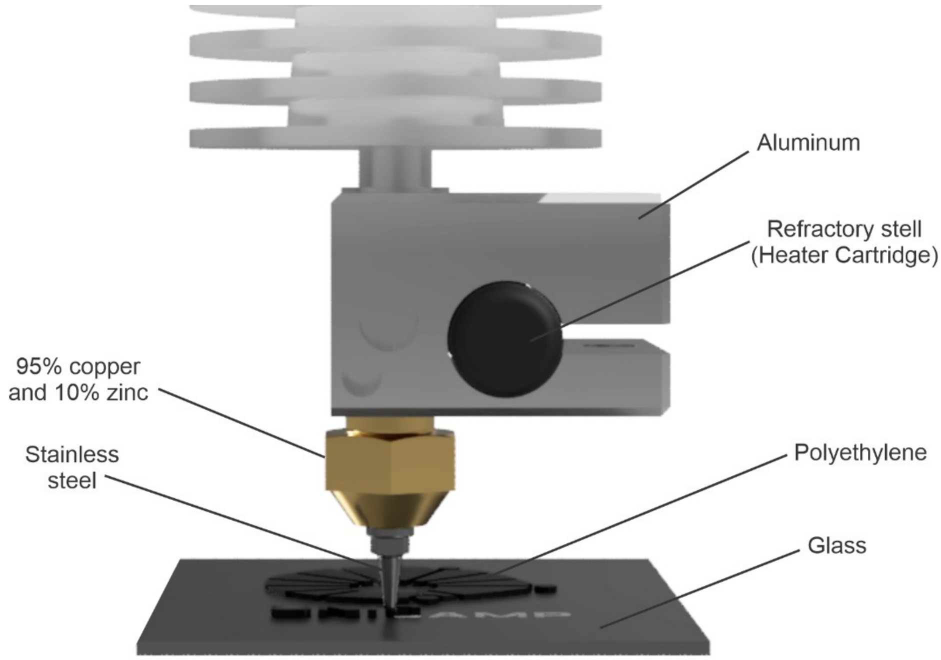
Figure S5: Generic code used to configure the piezoelectric sensor with Arduino.

```
/*******************************************************
*********************
Piezo_Vibration_Sensor.ino
sketch for Reverson´s Piezo Vibration Sensor
Unicamp @ Instituto de Quimica
March 04, 2021

- Connect a 1Mohm resistor across the Piezo sensor's
pins.
- Connect one leg of the Piezo to GND
- Connect the other leg of the piezo to A0

Vibrations on the Piezo sensor create voltags, which are
sensed by the Arduino's
A0 pin. Check the serial monitor to view the voltage
generated.

Development environment specifics:
Arduino 1.6.7
*******************************************************
*********************/
const int PIEZO_PIN = A0; // Piezo output

void setup()
{
  Serial.begin(9600);
}

void loop()
{
  // Read Piezo ADC value in, and convert it to a voltage
  int piezoADC = analogRead(PIEZO_PIN);
  float piezoV = piezoADC / 1023.0 * 5.0;
  Serial.println(piezoV); // Print the voltage.
}
```

Simulations

To perform thermal simulations, the composition of the components was respected in the project, as shown in Figure S6.

Figure S6: Components materials used for thermal simulations.

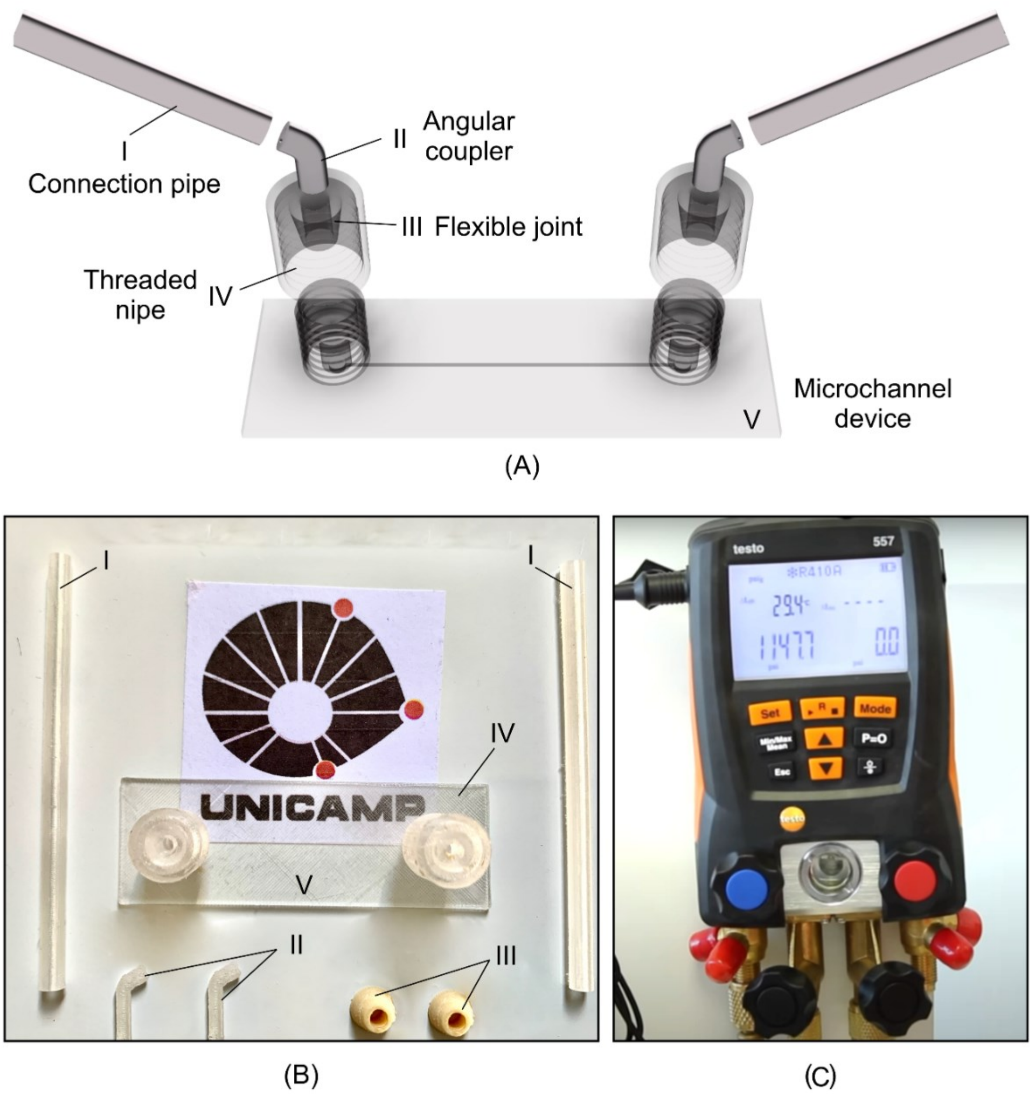


The values used for heat loads and thermal limit conditions were selected according to the real values to obtain a model closer to the real conditions. Thus, a thermal load of 230ºC was selected for the heating cartridge, and the contact detection tolerance was fixed at 0.10 mm for all parts. The thermal radiation between the hot end and the printed device has an emissivity value of 0.95. The simulation results included both temperature contact and heat flow.

Pressure tests

To perform the pressure tests, a Digital Testo manometer model 550, using valves manifold, was coupled in the outlet reservoir, and a syringe pump model Pump 11 Elite (Havard Apparatus) connected in the inlet reservoir. All the apparatus for the connections were 3D-printed, and they are shown in Figure S7.

Figure S7: A) 3D model of the device and connections. B) Device printed with the connections to perform the pressure test. C) Pressure test equipment, maximum pressure reached 1147 psi (approximately 80 bar).

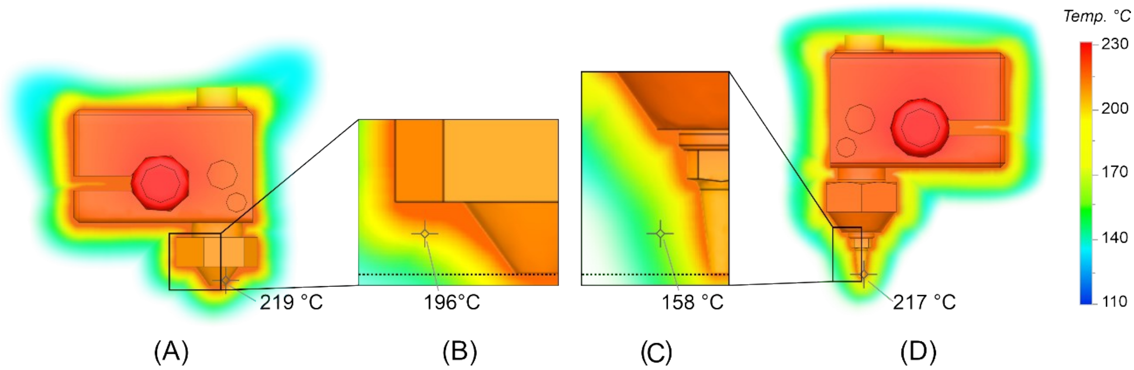


File format for modeling: DWG (available for download in LINK)

Simulation Results

Figure S8 depicts the results of the computational thermal simulations via CFD for the standard and adapted nozzle.

Figure S8: (A) Temperature to promote the melting of the material in a standard nozzle. (B) Thermal radiation around the nozzle structure. (C) Thermal radiation around the adapted nozzle. (D) Temperature to promote the melting of the material in the adapted nozzle.



A thermal camera was used to perform thermographic images of different parts of the systems. Results are depicted in Figure S9.

Figure S9: Image of the thermographic analysis of the extruder head. (A) Temperatures of the heating cartridge and nozzles of the conventional system (A-I) and the system with the adapted nozzle (A-II) before printing starts. (B) Temperatures of the conventional system (B-I) and the system with the adapted nozzle (B-II). (C) Surface temperature near the tip of the nozzle measured at the same distance for both the conventional nozzle (C-I) and the adapted nozzle (C-II).

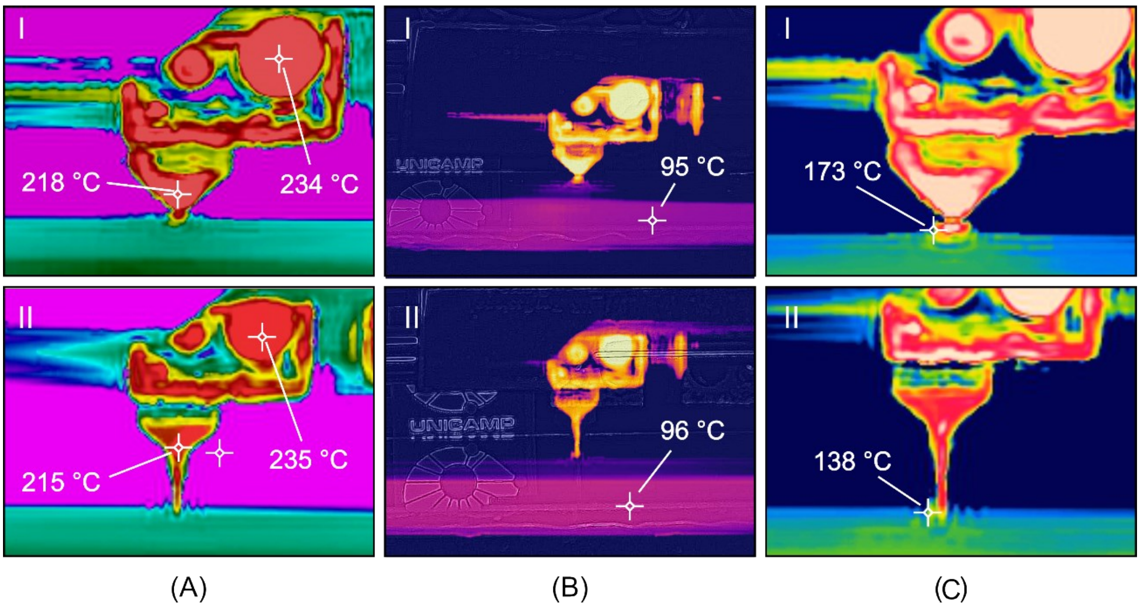


Figure S10 compares two devices obtained for both nozzles (standard and adapted) with the same height layer value.

Figure S10: Printed devices obtained with the same height layer using a (A) standard nozzle and (B) adapted nozzle.

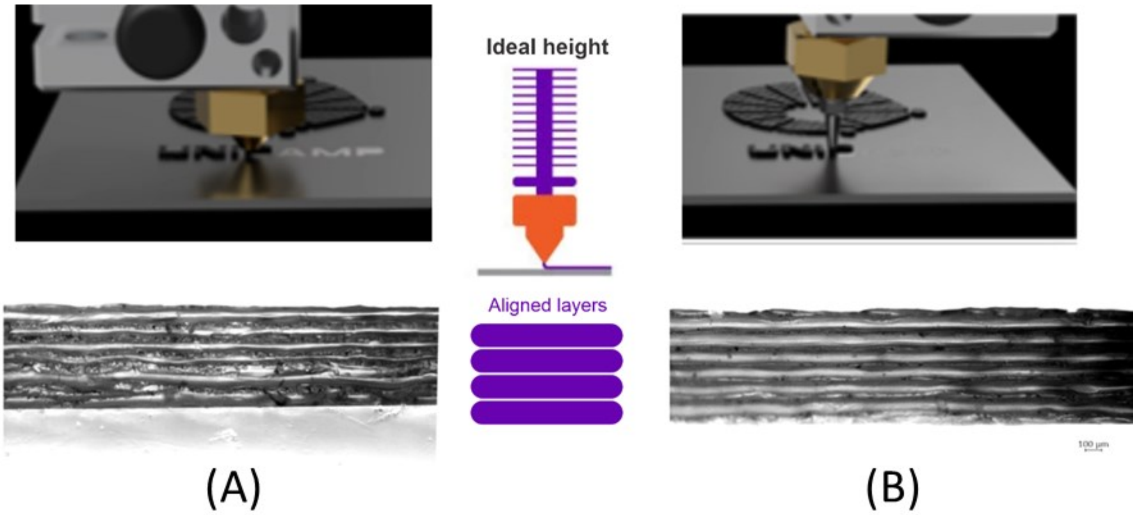


Figure S11. Adaptation of the quartz printing bed in the FDM 3D printer

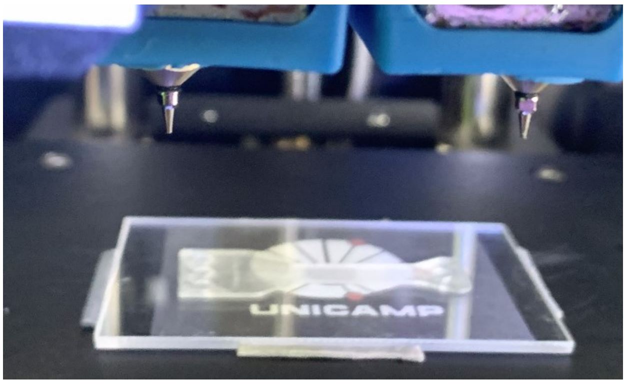
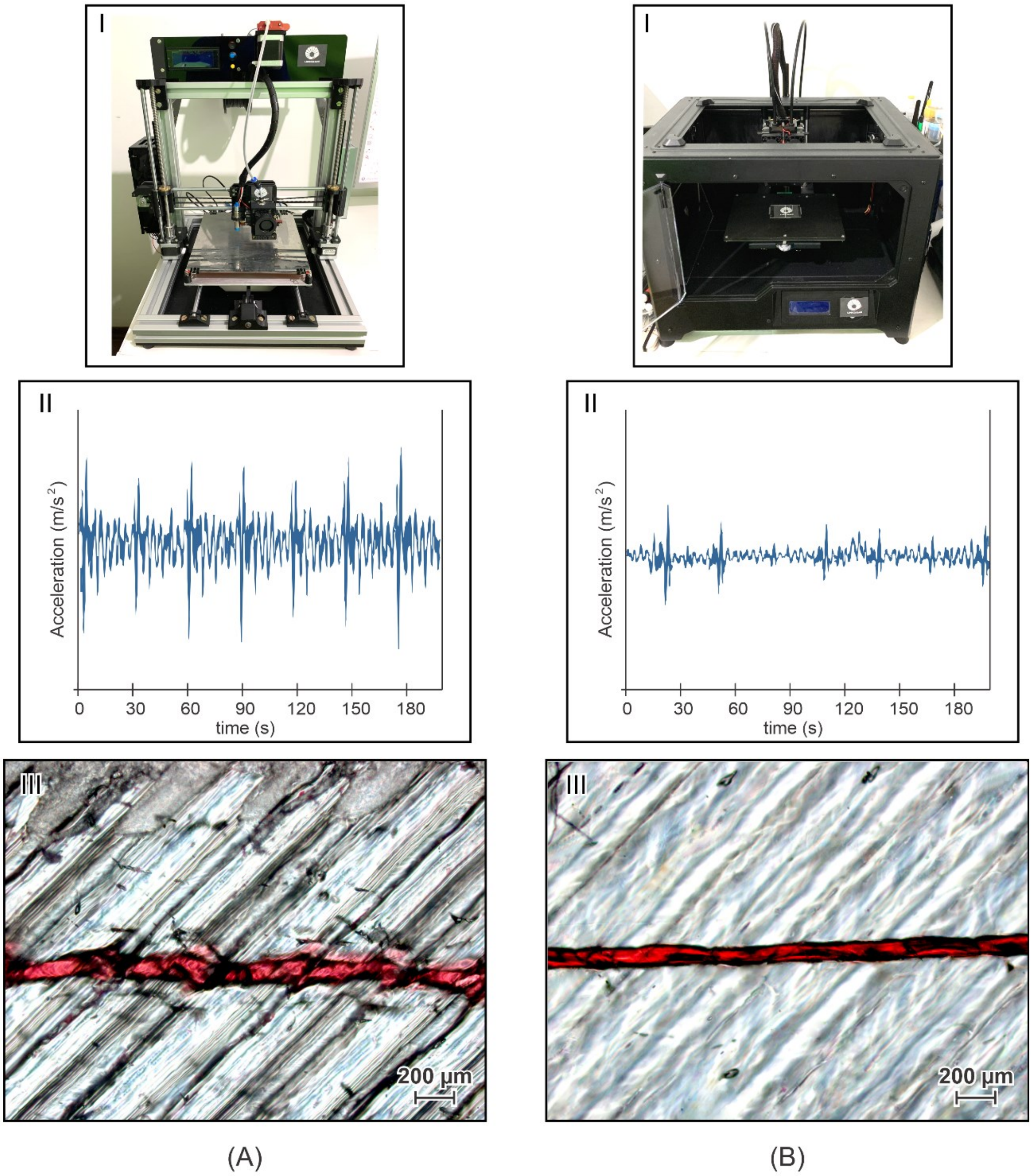


Figure S12: Vibrational effect for (A) an open and (B) closed cabinet printer and images of the printed obtained channels.



Statistical analysis

Statistica software (TIBCO ™ Software Inc., Palo Alto, USA) was used to carry out the experimental planning. The experimental design was Box-Behnken using three variables: layer height, extrusion width, and multiplier extrusion with three levels each, shown in Table S4. A response surface contour plot is showed in Figure S13.

Table S4: Parameters and levels used in the Box-Behnken experimental design.

Variables		Levels		
		-1	*0*	*1*
x_1	Layer height (mm)	0,08	0,10	0,12
x_2	Extrusion width (mm)	0,18	0,20	0,22
x_3	Multiplier extrusion (%)	96	100	104

Table S5: Transmittance percentage (transparency) obtained in this work and those reported in the literature

3D Printing technology	Material	Thickness (µm)	Transmittance (%)	Reference
FDM	PMMA	100 – 1000	40 – 50	52
FDM	PETG	300 - 600	20 – 25	26
FDM	PLA CC	300 - 600	20 – 30	26
FDM	PLA	400	8 - 20	53
FDM	PETG	200 - 1000	15 - 30	54
FDM	PLA	N/A	20	55
SLA	Commercial Resin	200	60	56
DLP	PEG-DA	300	80	57
i3DP (InkJet)	VisiJet	64 - 320	20 - 61	58
FDM	PETG	640	80[a]	This work

[a] Average value (N = 17)

Figure S13: Response surface contour plot of layer width vs layer height. Extrusion multiplier of 104%.

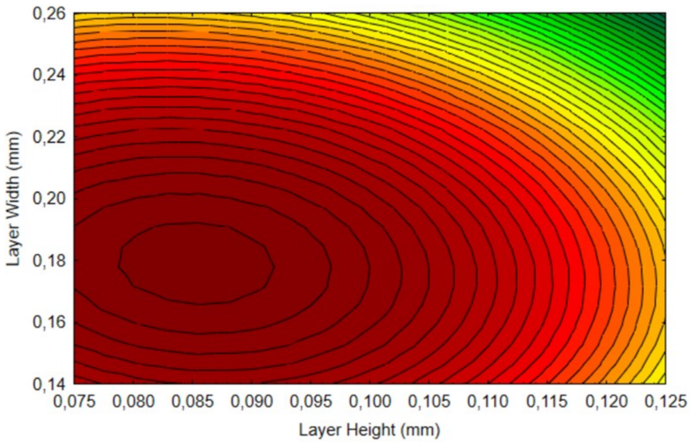
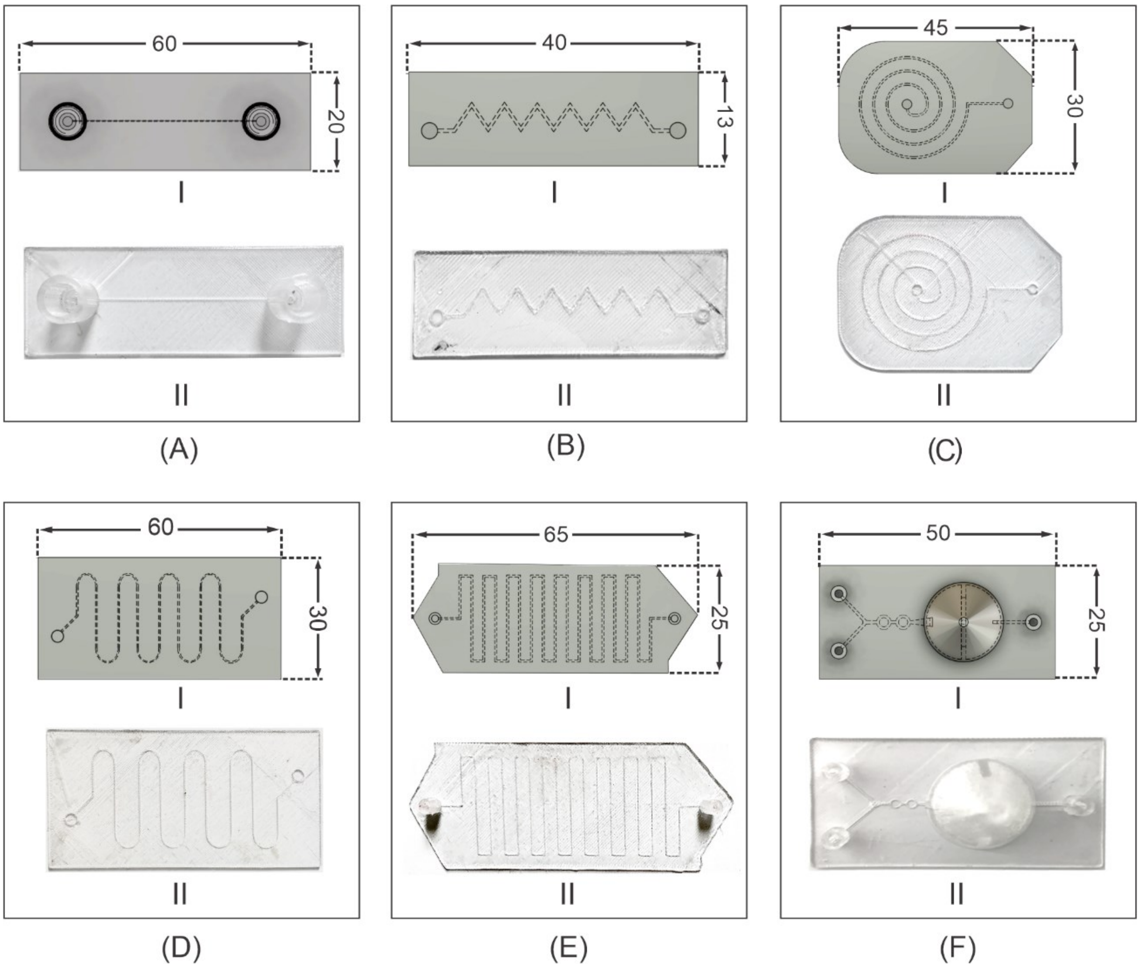


Figure S14: Different designs successfully printed after drawing adjustments. (I) Projected drawing; (II) Printed device



4. Videos

The links to access the supplementary videos cited in the manuscript are available below:

[Video S1: Nozzle Adaptation]

[Video S2: Light transmission measurements]