EPSRC Centre for
Innovative Manufacturing in
Additive Manufacturing

Biomedical applications of inkjet printing at the UoN

EPSRC
Engineering and Physical Sciences Research Council

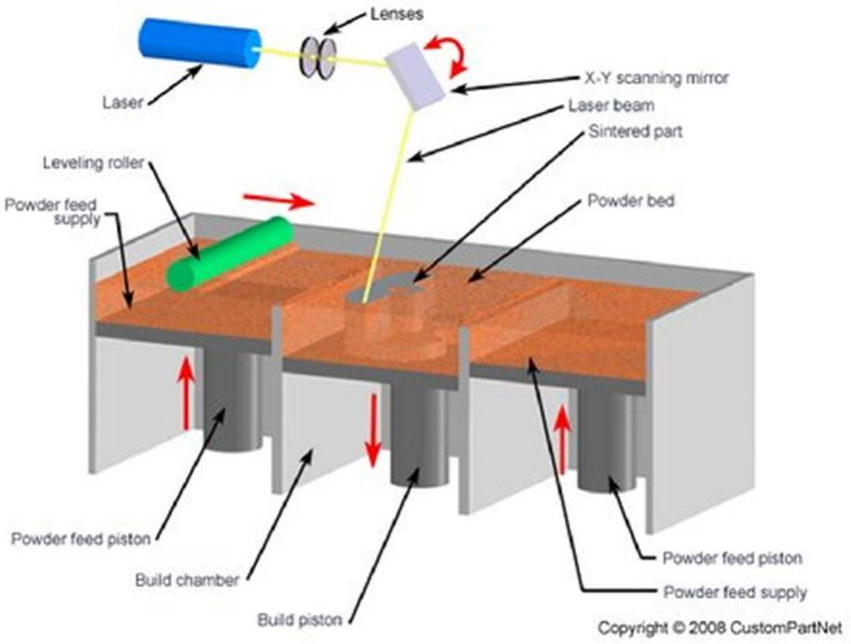
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Content

- Why Material Jetting?
- Printability requirement
- Material Jetting at UoN
  - Polycaprolactone: inkjet printing of bioresorbable material
  - 3D printing of materials with resistant to bacterial attachment
  - 3D printable biodegradable materials
  - Polymer particle formation using inkjet printing
  - 3D printing of human tissues
  - 3D printed smart limbs

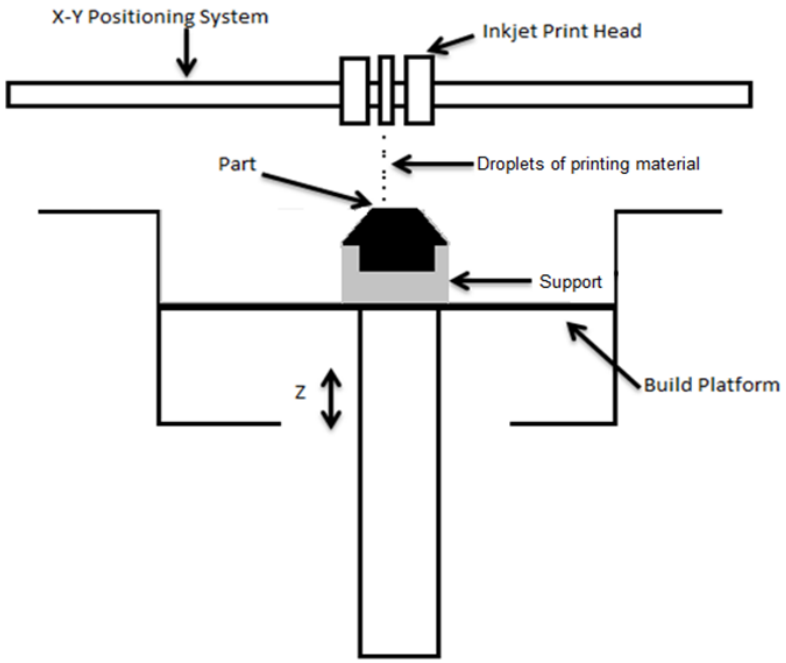
Why Material Jetting?

- Classification of the AM techniques (ASTM, 2012)
  - Binder Jetting
  - Powder Bed Fusion
  - Directed Energy Deposition
  - Sheet Lamination
  - Vat Photopolymerization
  - Material Extrusion
  - **Material Jetting**



Why Material Jetting?

- Material Jetting: Droplets of build material are selectively deposited



SINGLE MATERIAL

↓

MULTIMATERIAL

Printability requirement

- Fluid printability is defined by parameter Z

$$Z = \frac{\sqrt{\gamma \rho a}}{\eta}$$

- γ Surface tension
- ρ Density
- a Characteristic length
- η Dynamic viscosity

$1 < Z < 10$

Stable droplet formation

Material Jetting at UoN

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

Stratasys Objet Connex 260

Dimatix DMP-2800 and DMP-2831

Material Jetting at UoN

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

PiXDRO LP50

Material Jetting at UoN

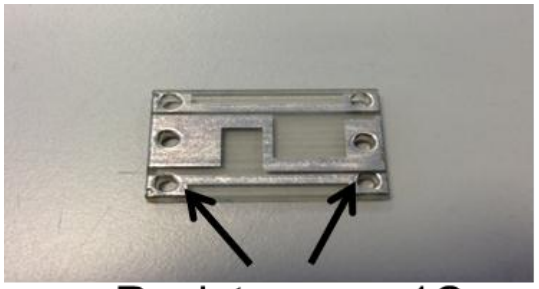
EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

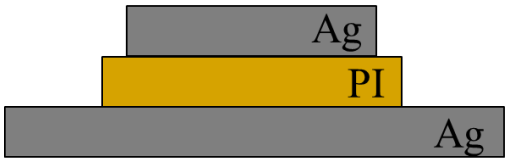
Material Jetting at UoN

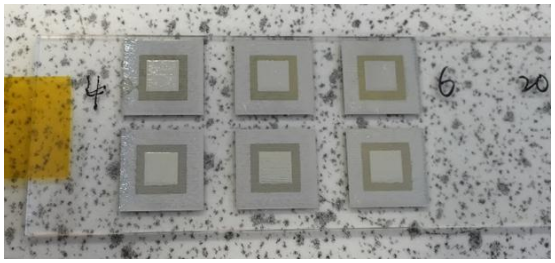
Nordson PICO

Material Jetting at UoN

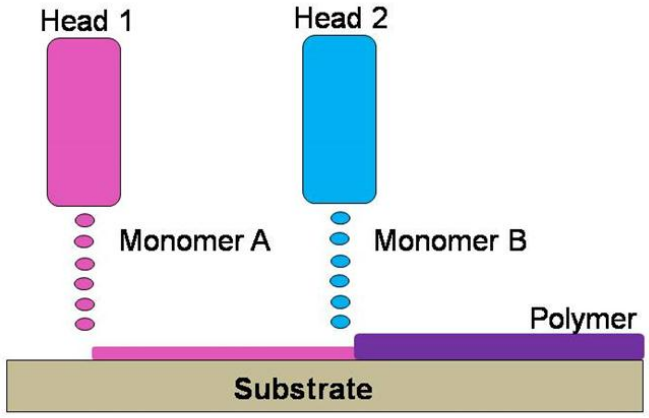
- Direct Printing
  - Jetting of Electronic Tracks
  - Inkjet printing of polyimide







- Reactive Printing
  - Reactive Jetting



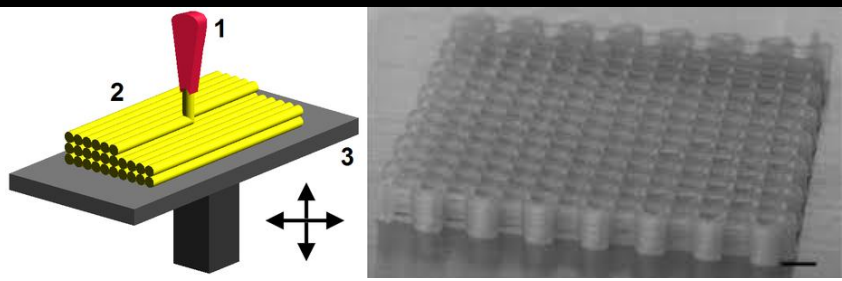
Material Jetting at UoN

- Reactive Printing
  - Photopolymers
    - Polycaprolactone: inkjet printing of bioresorbable material
    - 3D printing of materials with resistant to bacterial attachment
    - 3D printable biodegradable materials
    - Polymer particle formation using inkjet printing
    - 3D printing of human tissues

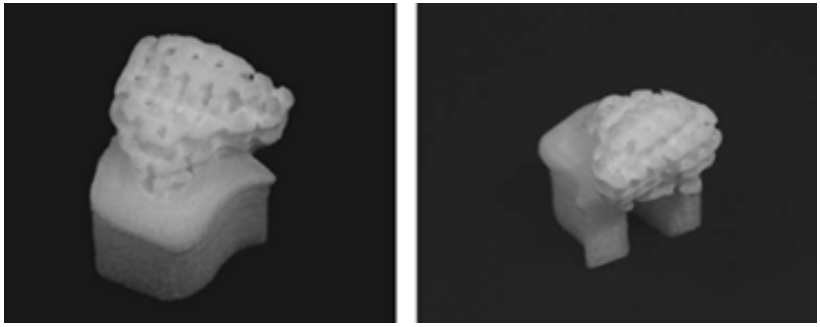
Polycaprolactone: inkjet printing of bioresorbable material

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Polycaprolactone is a bicompatible, biodegradable and bioresorbable material
- Mostly 3D printed by extrusion or energy deposition technique
- Lack of inks based on bioresorbable materials for inkjet printing
- Improvement of printing resolution
- Possibility of multimaterials



PCL printed by material extrusion technique [1]



PCL printed by direct energy deposition technique [2]

[1] Seyednejad, H. et al. Preparation and Characterization of a 3D-printed Scaffold Based on a Functionalized Polyester for Bone Tissue Engineering Application; *Functionalized Polyesters* 7, 2012, 5, 87.
[2] Williams, J. et al. Bone tissue engineering using polycaprolactone scaffolds fabricated visa selective laser sintering; Biomaterials, 2005, vol26, p.p: 4817-4827

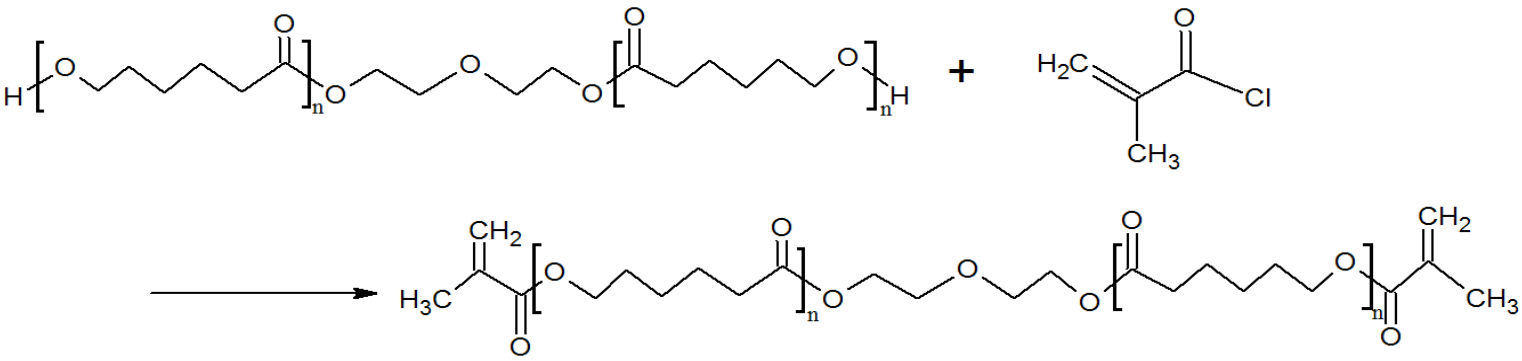
EPSRC Engineering and Physical Sciences Research Council

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

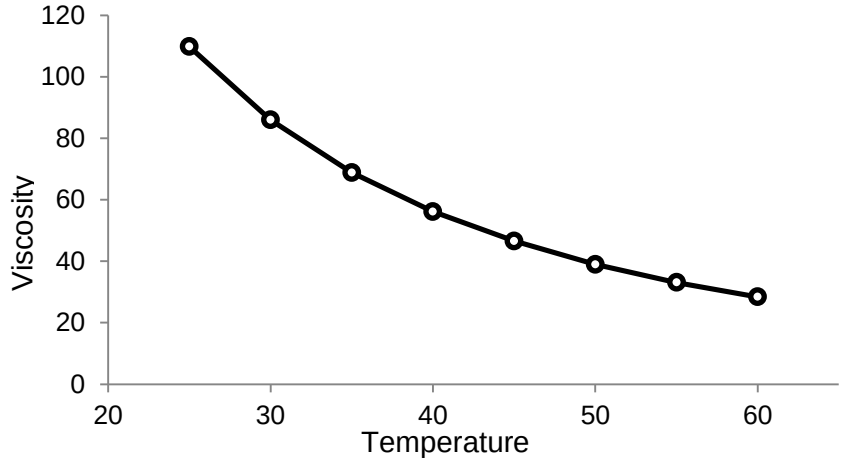
Polycaprolactone: inkjet printing of bioresorbable material

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Synthesis: Preparation of UV curable Polycaprolactone-derivative (PCLDMA)



- Printability assessment and modification

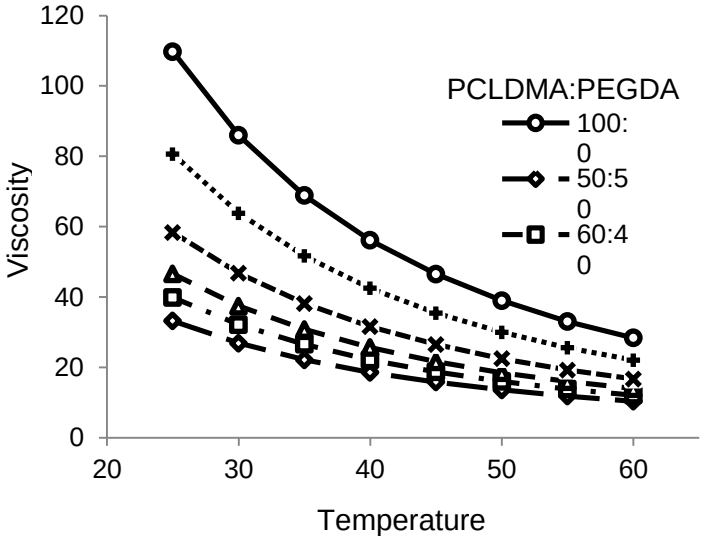


Viscosity of pure PCLDMA

Polycaprolactone: inkjet printing of bioresorbable material

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

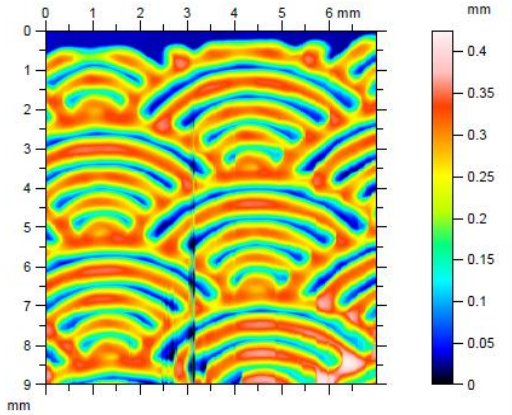
- Printability assessment and modification
  - Poly(ethylene glycol) diacrylate was used as diluent.
  - The viscosity of PCLDMA with different diluent proportion was measured
  - Based on the viscosity measurement, PCLDMA:PEGDA =70:30 was chosen as the printing composition

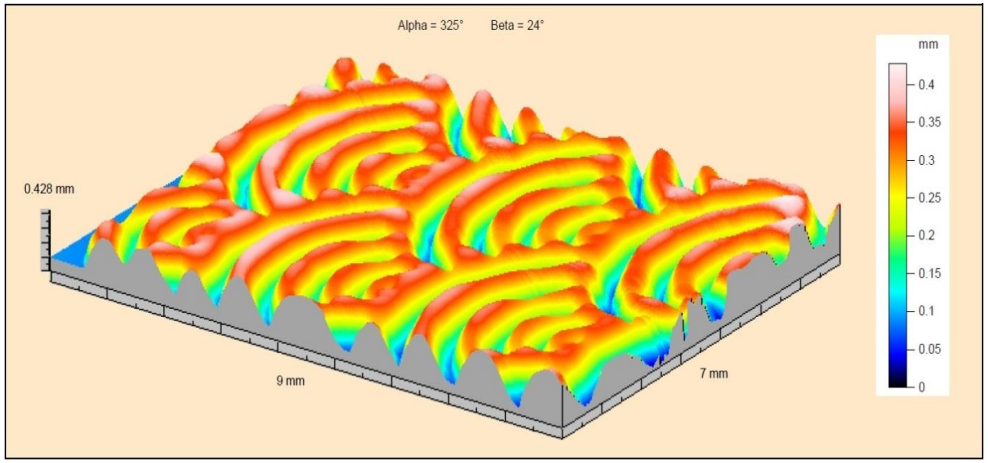


Temperature	PCLDMA:PEGDA Proportion					
	50:50	60:40	70:30	80:20	90:10	100:0
30 ºC	29.22±1.00	34.97±1.00	40.07±0.97	50.45±0.98	69.68±0.95	96.14±0.92
35 ºC	24.44±1.01	29.00±0.98	33.00±0.99	41.25±0.96	56.47±1.00	76.96±0.93
40 ºC	20.90±1.00	24.44±1.00	27.58±1.00	34.21±0.99	46.45±0.99	62.64±0.94
45 ºC	18.24±1.02	20.99±1.00	23.41±1.01	28.81±0.98	39.15±0.98	51.78±0.97
50 ºC	16.18±1.02	18.33±1.03	20.15±1.03	24.51±1.00	33.05±0.99	43.28±1.00
55 ºC	14.56±1.02	16.25±1.02	17.60±1.03	21.14±0.99	28.24±1.01	36.62±1.00
60 ºC	13.30±1.02	14.65±1.02	15.63±1.03	18.84±0.99	24.48±1.00	31.48±1.00

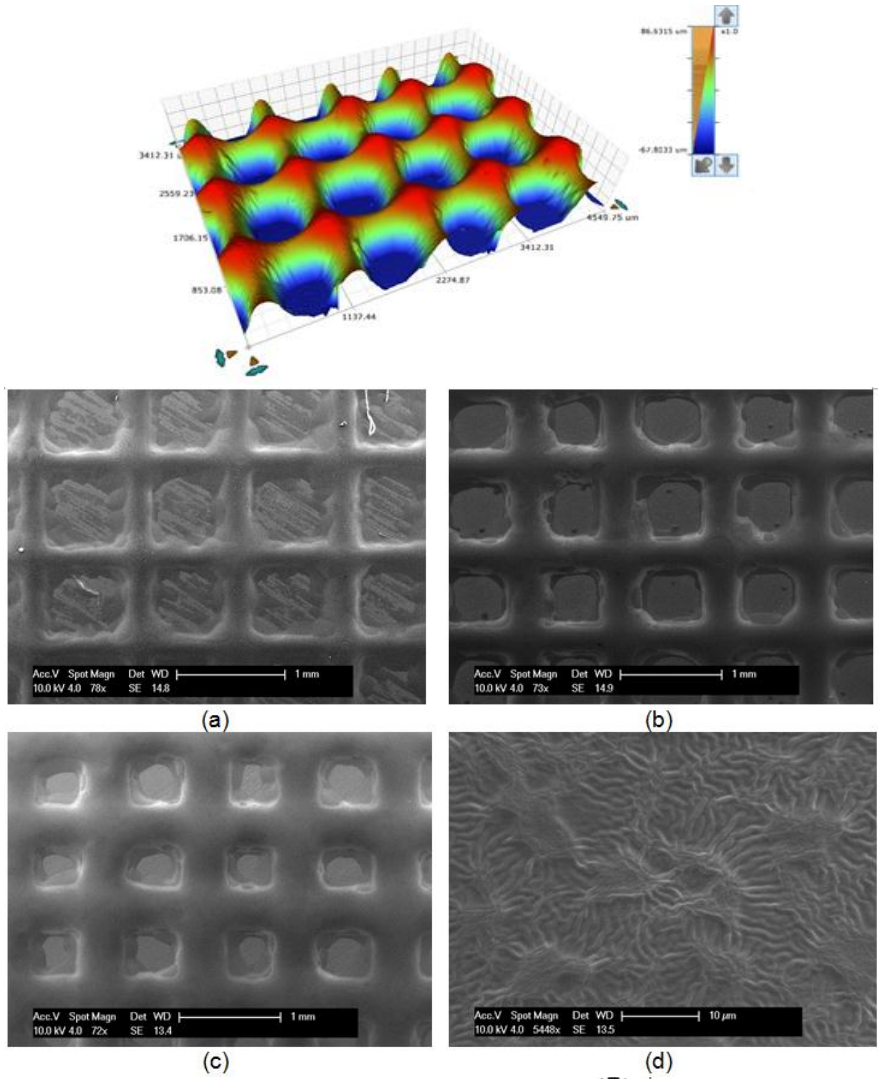
Polycaprolactone: inkjet printing of bioresorbable material

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing





Surface profile of printed mesh samples



SEM pictures of printed mesh structure with different wall thickness: (a) 150µm, (b) 300µm, (c) 500µm, (d) winkle found at sample surface

3D printing of materials with resistant to bacterial attachment

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Most healthcare-associated infections are associated with biofilms which form on the surfaces of medical devices.
- These microbial colonies develop up to 1000 times higher tolerances to antibiotic treatment and the host immune system compared with their planktonic counterparts
- The discovery of new materials with resistance to bacterial attachment opens a door to the fabrication of bacteria-free implants, with a direct reduction in the incidence rate of infections and therefore an increment in the cost saving.

LBSA Laboratory of Biophysics and Surface Analysis

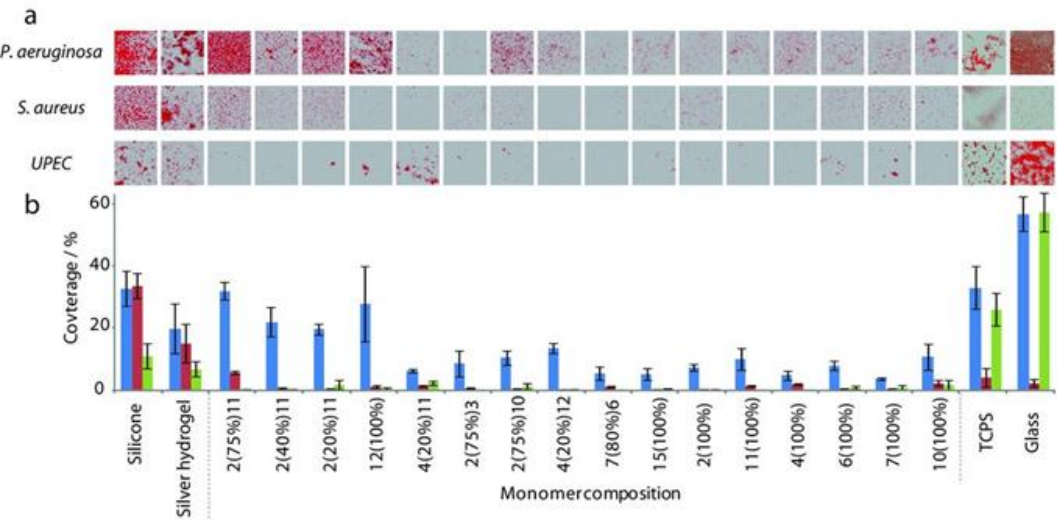
EPSRC Engineering and Physical Sciences Research Council

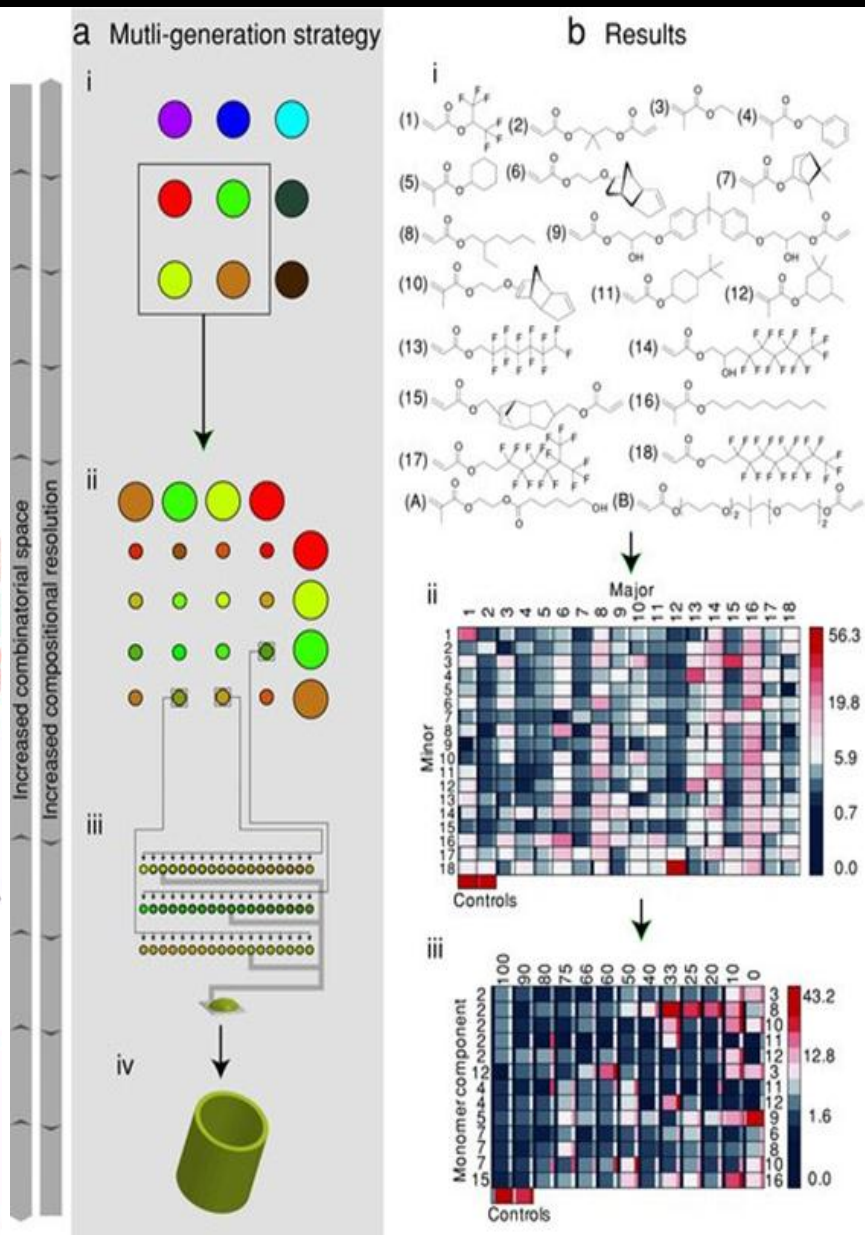
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

3D printing of materials with resistant to bacterial attachment

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Alexander, M et al.; Discovery of novel materials with broad resistance to bacterial attachment using combinatorial polymer microarrays, *Advanced Materials* **2013**, *25*, 2542-47





3D printing of materials with resistant to bacterial attachment

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- The aim of this work is to develop a methodology to inkjet print customised parts for biomedical applications with graded compliance and such antibacterial property, using a combination of inks with widely separated moduli.

Rigid material

Flexible material

LBSA Laboratory of Biophysics and Surface Analysis

EPSRC Engineering and Physical Sciences Research Council

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

3D printing of materials with resistant to bacterial attachment

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Printability of both inks tested.
- First trial for gradation of properties using comercial inks

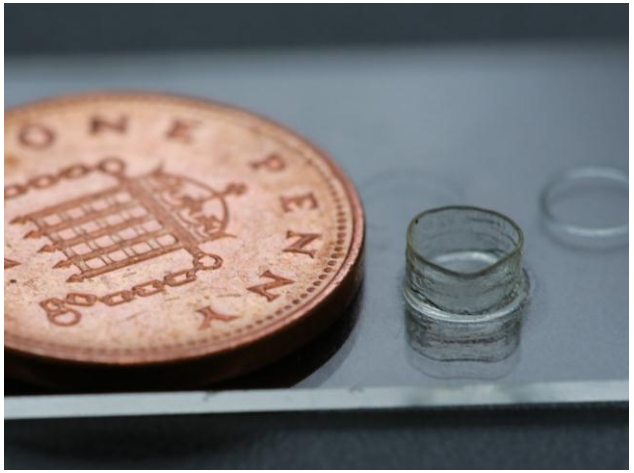
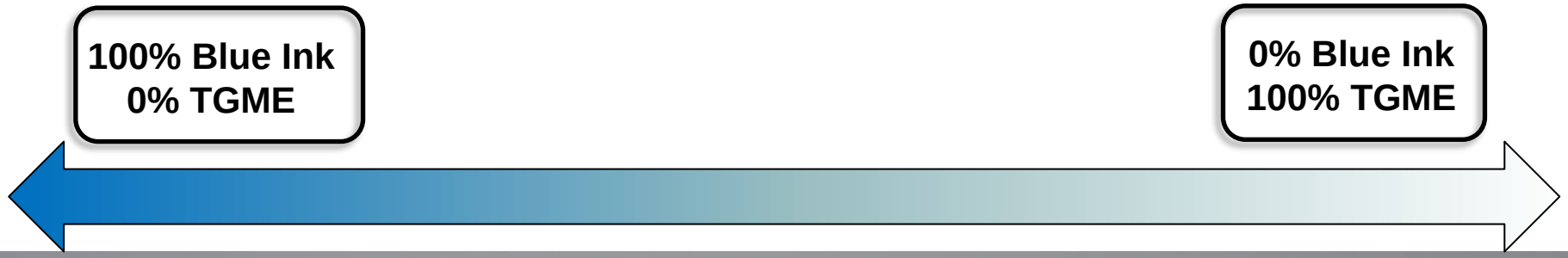


Image 1: Aprox. 120 µm wall thicknes cylinder printed with the rigid monomer

Image 2: Gradation of color using comercial inks



3D printable biodegradable materials

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- 3D printing technologies allows a precise shape and morphology for personalised structures.
- In order to completely optimize the material to the application, new families of safe biomaterials for personalized medicine need to be developed

Synthetic Biodegradable and Photocurable polymer-based Materials

LBSA Laboratory of Biophysics and Surface Analysis

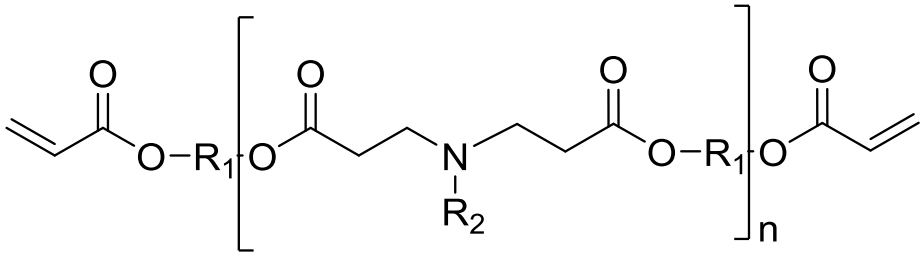
EPSRC Engineering and Physical Sciences Research Council

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

3D printable biodegradable materials

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Synthesis of macromonomers
  - D.. G. Anderson, C. A. Tweedie, N. Hossain, S. M. Navarro, D. M. Brey, K. J. Van Vliet, R. Langer, J. A. Burdick, *Adv. Mater.* **2006**, *18*, 2614–2618.



- Biodegradable (24h- > 3 months)
- Very high viscosity

- Solution: Ink formulation by mixing the macromers with photocurable degradable monomers of low viscosity.
- A combinatorial approach is going to be used for screening

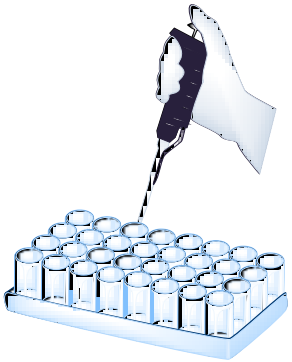
LBSA Laboratory of Biophysics and Surface Analysis

EPSRC Engineering and Physical Sciences Research Council

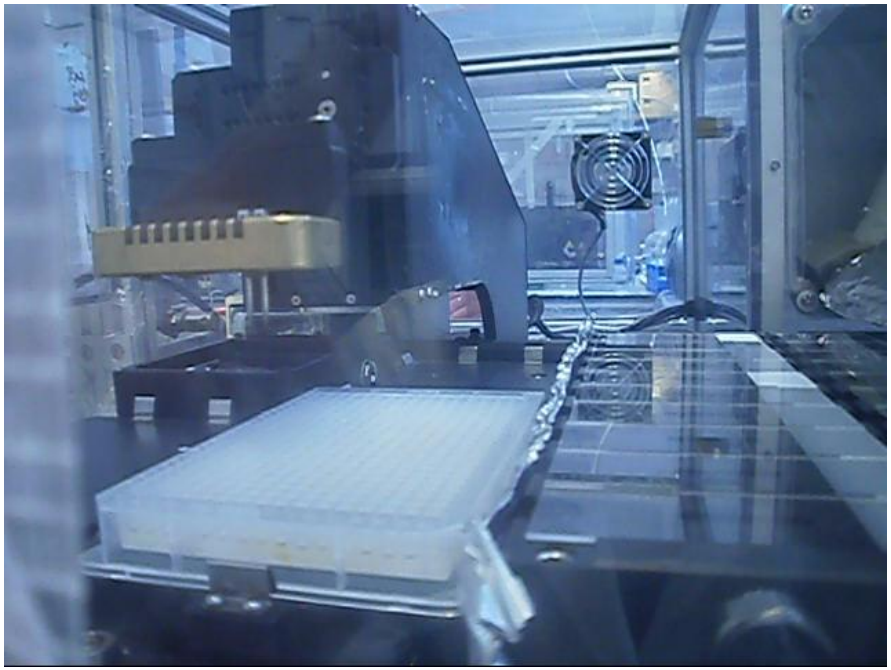
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

3D printable biodegradable materials

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing



Preparation of mixtures on a plate



2D printing of spots

Microarrays

Laboratory of Biophysics and Surface Analysis

EPSRC Engineering and Physical Sciences Research Council

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

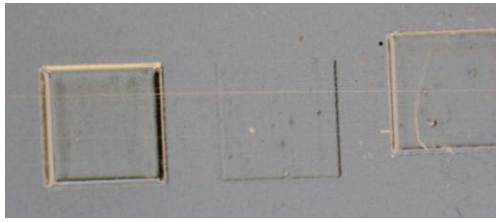
3D printable biodegradable materials

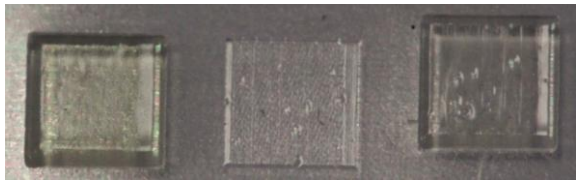
EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

High-throughput experiments

- AFM-QNM: Mechanical properties
- Cell toxicity experiments
- Cell attachment experiments

Printable Biomaterials





LBSA Laboratory of Biophysics and Surface Analysis

EPSRC Engineering and Physical Sciences Research Council

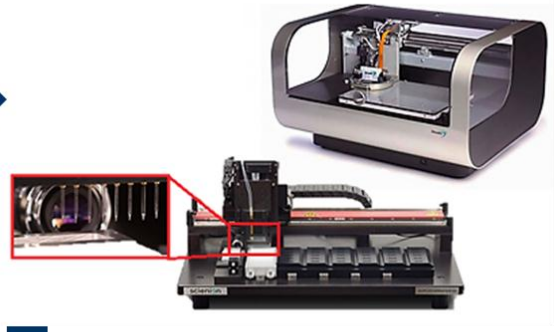
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Polymer particle formation using inkjet printing

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Design of new materials is hindered by the lack of knowledge on the physiochemical parameters controlling the range of cellular responses required of modern devices

Library of different materials



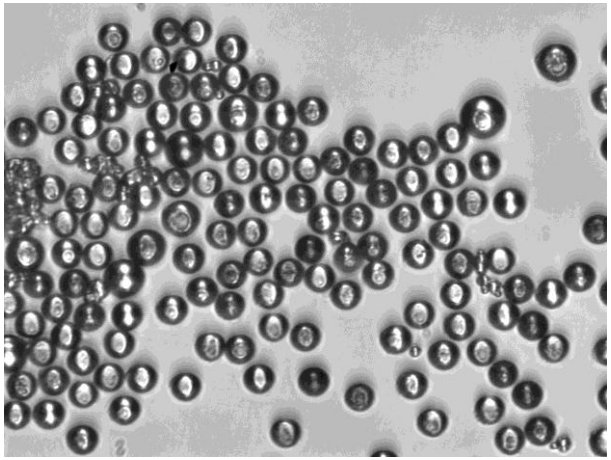
3D printing

Core-shell particles

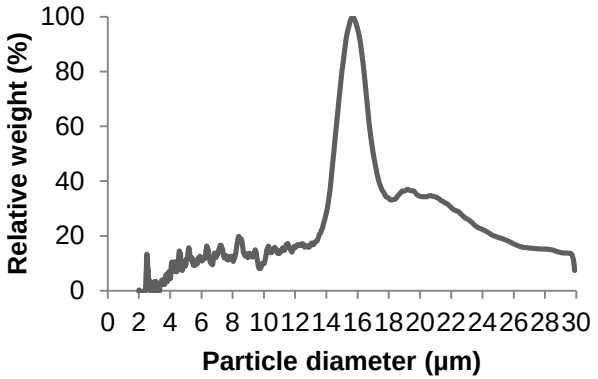
Biomedical applications

Polymer particle formation using inkjet printing

- Polymer particle formation using 3D printer Dimatix

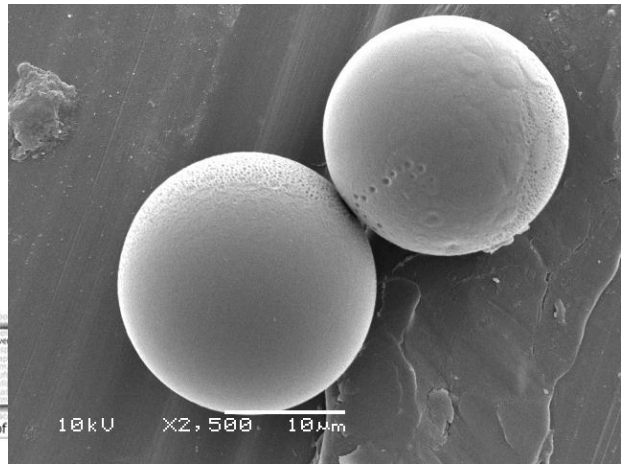


Particle sizing

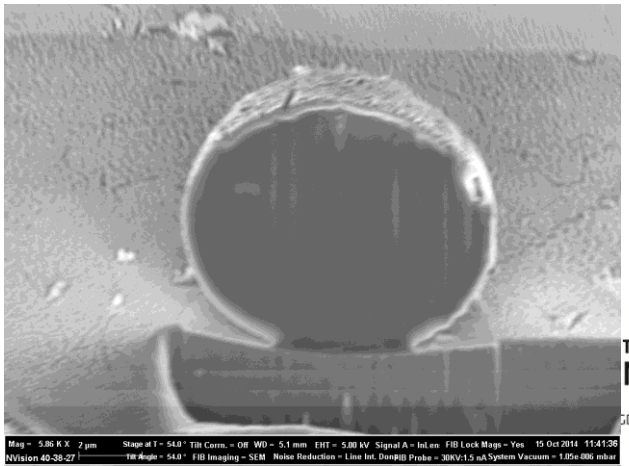


Average diameter: 17.37 µm
Coefficient of variance: 33.24%
Polydispersity index: 2.45

SEM



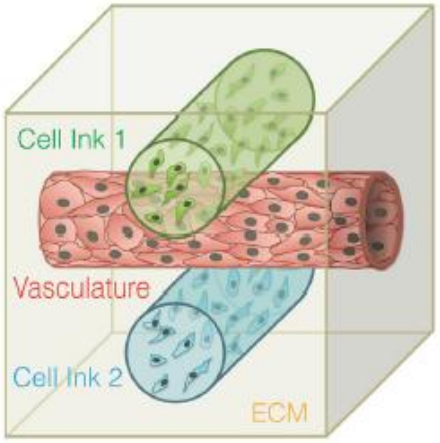
FIB

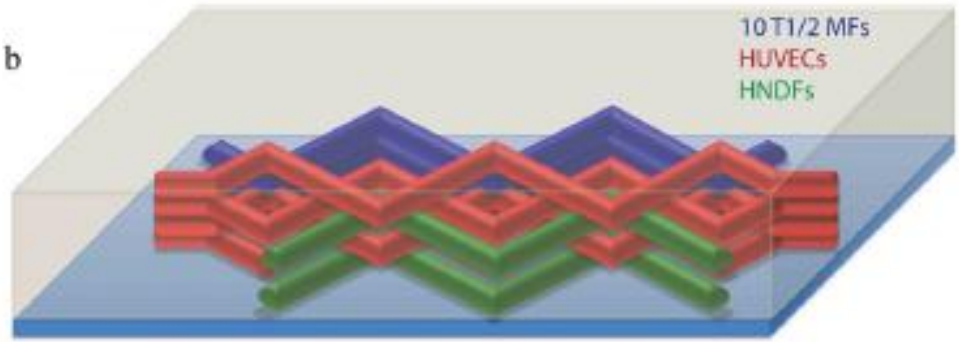


3D printing of human tissues

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Aim of the project: Build a tissue constructs by directed cell deposition
- Vasculature, cells, and extra-cellular matrix (ECM) are co-printed to yield engineered tissue constructs composed of heterogeneous subunits
- The vascular tissue is later dissolved or evacuated to let nutritious perfused through the empty fluidic channels.



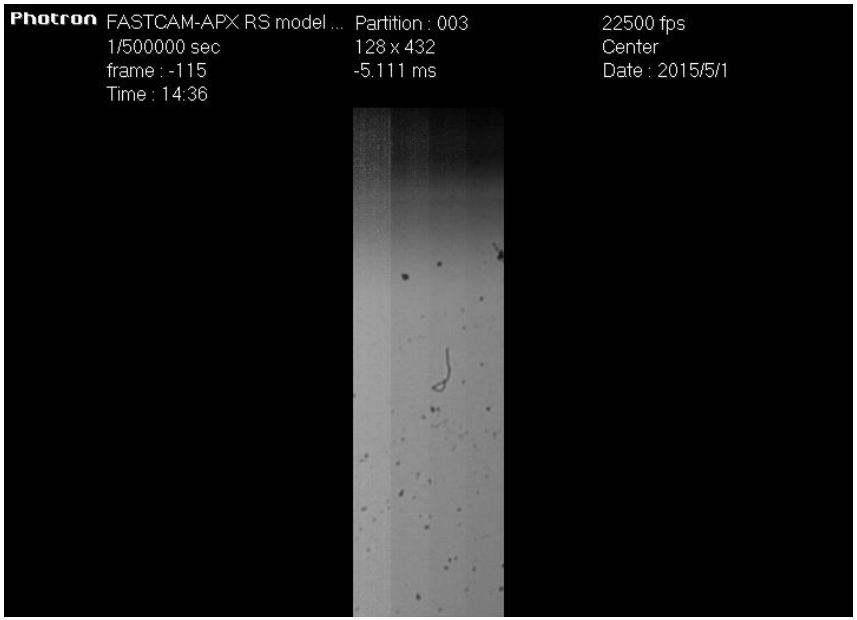


D. B. Kolesky , R. L. Truby , A. S. Gladman , T. A. Busbee , K. A. Homan , J. A. Lewis , Adv. Mater. 2014 , 26 , 3124 .

3D printing of human tissues

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- Our Group proposal: 3D printing of gelatin derivatives as structural and vascular tissues, using high viscosity jetting valve system (PicoDot Nordson)



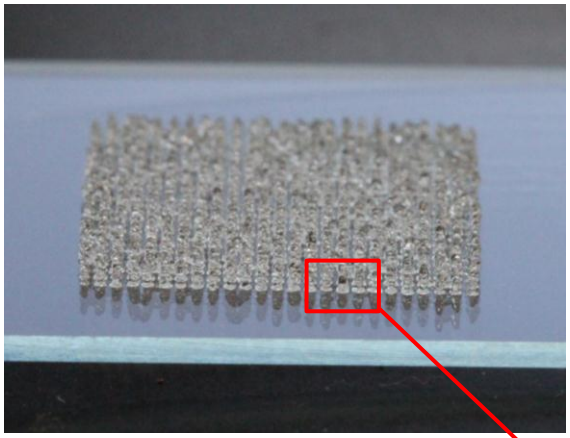
EPSRC Engineering and Physical Sciences Research Council

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

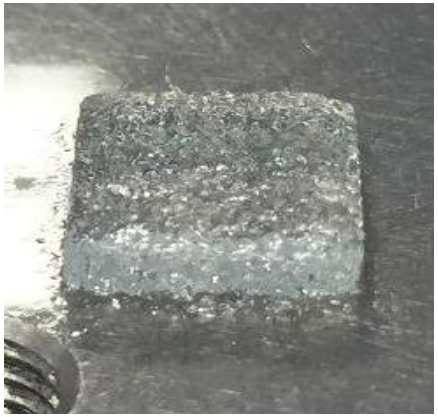
3D printing of human tissues

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

Gelatine pillars, 10 layers, 15x15 mm^2



Gelatine cube, 10 layers



EPSRC Engineering and Physical Sciences Research Council

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

3D printed smart limbs

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- 3D-printed pressure sensitive finger
  - UV curable polymeric ink forms the finger structure.
  - 3 silver tracks were inkjet printed to power up a pressure sensor in the finger tip and also collect pressure data.

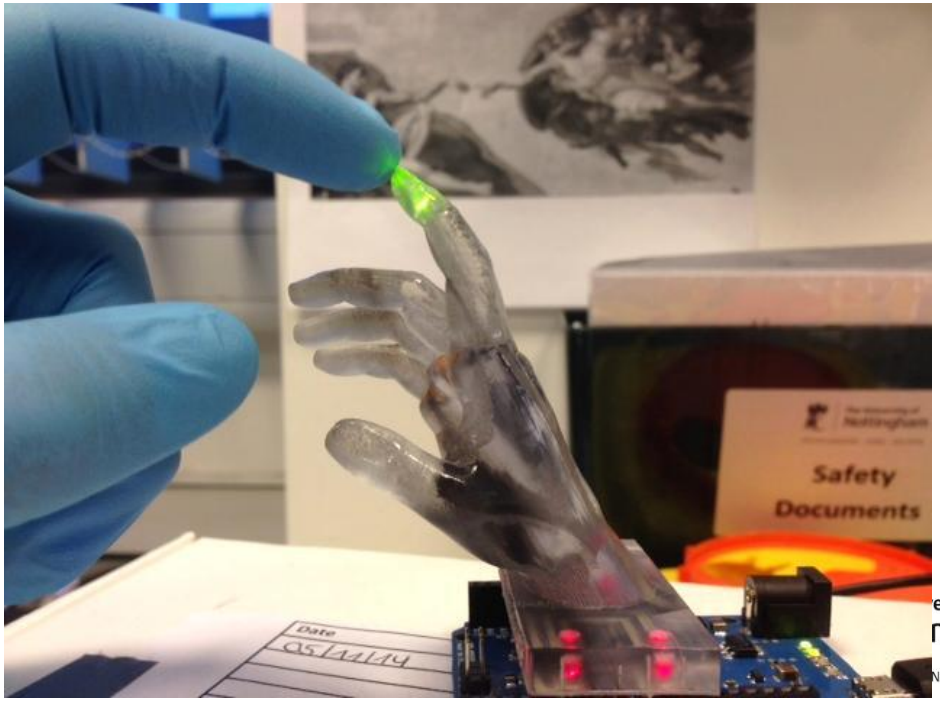
Pressure sensor was inserted and a rubbery cap was printed to seal the pressure around the sensor

3D printed smart limbs

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

- All 3D-printed capacitive touch sensitive hand.
  - UV curable polymeric ink forms the hand structure.
  - Touch sensitive silver tracks were printed within the hand structure connecting a data line to a microprocessor at the bottom of the hand.

Silver ink printed inside the Objet VeroClear structure. The conductive track acts as a capacitive touch sensor to activate embedded LEDs.



ersity of
ngham
NA · MALAYSIA

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

Thank you very much

Belen Begines

belen.begines@nottingham.ac.uk

The University of Nottingham

UNITED KINGDOM · CHINA · MALAYSIA