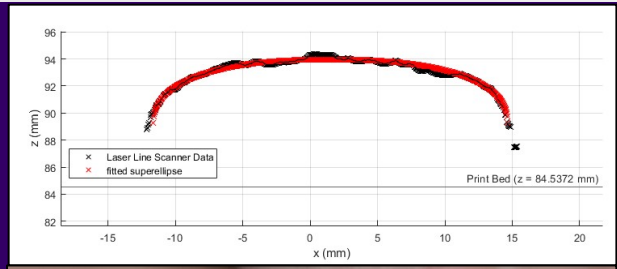
3DMC 3D METROLOGY CONFERENCE



An In-line Measurement Strategy for Quality Monitoring in 3D Concrete Printing

3DMC – 3D Metrology Conference 2023 in Bilbao, Spain

Connor Gill
Laura Justham, Niels Lohse, Adam Haynes, Jie Xu, Jim Dobrzanski, Richard Buswell, Peter Kinnell

Loughborough University

mtc Manufacturing Technology Centre

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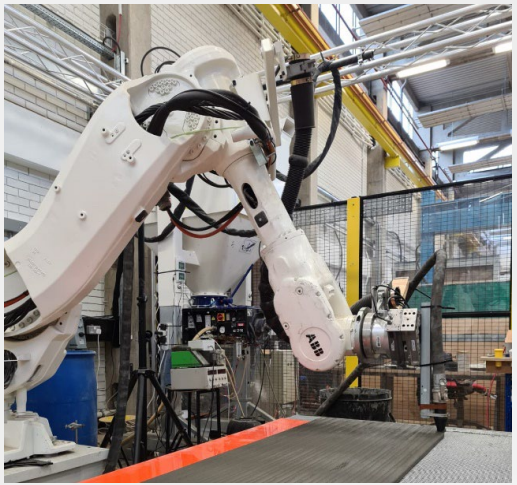
Who Am I?

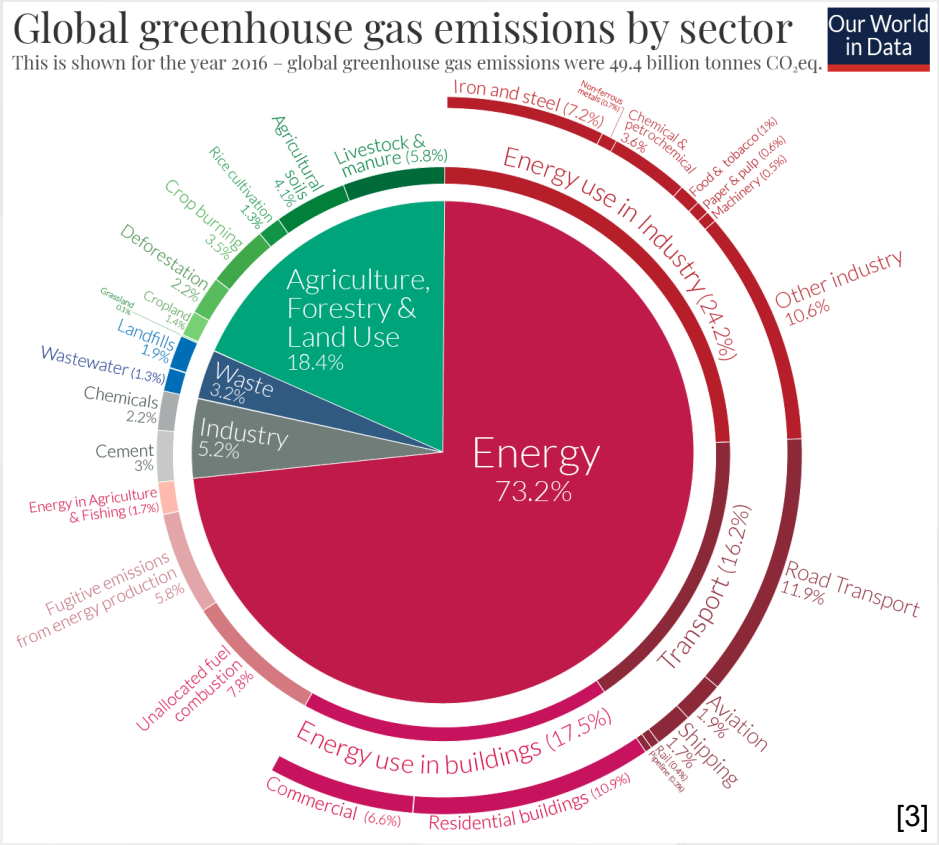
- Connor Gill, PhD student at Loughborough University
- Email: M.C.Gill@lboro.ac.uk



Why 3D Concrete Printing?

- Cement productions accounts for around 8% of global CO2 emissions [1]
- Concrete is the second most used material in the world (behind water) [2]

[4]



[3]

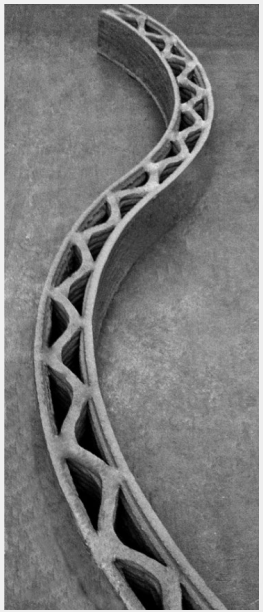
[1] Lehne J, Preston F. Making concrete change. Innovation in Low-carbon Cement and Concrete. 2018.
[2] Hendrik Van Oss G. Mineral Commodity Summaries. Prepared for the US Geological Survey. 2007.
[3] Hannah Ritchie, Max Roser and Pablo Rosado (2020) - "CO_2 and Greenhouse Gas Emissions". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/co2-and-greenhouse-gas-emissions' [Online Resource].
[4] https://www.archdaily.com/979145/3d-printing-with-low-carbon-concrete-reducing-co2-emissions-and-material-waste

Why 3D Concrete Printing?

[1]

[1] https://www.construx.eu/en/precast-moulds/stair-moulds/

What is 3D Concrete Printing?

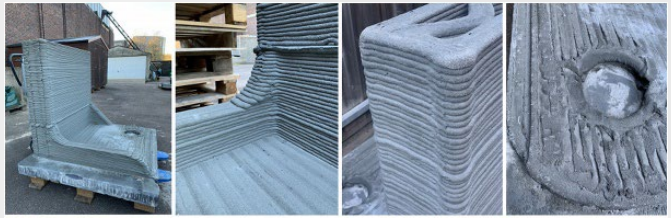


[1]

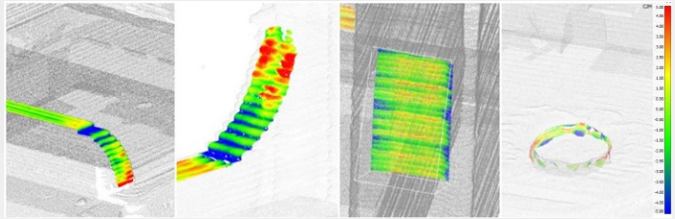
Striatus Bridge, Venice, 2021 [2]

[1] Everett, H. *Vertico opens Eindhoven 3D concrete printing facility - 3D Printing Industry*. [Accessed on September 17 2020] https://3dprintingindustry.com/news/vertico-opens-eindhoven-3d-concrete-printing-facility-175892/
[2] Bhooshan, S., Bhooshan, V., Dell'Endice, A. et al. The Striatus bridge. Archit. Struct. Constr. 2, 521–543 (2022). https://doi.org/10.1007/s44150-022-00051-y

What We Do



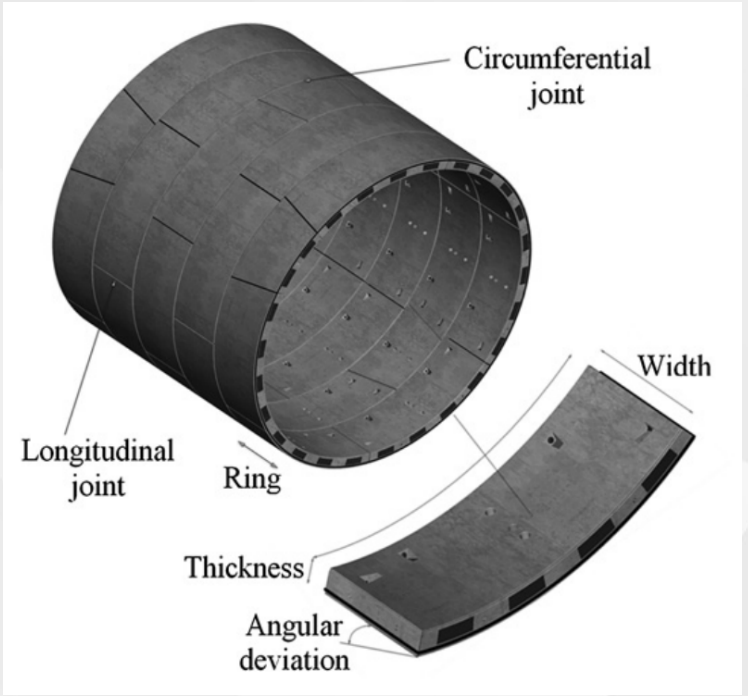
[1]



[1] Buswell R, Xu J, De Becker D, Dobrzanski J, Provis J, Kolawole JT, Kinnell P. Geometric quality assurance for 3D concrete printing and hybrid construction manufacturing using a standardised test part for benchmarking capability. Cement and Concrete Research. 2022 Jun 1;156:106773.

Accuracy in Concrete

- +/- 5 mm typical window opening a few meters in size[1]
- +/- 0.3 to 1.6 mm on 2 m wide tunnel segments[2]
- +/- 2 to 6.4 mm on segments 300 - 500 mm thick[2]



[2]

[1] Milberg C T, Tommelein I D, 2020 Methods for managing tolerance compatibility: Windows in cast-in-place concrete J. Constr. Eng. Manag, 146(2), 04019105
[2] Cavalaro, S. H. P., et. al. (2012). New design method for the production tolerances of concrete tunnel segments. J. Perform. Constr. Facil., 26(6), 824-834

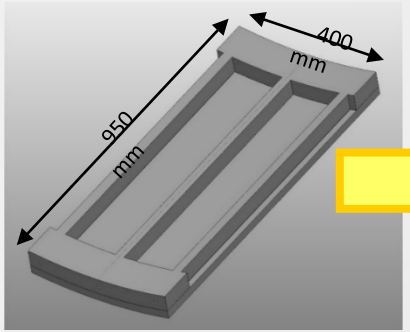
Accuracy in Concrete

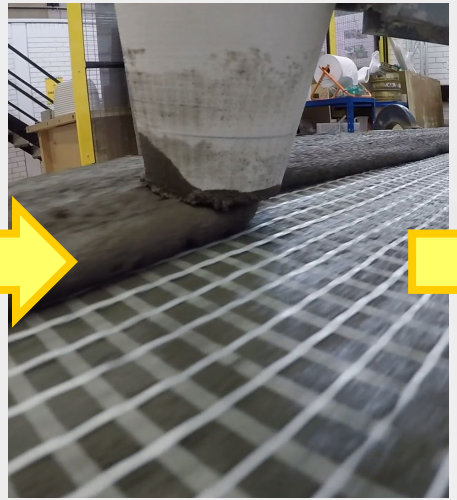
[1]

[2]

[1] Grasser G, Pammer L, Koell H, Werner E, Bos FP. Complex architecture in printed concrete: the case of the Innsbruck University 350 th Anniversary Pavilion COHESION. InSecond RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 2 2020 (pp. 1116-1127). Springer International Publishing.
[2] https://www.incremental3d.eu/projects.html

3D Concrete Printing Process





"Hybrid" process

CAD

Print

Post-Process

Final Part

Common Failure Modes

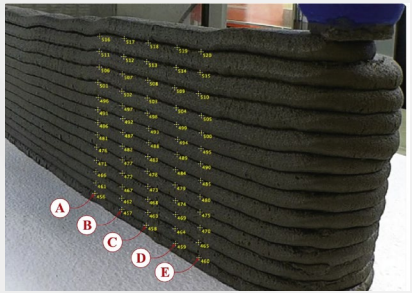
Voiding (underfilling)

[1]

Tearing

[2]

Layer Inconsistency



[1]

And more…

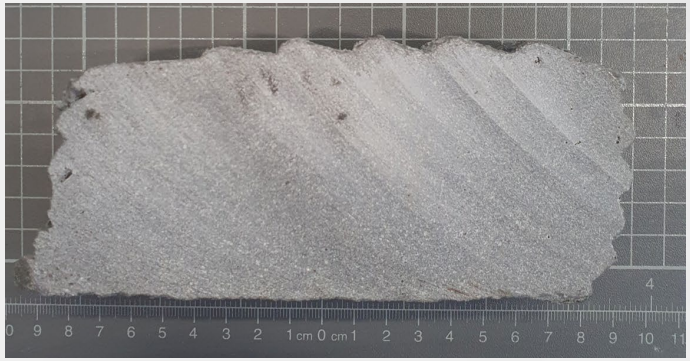
[3]

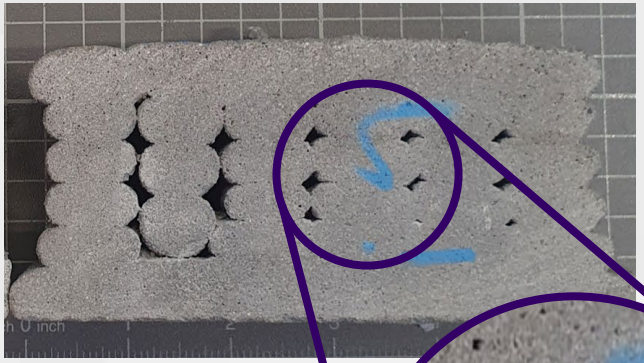
[1]

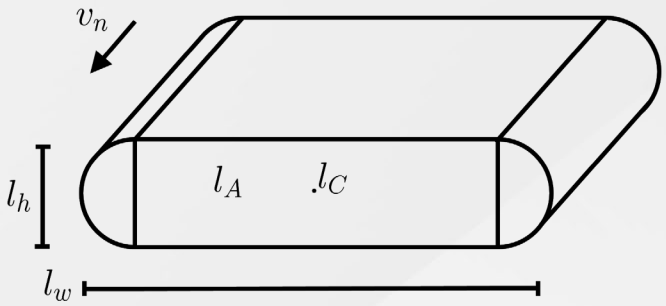
[4]

[1] Buswell RA, De Silva WL, Jones SZ, Dirrenberger J. 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research. 2018 Oct 1;112:37-49
[2] Senthilnathan S, Raphael B. Using Computer Vision for Monitoring the Quality of 3D-Printed Concrete Structures. Sustainability. 2022 Nov 25;14(23):15682.
[3] De Schutter G, Lesage K, Mechtcherine V, Nerella VN, Habert G, Agusti-Juan I. Vision of 3D printing with concrete—Technical, economic and environmental potentials. Cement and Concrete Research. 2018 Oct 1;112:25-36.
[4] Suiker AS, Wolfs RJ, Lucas SM, Salet TA. Elastic buckling and plastic collapse during 3D concrete printing. Cement and Concrete Research. 2020 Sep 1;135:106016.

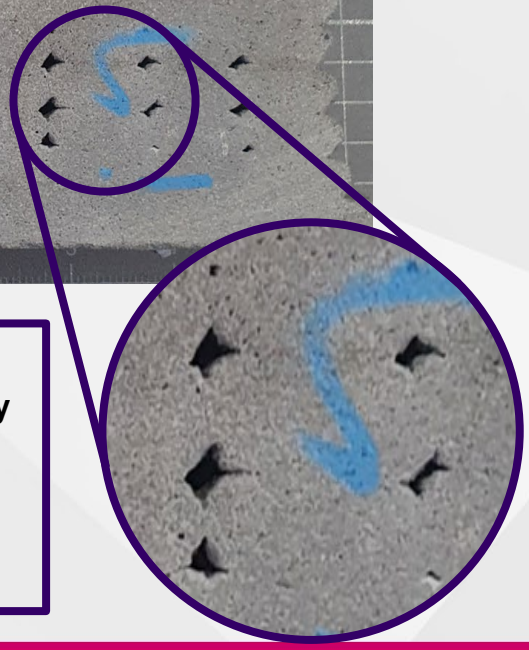
Problem & Approach





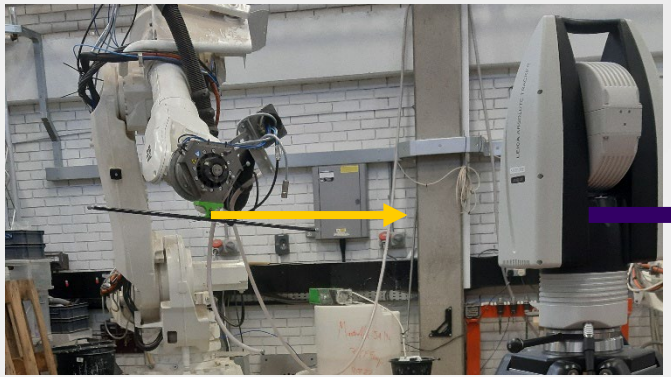


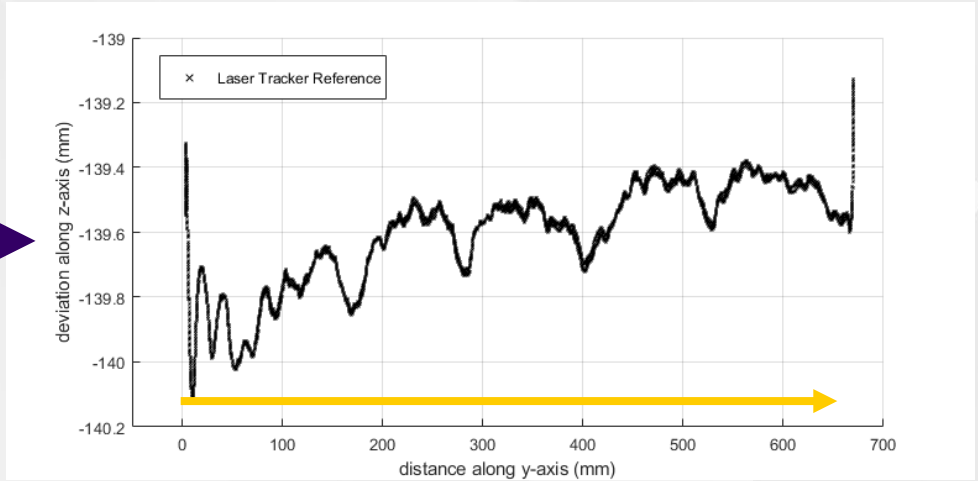
- Parameters of interest:
  - **Nozzle Position/Velocity**
  - **Bead Shape**
    - Height,
    - Width,
    - Centroid,
    - Geometry, etc



Nozzle Velocity

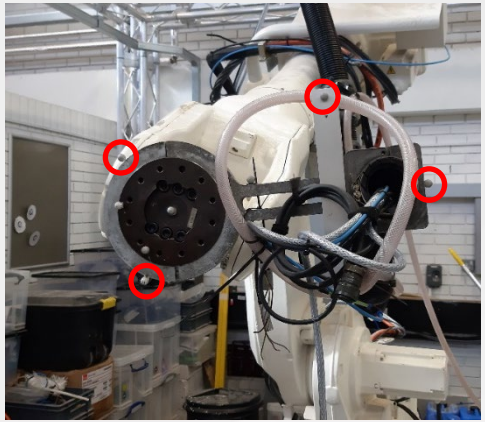
- Reported robot positional data is not accurate enough for this work
  - Previous results identified an error of approx. 5 mm overshoot over a 1 m length
- AT960 Laser Tracker identified a dynamic position error in the robot of approximately 0.5 mm

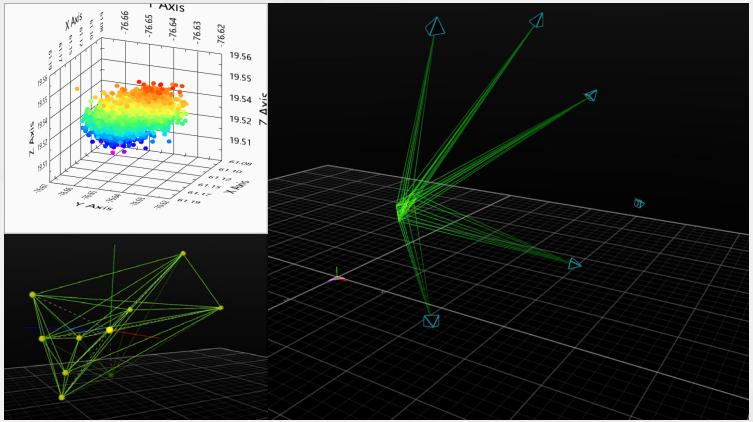


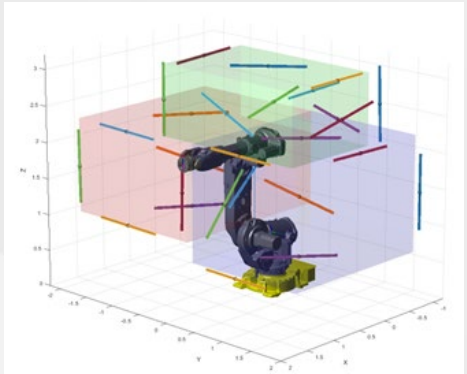


Nozzle Velocity

- External measurement system (Optical Motion Capture) used to measure nozzle position
  - 8x Prime x13 1.3MP resolution cameras
  - Residual calibration error of 500 mm artefact is given as 0.2-0.4 mm





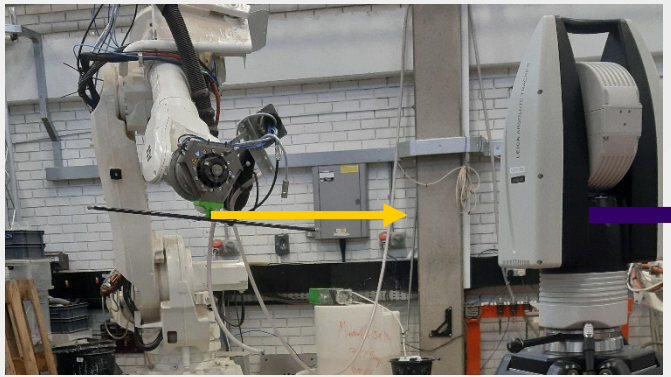


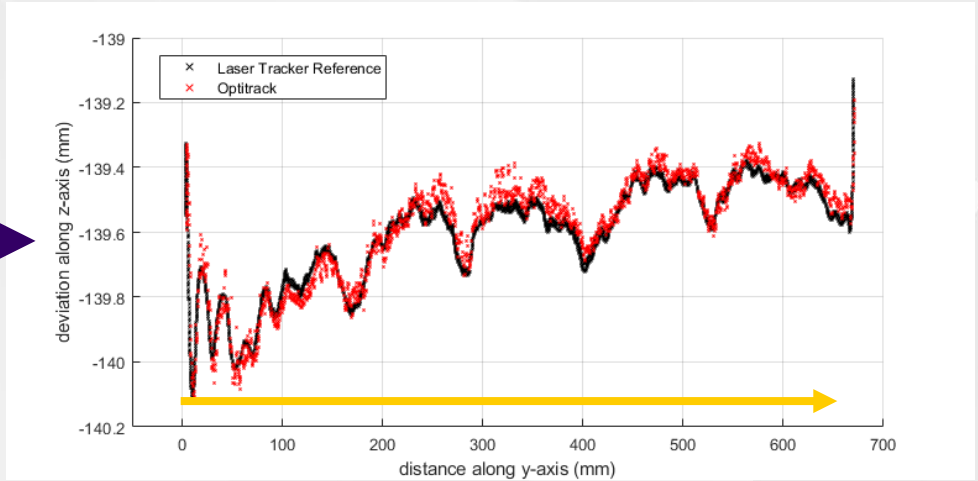
VDE 2634 verification

Average error: 1 mm/m across 2x2x2 m

Nozzle Velocity

- Optitrack measurements of nozzle position closely match a high accuracy reference (AT 960 Laser Tracker), to within approximately 0.1 mm

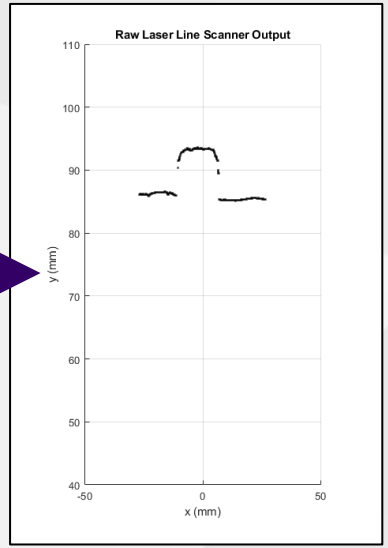




Bead Shape

2900-50 Micro-Epsilon Laser Line Scanner:

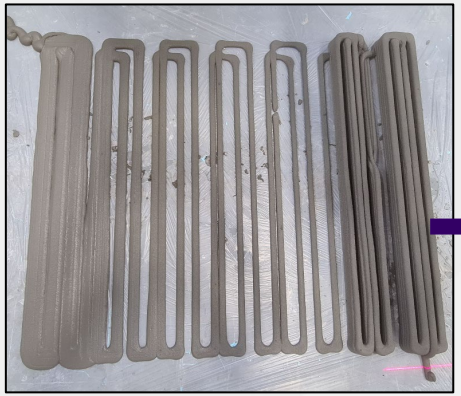
- IP65 Rated
- Small form factor
- Up to 300Hz measurement frequency
- MSE for measurement of a ground aluminium plate is ~0.05 mm
- 4 micron lateral resolution

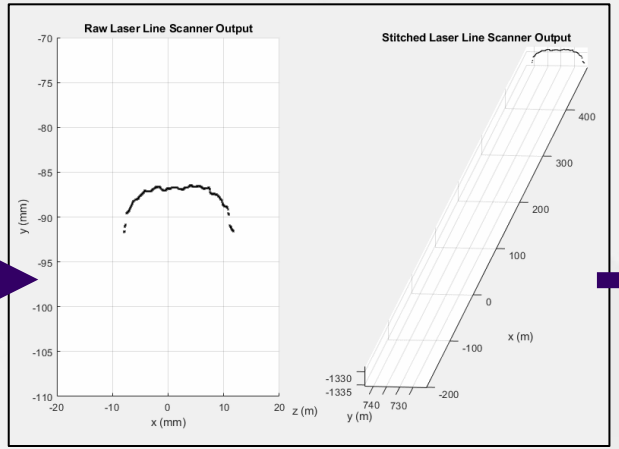


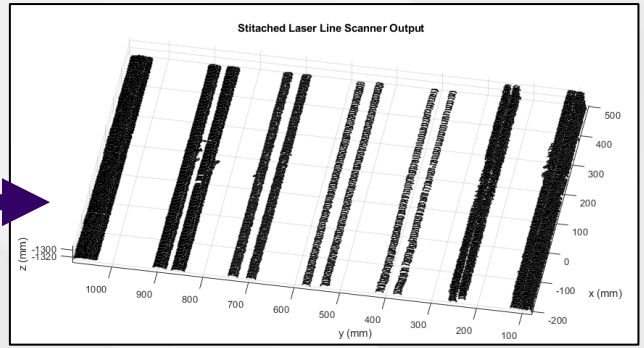
- **Parameters:**
  - Height,
  - Width,
  - Centroid,
  - Geometry, etc

The Test Sample

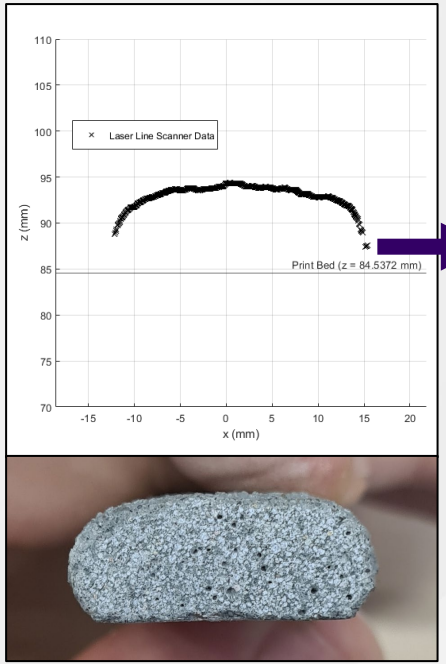
- 10x 800 mm single-bead segments were printed at speeds 40 mm/s, 80 mm/s, 120 mm/s, 160 mm/s, and 200 mm/s to test a range of over-printing and under-printing scenarios
- 2x 800 mm double-bead segments were printed at 100 mm/s, and 140 mm/s.

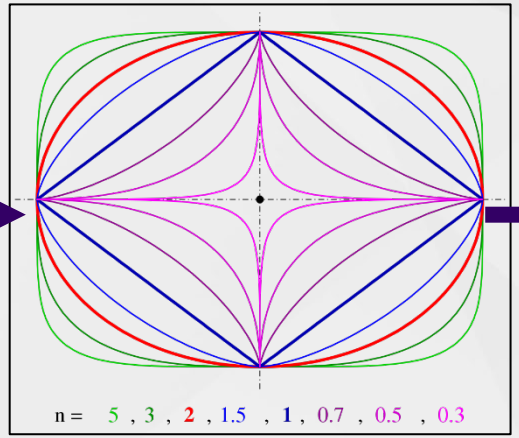






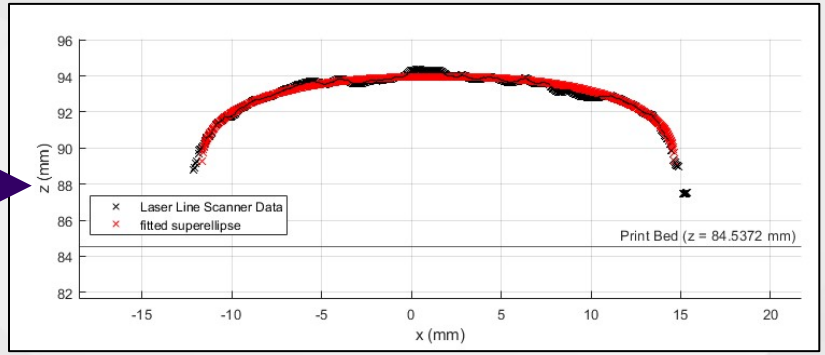
Bead Shape Filtering





[1]

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1$$



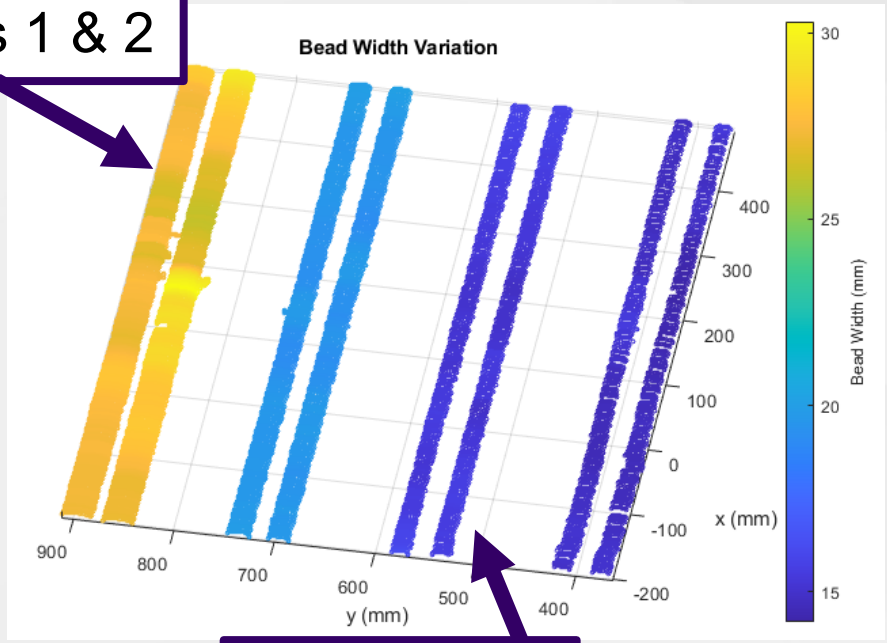
Optimisation parameters:

- x = **Centroid x**
- a = **Width**
- b = **Height**
- n = **Shape Parameter**

[1] https://en.wikipedia.org/wiki/Superellipse

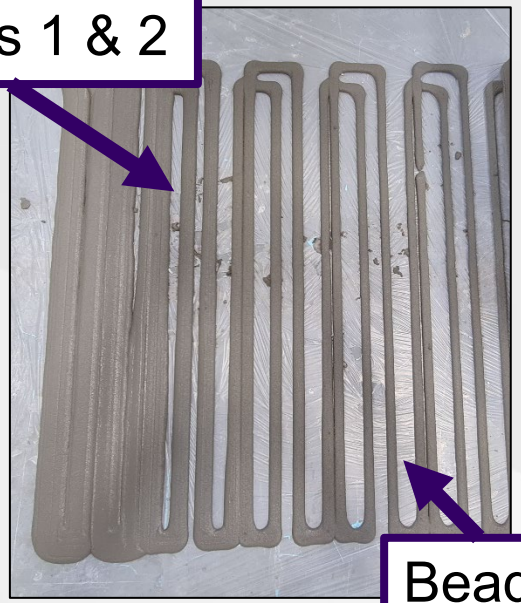
Monitoring Bead Width

Beads 1 & 2



Beads 5 & 6

Beads 1 & 2

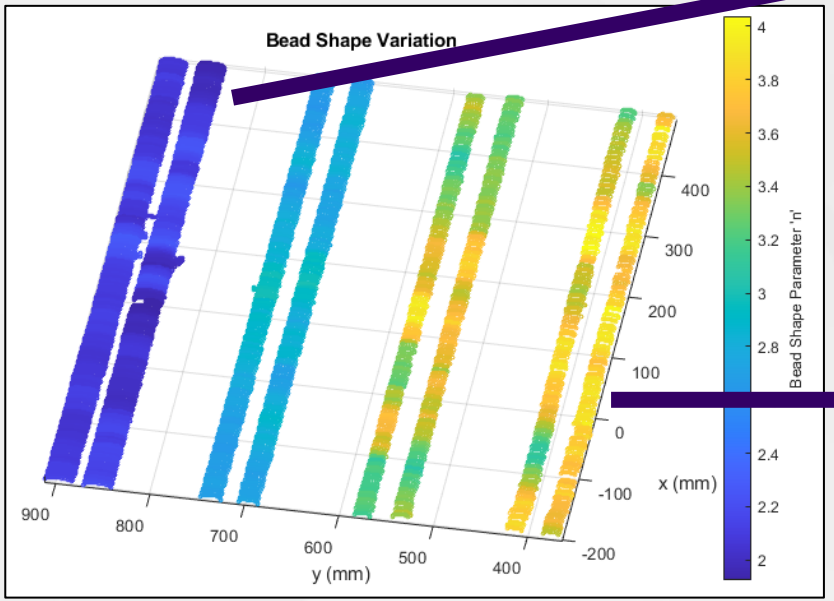


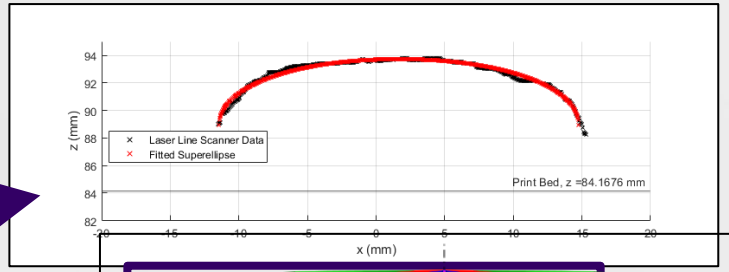
Beads 5 & 6

Optimisation parameters:

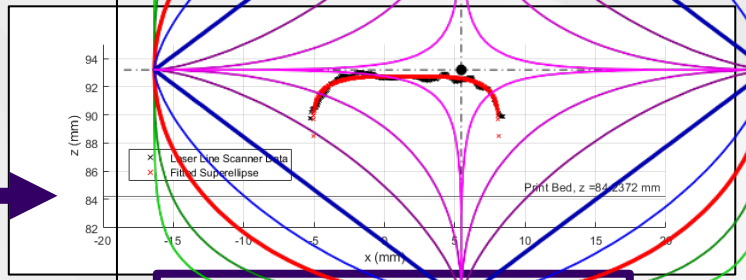
- x = Centroid x
- $\boldsymbol{a}$ = **Width**
- b = Height
- n = Shape Parameter

Monitoring Bead Shape





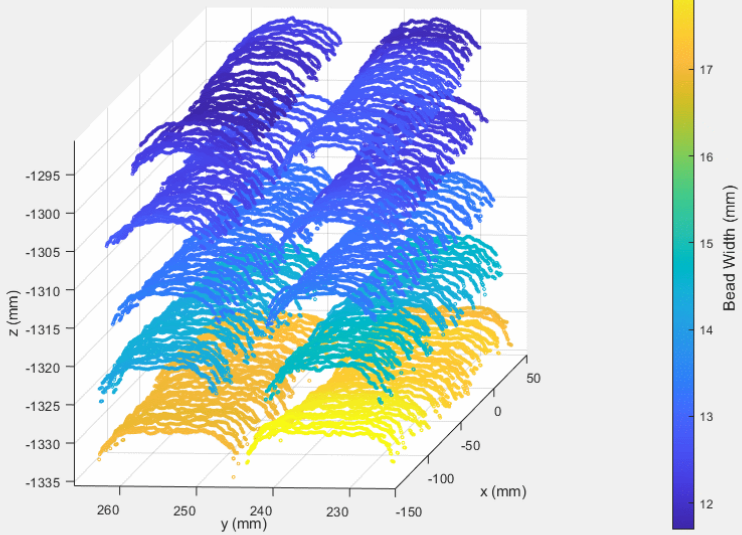
Width = 26.2 mm
Height = 9.56 mm
'n' = 2.10 mm
Cross-sectional Area = 200.20 mm^2

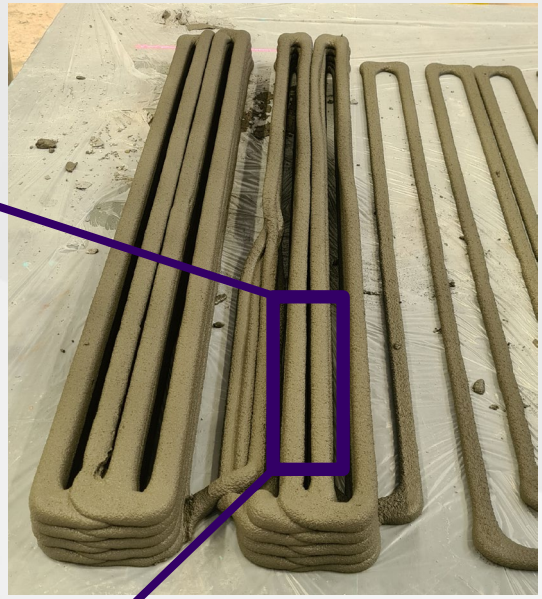


Width = 13.15 mm
Height = 8.50 mm
'n' = 3.92 mm
Cross-sectional Area = 103.35 mm^2

n = 5 , 3 , 2 , 1.5 , 1 , 0.7 , 0.5 , 0.3

Internal Bead Monitoring

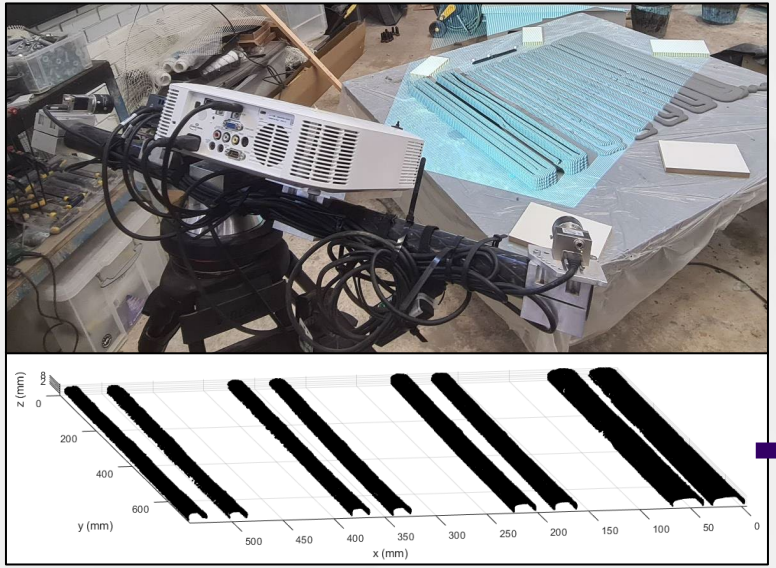


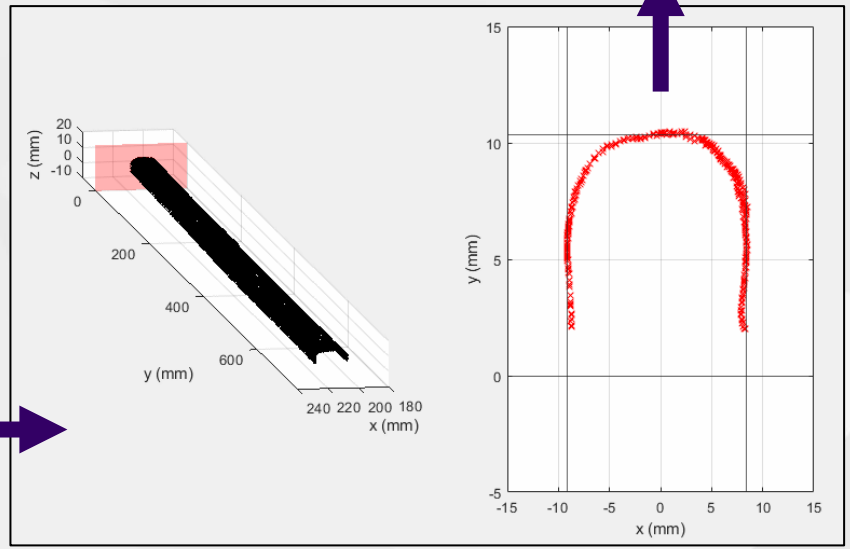


Optimisation parameters:

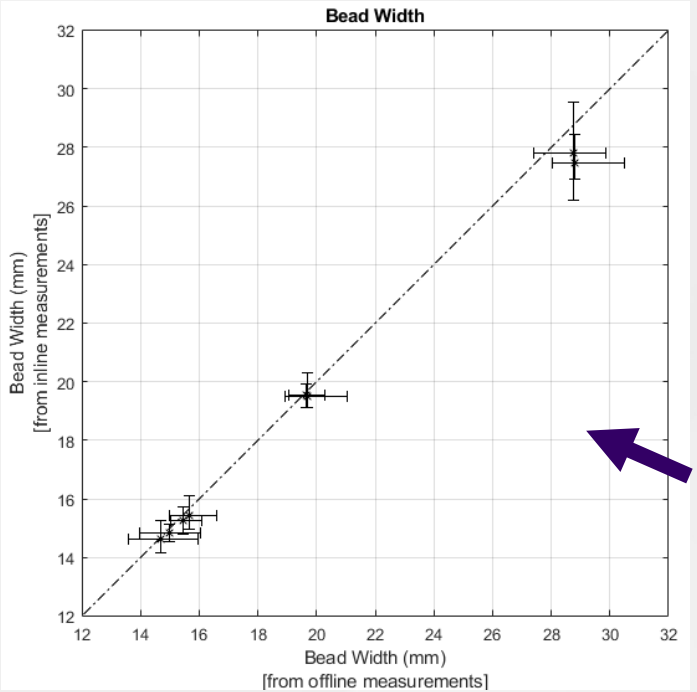
- x = Centroid x
- a = Width
- b = Height
- n = Shape Parameter

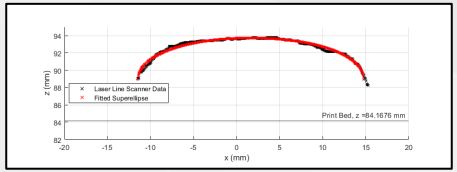
Bead Shape Measurements

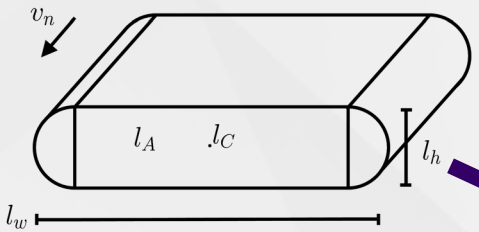


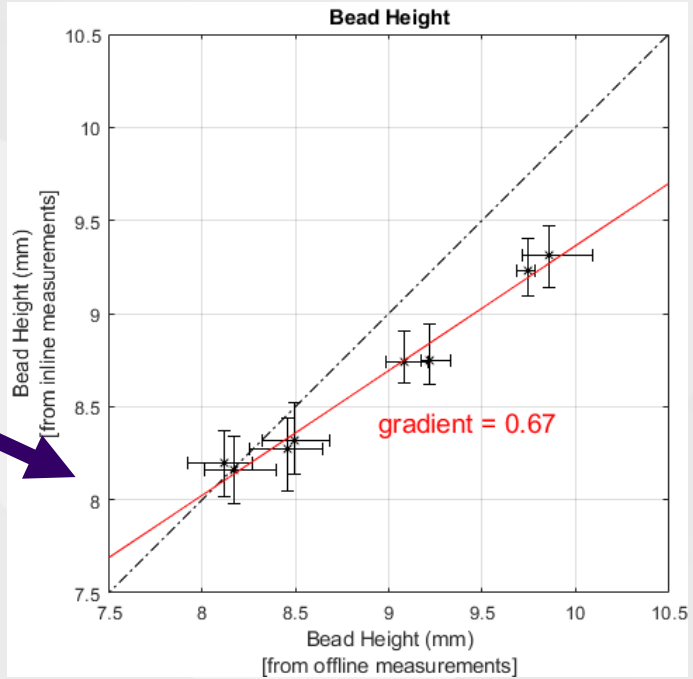


Comparison between Inline and Online Results







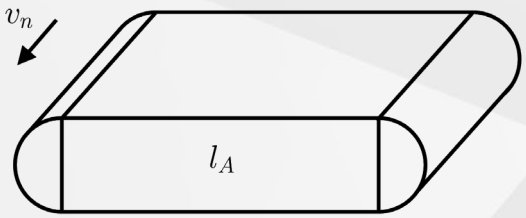


Mass Flow Rate

- Good inline measurement helps to describe overprinting and underprinting conditions
- Can be measured using a variety of techniques:

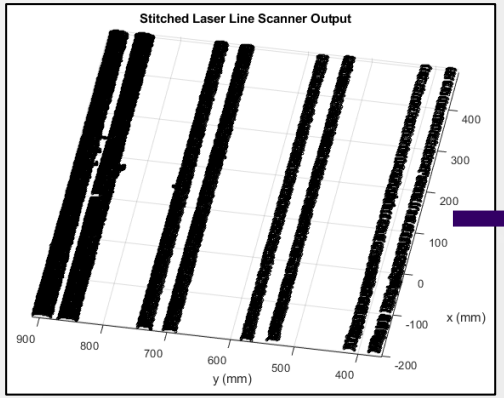
Electromagnetic flow meter
SITRANS FM MAG 1100
- Accuracy: 0.2% ±1 mm/s

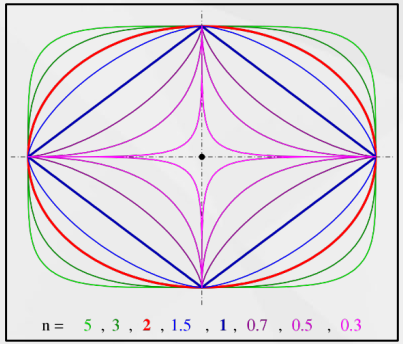
Calculated from pump parameters
$\dot{m} = Q * \omega - losses$
- Accuracy: dependant on flow conditions & material

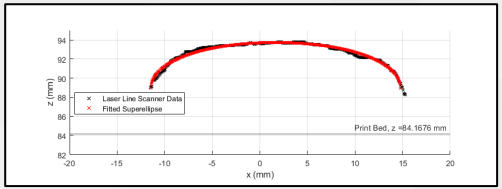


Calculated from printing parameters
$\dot{m} = l_A * v_n$
Accuracy: ???

Mass Flow Rate Measurements – Inline





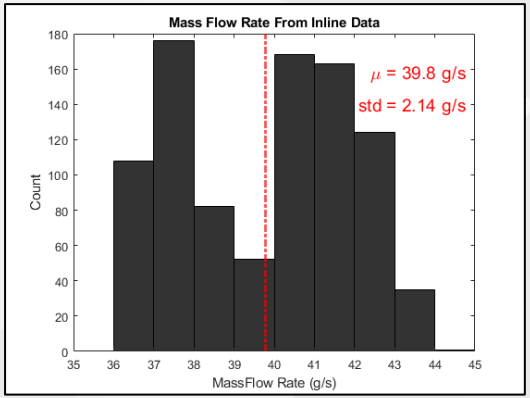


$$\text{Area} = 4ab\frac{\left(\Gamma\left(1+\frac{1}{n}\right)\right)^2}{\Gamma\left(1+\frac{2}{n}\right)}$$

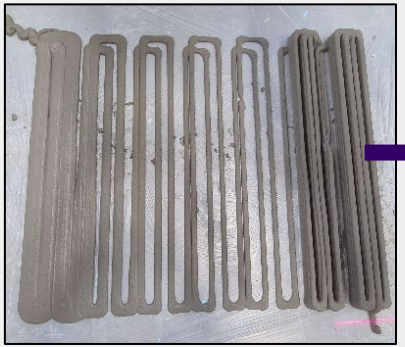
[Concrete Density = 0.002297g/mm^3]

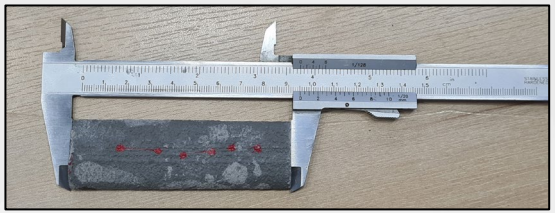
Mass Flow Rate

$$(= Nozzle\ speed\ (mm/s^{-1}) * Area\ (mm^2) * Density\ (\frac{g}{mm^2}))$$



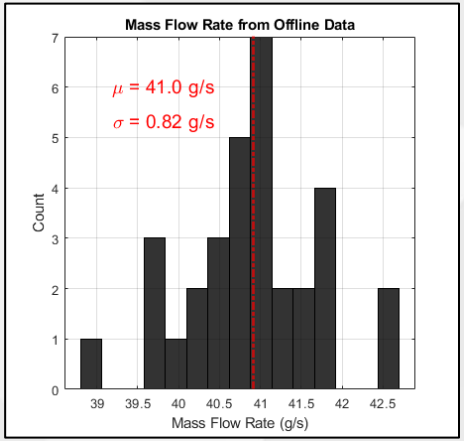
Mass Flow Rate Measurements – Offline





Mass Flow Rate

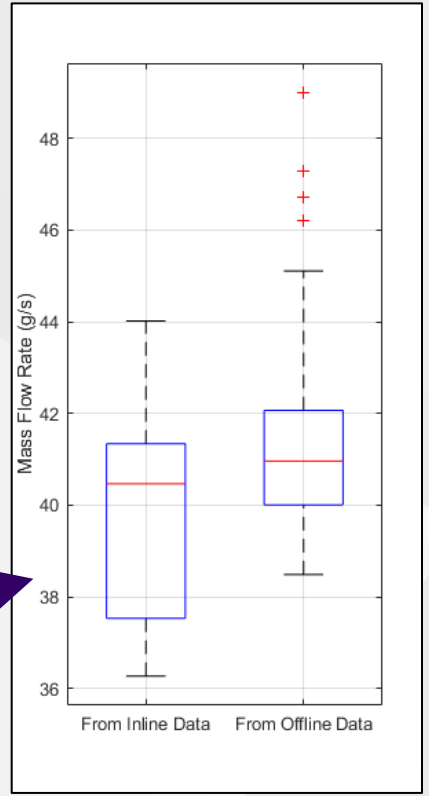
$$(= Nozzle\ speed\ (mm/s)\ *\ \frac{Weight\ (g)}{Length\ (mm)})$$



Mass Flow Rate

- Both techniques have large range of errors either due to measurement error, or correct observation of the parameter varying.
- Error is greatly reduced by averaging

(g/s)	Inline Data	Offline Data
Mean	39.8	41.0
Standard Deviation	2.14	0.82



Conclusion

- 3D Concrete Printing is an exciting area of development in construction, but monitoring of safety-critical features is still a challenge
- By utilising two easily integrated sensors, and elegant processing, we have been able to detect, predict, and monitor a range of key parameters inline
- Future work will be focused on:
  - increasing model fidelity, especially in terms of modelling of the slumping of the material
  - Integration of more sensors.

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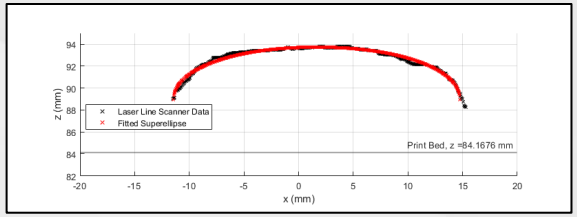
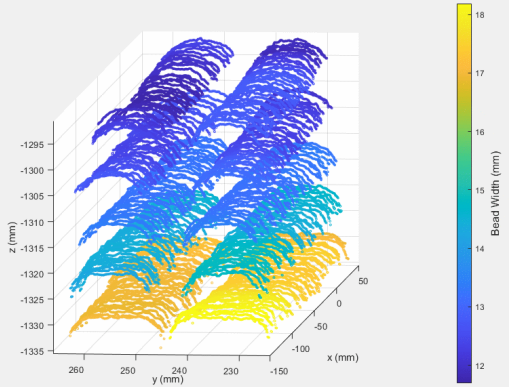
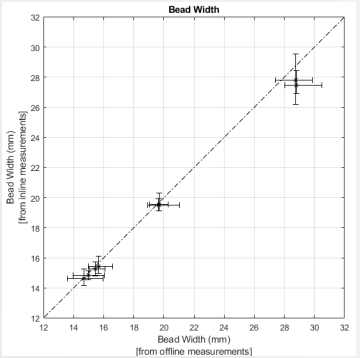
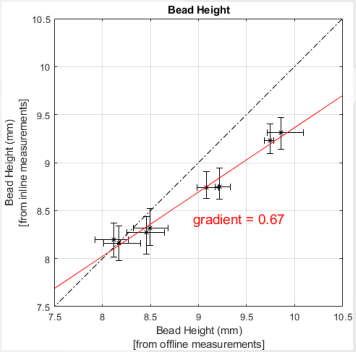




Any Questions?





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