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Laboratory of Biological Electron Microscopy

Dynamic interface printing

Chinmaya KV
Laboratory of Biological Electron Microscopy
Department of Physics (EDPY), EPFL

3D printing with light
13-10-2025

Article

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https://doi.org/10.1038/s41586-024-08077-6

Received: 6 July 2023

Accepted: 19 September 2024

Callum Vidler[1✉], Michael Halwes[1], Kirill Kolesnik[1], Philipp Segeritz[1,2,3], Matthew Mail[1], Anders J. Barlow[4], Emmanuelle M. Koehl[5], Anand Ramakrishnan[5,6], Lilith M. Caballero Aguilar[1,7,8], David R. Nisbet[1,7,8,9], Daniel J. Scott[2,3], Daniel E. Heath[1,8], Kenneth B. Crozier[10,11,12] & David J. Collins[1,8✉]

Additive manufacturing is an expanding multidisciplinary field encompassing applications including medical devices[1], aerospace components[2], microfabrication strategies[3,4] and artificial organs[5]. Among additive manufacturing approaches, light-based printing technologies, including two-photon polymerization[6], projection micro stereolithography[7,8] and volumetric printing[9–14], have garnered significant attention due to their speed, resolution or potential applications for biofabrication. Here we introduce dynamic interface printing, a new 3D printing approach that leverages an acoustically modulated, constrained air–liquid boundary to rapidly generate centimetre-scale 3D structures within tens of seconds. Unlike volumetric approaches, this process eliminates the need for intricate feedback systems, specialized chemistry or complex optics while maintaining rapid printing speeds. We demonstrate the versatility of this technique across a broad array of materials and intricate geometries, including those that would be impossible to print with conventional layer-by-layer methods. In doing so, we demonstrate the rapid fabrication of complex structures in situ, overprinting, structural parallelization and biofabrication utility. Moreover, we show that the formation of surface waves at the air–liquid boundary enables enhanced mass transport, improves material flexibility and permits 3D particle patterning. We, therefore, anticipate that this approach will be invaluable for applications where high-resolution, scalable throughput and biocompatible printing is required.

Limitations of Current 3D Printing – Why We Need DIP

Slow fabrication: Layer-by-layer printing is time consuming, cm-scale objects often take hours.

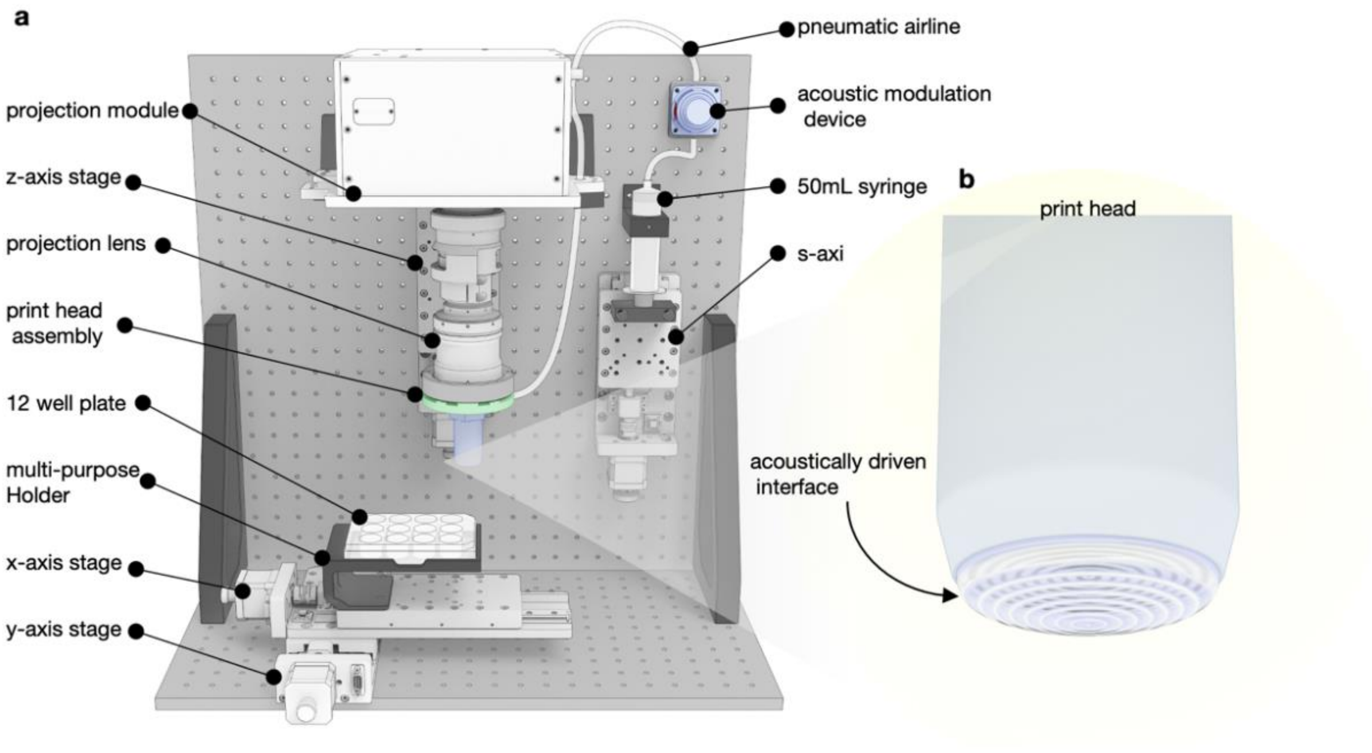
Material restrictions: Most systems require clear, low-viscosity resins; opaque or cell-laden materials fail.

High shear on bioinks: Extrusion methods damage living cells and delicate soft materials.

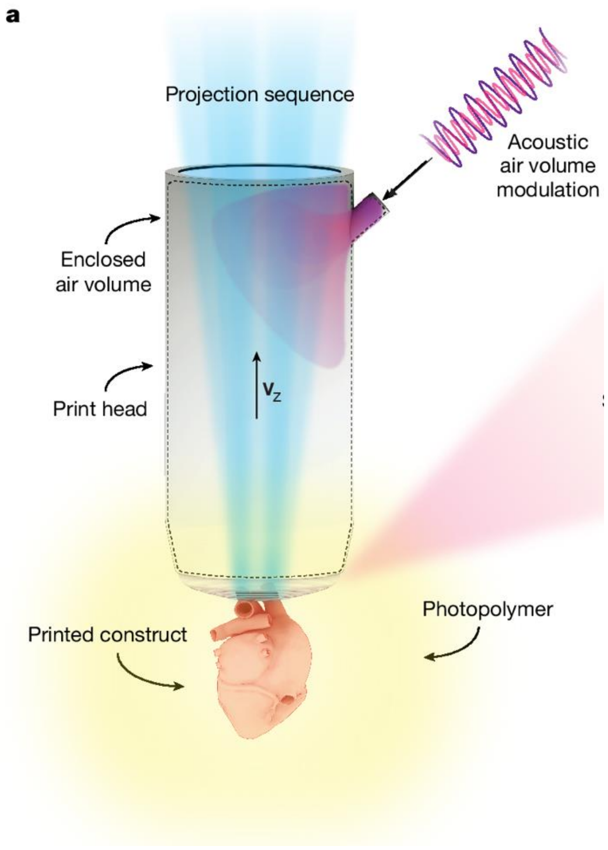
Geometric constraints: Overhangs and internal channels need supports, limiting freeform design.

Poor resin flow: Limited mass transport during curing causes defects and slows continuous printing.

- The paper introduces a new 3D printing approach called Dynamic Interface Printing (DIP)
- which uses an acoustically modulated, constrained air–liquid boundary to rapidly generate centimetre-scale
- 3D structures in tens of seconds.


a
projection module
z-axis stage
projection lens
print head assembly
12 well plate
multi-purpose Holder
x-axis stage
y-axis stage
pneumatic airline
acoustic modulation device
50mL syringe
s-axi
b
print head
acoustically driven interface

DIP



Print Head Setup

- Hollow print head with top glass window
- Submerged in liquid prepolymer → traps air pocket

Projection of Air–liquid **meniscus forms at bottom opening** acts as print surface

Patterned Light

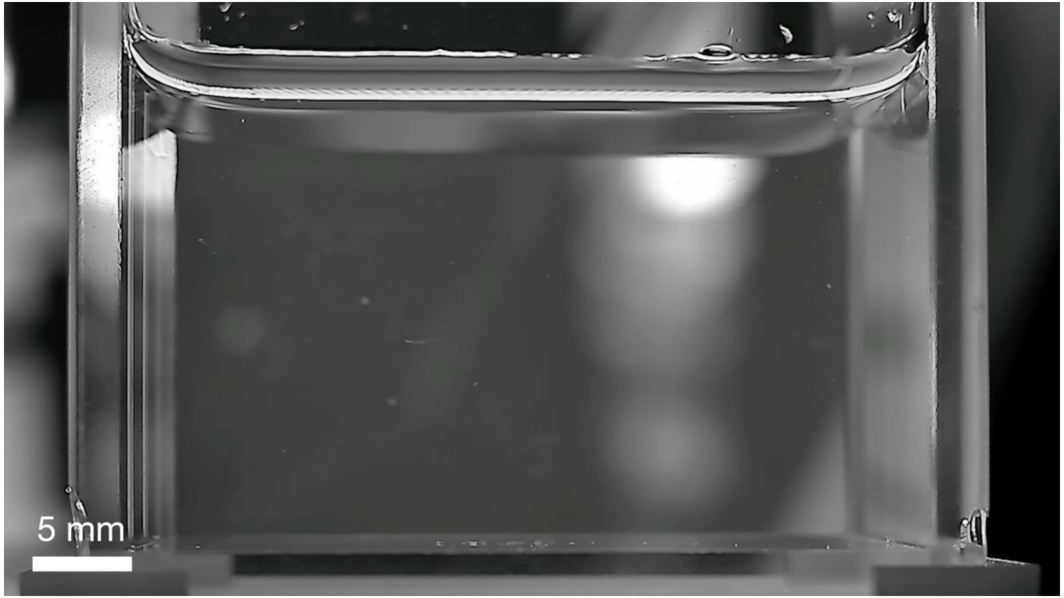
- **405 nm visible light** projected through glass onto meniscus
- Light pattern = 2D cross-section of 3D model
- Photopolymerization occurs **directly at the interface**

Meniscus Control

- Adjust **air pressure**, **vertical position**, and **acoustic drive**
- Tunes curvature + position so meniscus aligns with **optical focal plane**

Continuous Build

- Object grows as the **print head lifts upward**
- Fresh prepolymer flows in beneath the interface
- Enables **continuous printing** (no layer-by-layer resets)


5 mm


d
38 s
Print head
v_z
Air–liquid boundary
e

Convex slicing

Convex slicing & projection mapping: The meniscus is curved, they compute the slicing differently
revolve Bézier curves of interface profile - compute voxel intersections
generate projection sequence that matches curved interface, so that the 3D object is correctly formed.

The algorithm does the following:

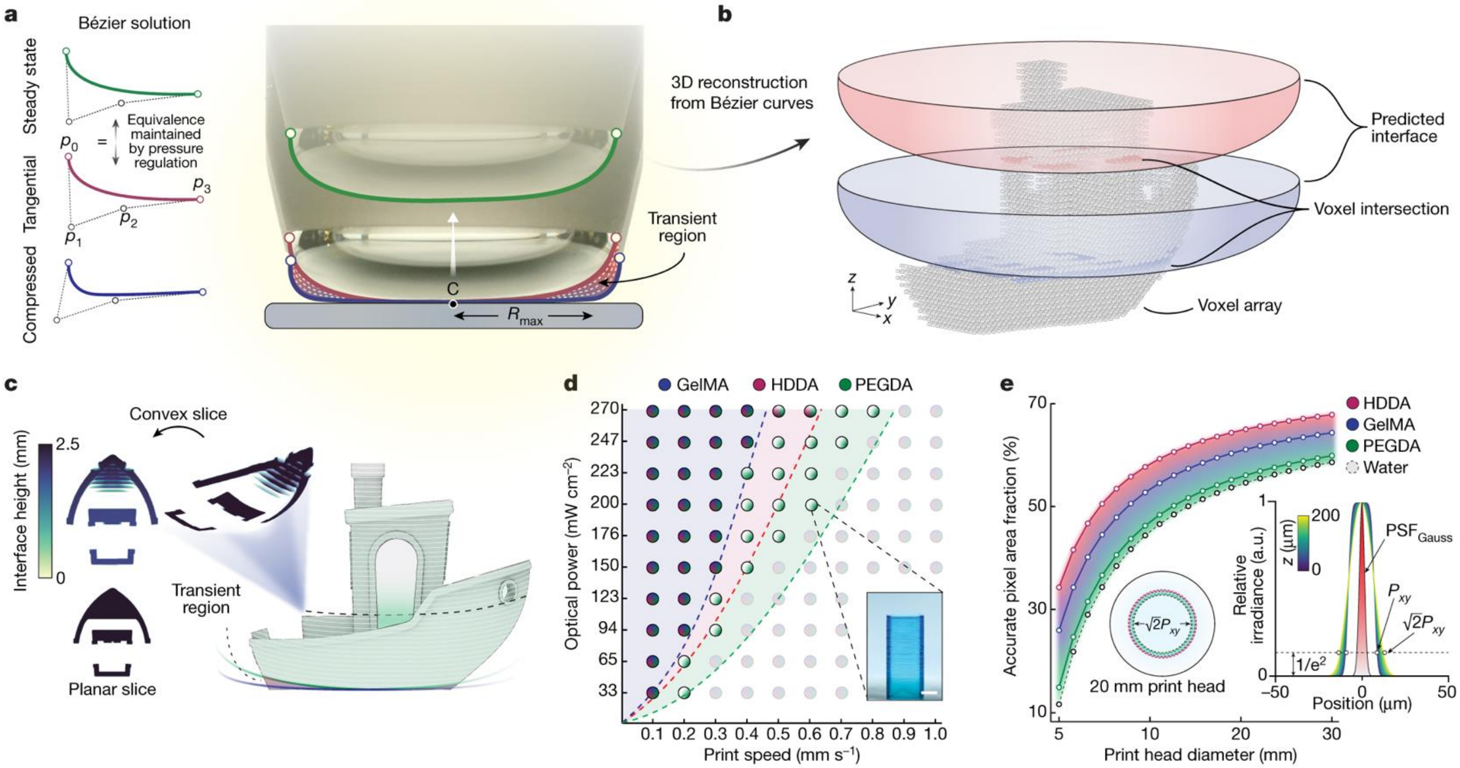
1. **Computes meniscus shape** using the *Young–Laplace equation* (surface tension vs pressure difference).

2. **Fits the interface** with a **Bézier curve** model (for smooth curvature).

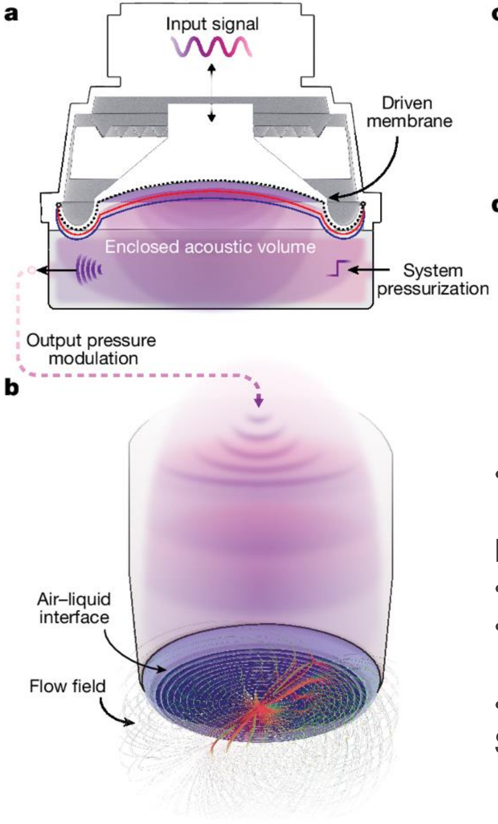
3. **Reprojects** the 3D geometry onto this curved surface.

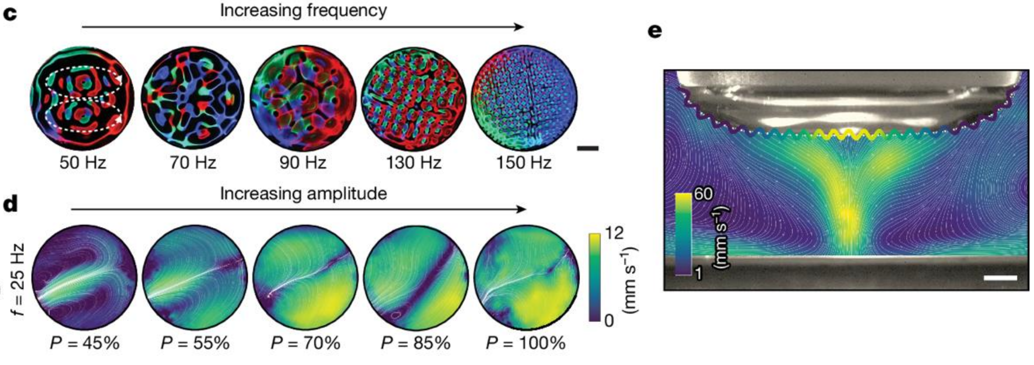
4. **Generates projection masks** (2D bitmap images) that correspond to each incremental meniscus position as the print head rises.

Convex slicing



Acoustic modulation





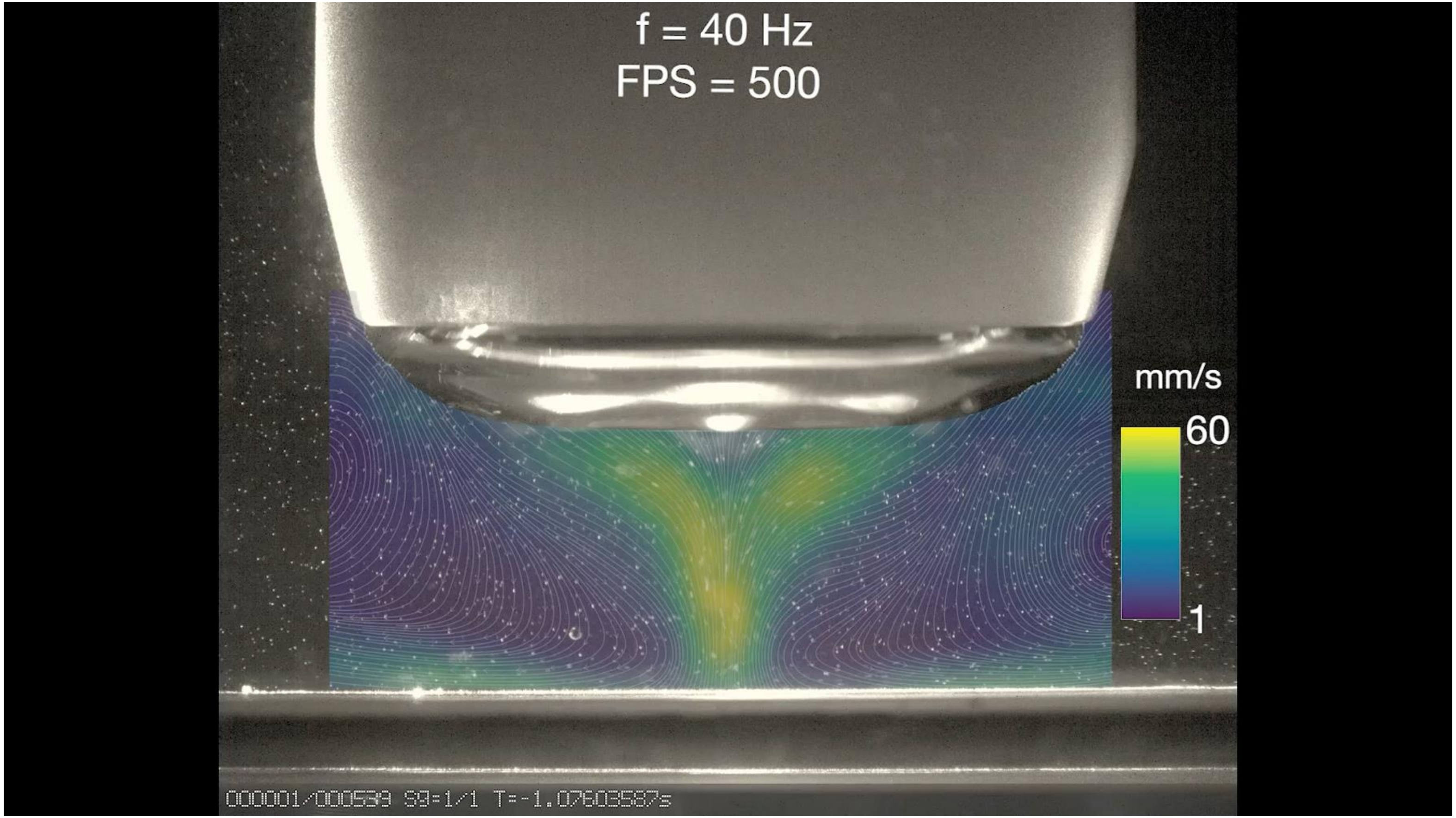
- Print speed depends on **optical power density** (mW/cm²) and resin reactivity.

For example:

- At 270 mW/cm² > 700 µm/s print rate (PEGDA).
- At 30–50 mW/cm² - slower, but cell-friendly.

- Too high power : overheating or overcuring; too low → underpolymerization.

So the light intensity is carefully tuned to match resin kinetics.


f = 40 Hz
FPS = 500
mm/s
60
1
000001/000539 S9=1/1 T=-1.07603587s

Novelty

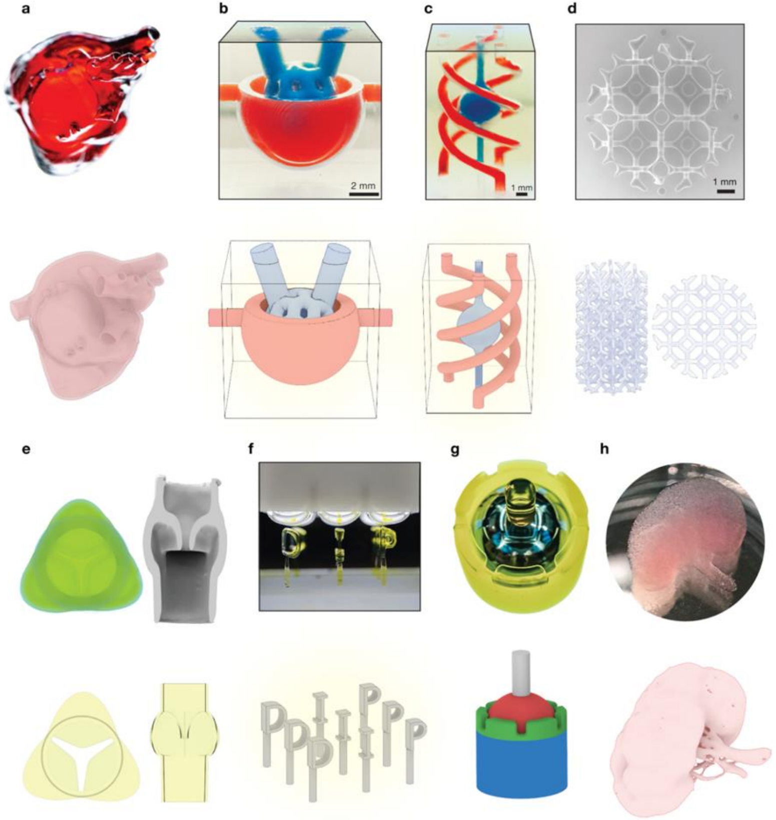
- Acoustic modulation / capillary-gravity waves: by modulating the air volume or otherwise acoustically driving the interface, one can shape/control that meniscus and fluid flows, enhancing influx of material, reducing mass-transport limitations.

- Convex slicing: because the interface is curved (meniscus), one cannot treat the cross sections as flat: they compute slicing accordingly using Bézier curves + Young-Laplace solutions to map the 3D model to the curved interface.

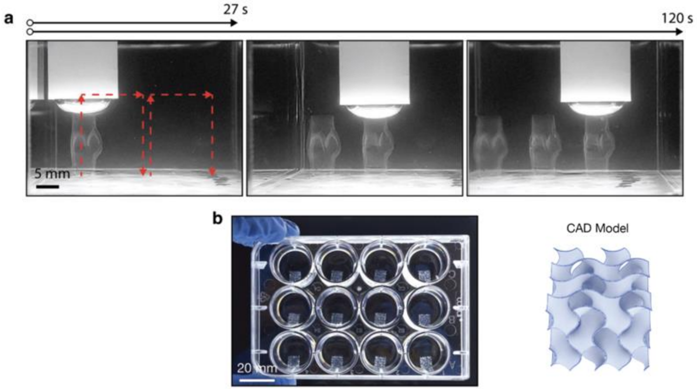
- High throughput + many materials + soft / biomaterials compatibility: They show the method works for hard acrylates, hydrogels (e.g., PEGDA, GelMA), opaque materials (cells, granular additives) etc. The print speeds and volumes are high.

- 3D particle/ cell patterning and overprinting: They illustrate ability to pattern suspended particles via standing waves, and ability to overprint objects (multi-material, embed parts).

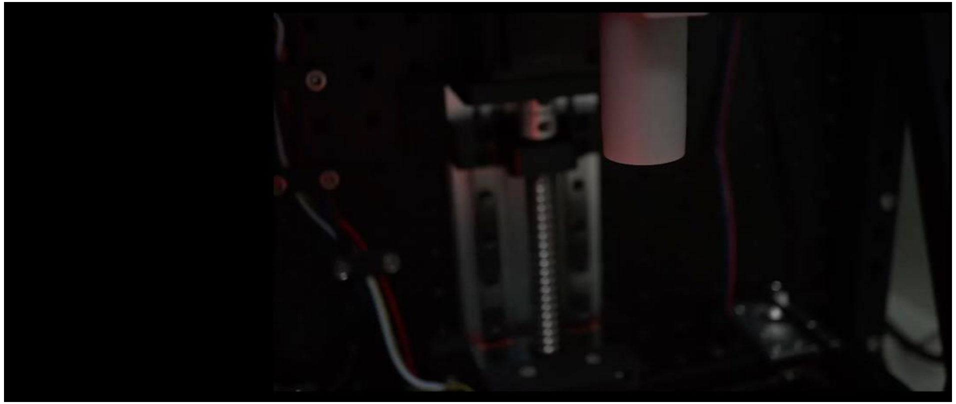
DIP capabilities



Supplementary Fig.28| Comparison of the printed structures with their corresponding CAD models, as presented in the main text. a, Printed heart model. **b**, Bowmans Capsule. **c**, Tri-helix. **d**, Kelvin cell lattice. **e**, Tricuspid valve. **f**, Letters 'DIP'. **g**, Ball and socket joint. **h**, Anatomical kidney.

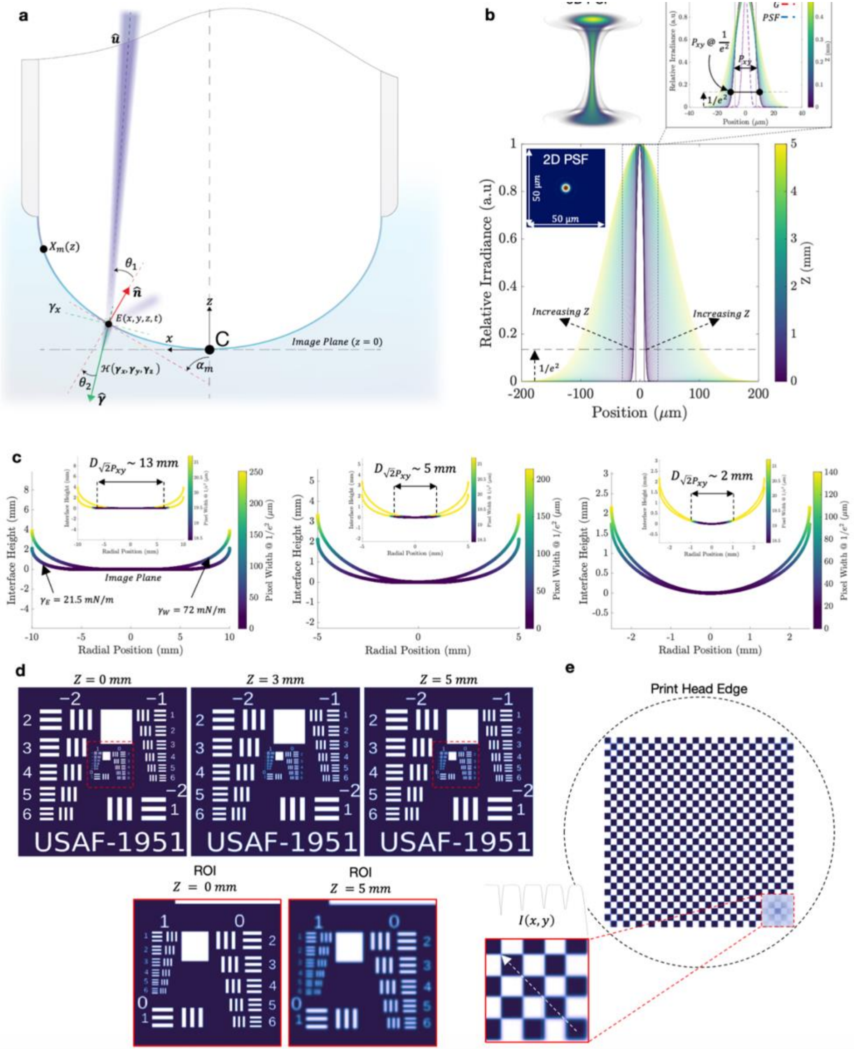


Supplementary Fig.16| Multi-step printing and direct in well printing. **a**, Time lapse images of three tricuspid valves printed in just under 120 seconds via three-dimensional placement of the print head. **b**, Direct in well printing of 12 gyroid lattices, created in just under 8 minutes.



Limitations

- Meniscus curvature & optical defocus.
- Light scattering in opaque or cell-laden materials
- Acoustic exposure for cells
- Scalability & Practical Deployment


a
$\hat{u}$
$X_m(z)$
θ_1
$\hat{n}$
γ_x
$E(x,y,z,t)$
z
x
C
Image Plane ($z = 0$)
$\mathcal{H}(\gamma_x, \gamma_y, \gamma_z)$
α_m
θ_2
$\hat{\gamma}$
b
3D PSF
P_{xy} @ $\frac{1}{e^2}$
P_{xy}
$1/e^2$
G
PSF
Position (μm)
2D PSF
50 μm
50 μm
Relative Irradiance (a.u)
Increasing Z
Increasing Z
$1/e^2$
Position (μm)
Z (mm)
c
$D_{\sqrt{2}P_{xy}}$ ~ 13 mm
$D_{\sqrt{2}P_{xy}}$ ~ 5 mm
$D_{\sqrt{2}P_{xy}}$ ~ 2 mm
Interface Height (mm)
Radial Position (mm)
Image Plane
γ_E = 21.5 mN/m
γ_W = 72 mN/m
Pixel Width @ $1/e^2$ (μm)
d
Z = 0 mm
Z = 3 mm
Z = 5 mm
USAF-1951
ROI
Z = 0 mm
ROI
Z = 5 mm
e
Print Head Edge
$I(x,y)$