Detection of Race-tracking and Other Defects in Resin Transfer Moulding

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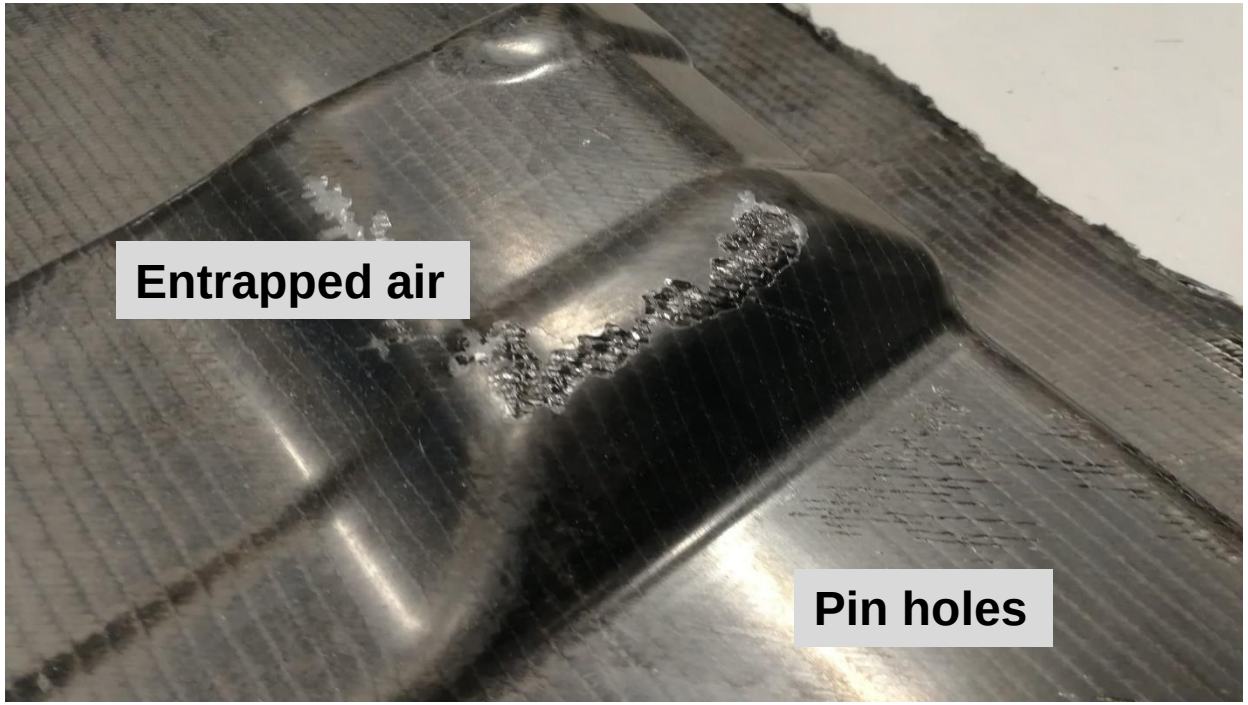
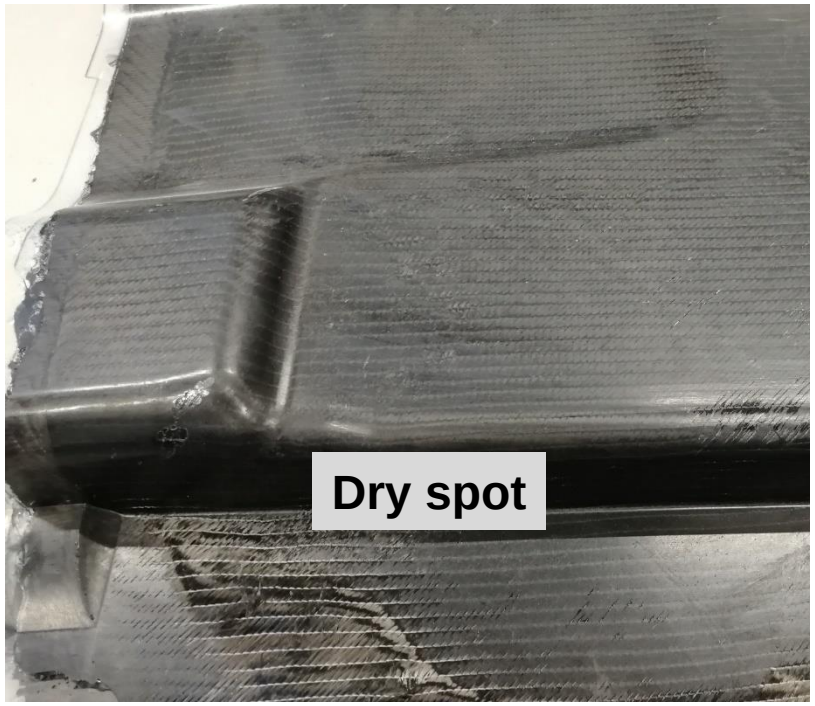
Resin Transfer Moulding





- Numerous types of defects are possible in LCM
- Long-range resin flow implicates higher probability of defect formation because of various local non-uniformities in the preform
- At the same time, longer flow times make process control more feasible

Detection of local non-uniformity and process control

Motivation:

- Detecting local changes in porosity and permeability provides a good starting point for reliable process control

- Detecting local changes in porosity during the process may be used to speed up the post-process inspection

Challenges:

- Multitude of scenarios: combination of various preform variations such as race-tracking and preform non-uniformity (wrinkles etc.)

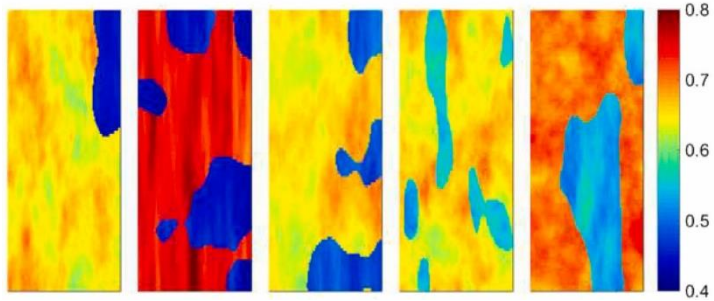
- Development of online physics-based process control

Effect of “mild” race-tracking and a local inclusion in the preform

Regularizing Ensemble Kalman Algorithm (REnKA)

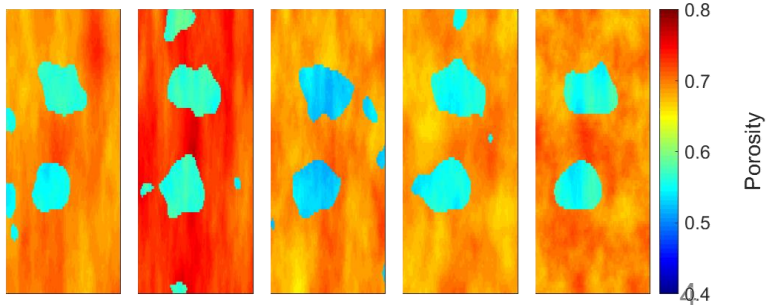
- 3-level parameterisation allows description of **arbitrary** local non-uniformities with only few parameters
- *N* samples in a prior (ca. 400 samples)
- RTM simulation is required for each
- Samples are run in parallel

Initial guess of permeability and porosity distributions



Iterative approximation using experimental data

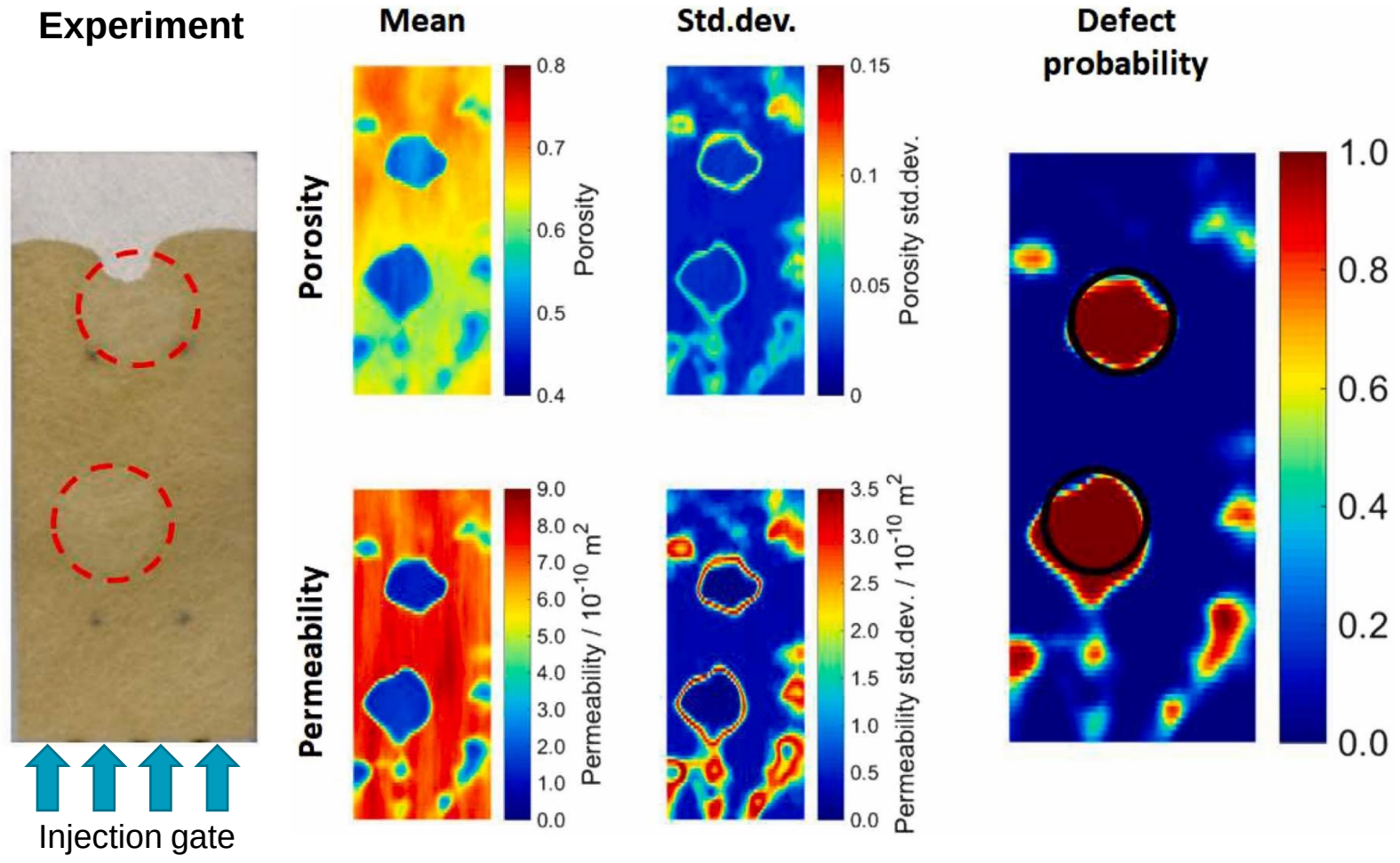
Computed posterior distributions of permeability and porosity



Iglesias et al.. “Bayesian inversion of resin transfer moulding”, Inverse Problems, 34, 2018.
Matveev et al. “Bayesian inversion algorithm for estimating local variations in permeability and porosity of reinforcements using experimental data”, Composites Part A, 143, 2021.

Defect detection – examples

- Experimental data: 6 pressure sensors + 7 linear flow front sensors
- Position and shape of local inclusions recovered correctly using real lab data
- Distribution of permeability and porosity
- Map of probabilities – certainty about detection



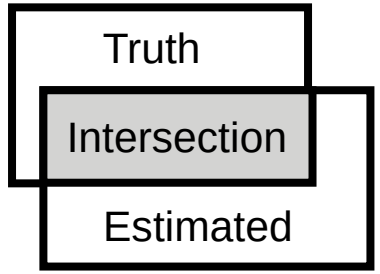
Mould size:
0.12 m × 0.3 m

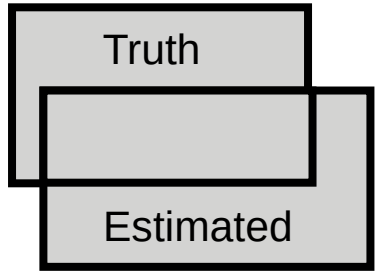
Sensor density

Minimising the number of sensors:

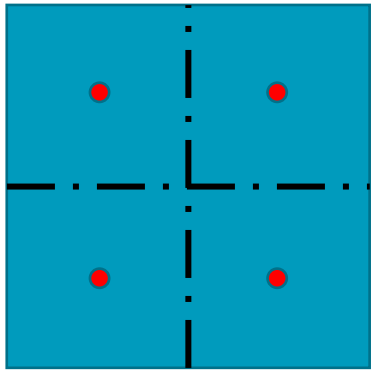
- Uniform sensor density
- Random position of the non-uniformity
- Intersection over Union is used as a metric for “detected” (≥0.5) vs “not detected” (<0.5)

$$IoU = \frac{\text{Area of Overlap}}{\text{Area of Union}}$$

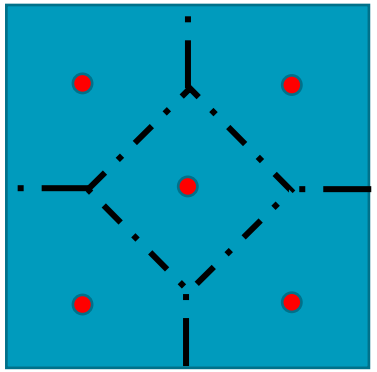




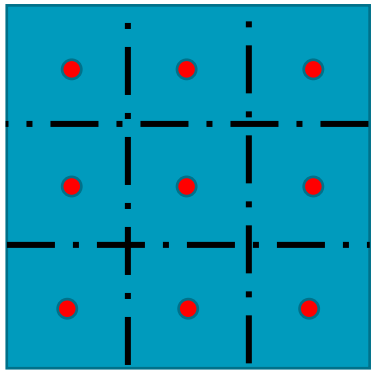
4 sensors



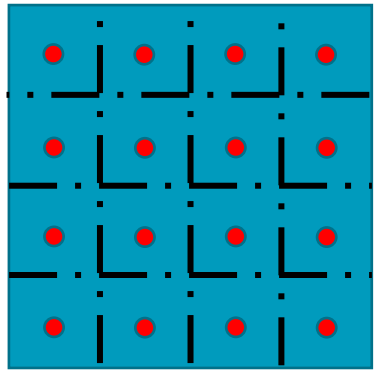
5 sensors



9 sensors

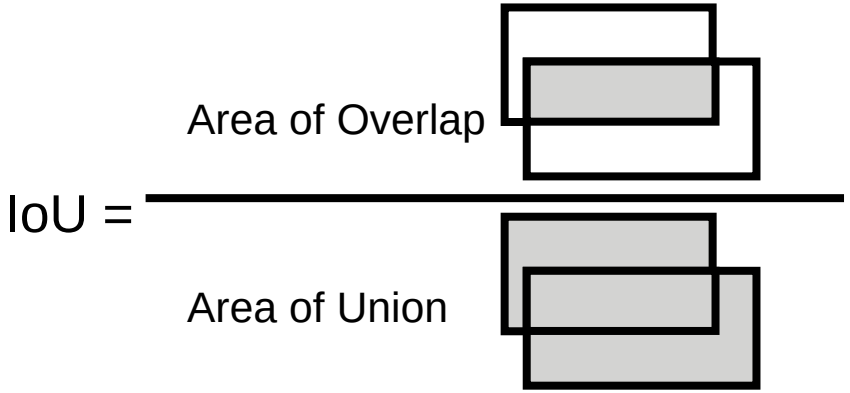


16 sensors

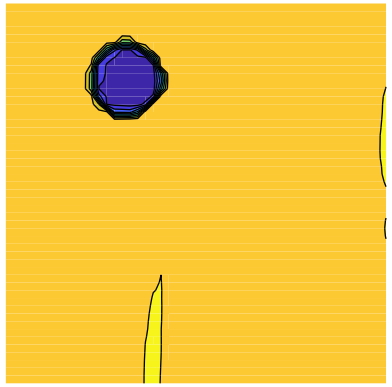


Defect detection – examples

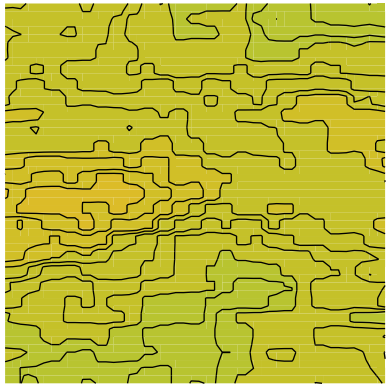
- More sensors typically gives better detection. However, gain can be relatively low
- Predictions strongly depend on position of non-uniformity relative to the sensors



Truth

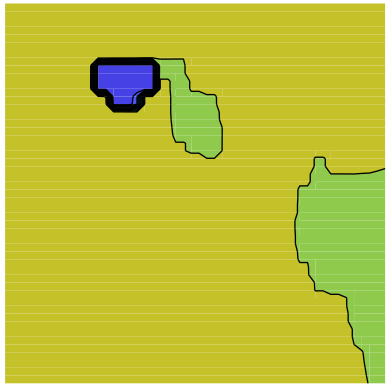


4 sensors



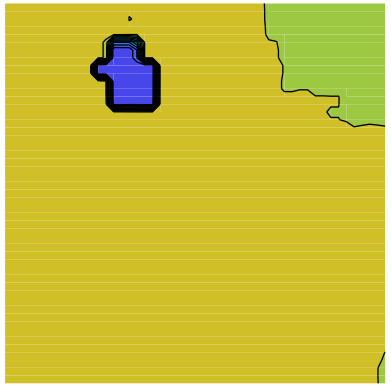
IoU = 0
NRMSE = 1.0

9 sensors

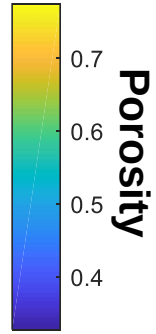


IoU = 0.64
NRMSE = 0.36

16 sensors

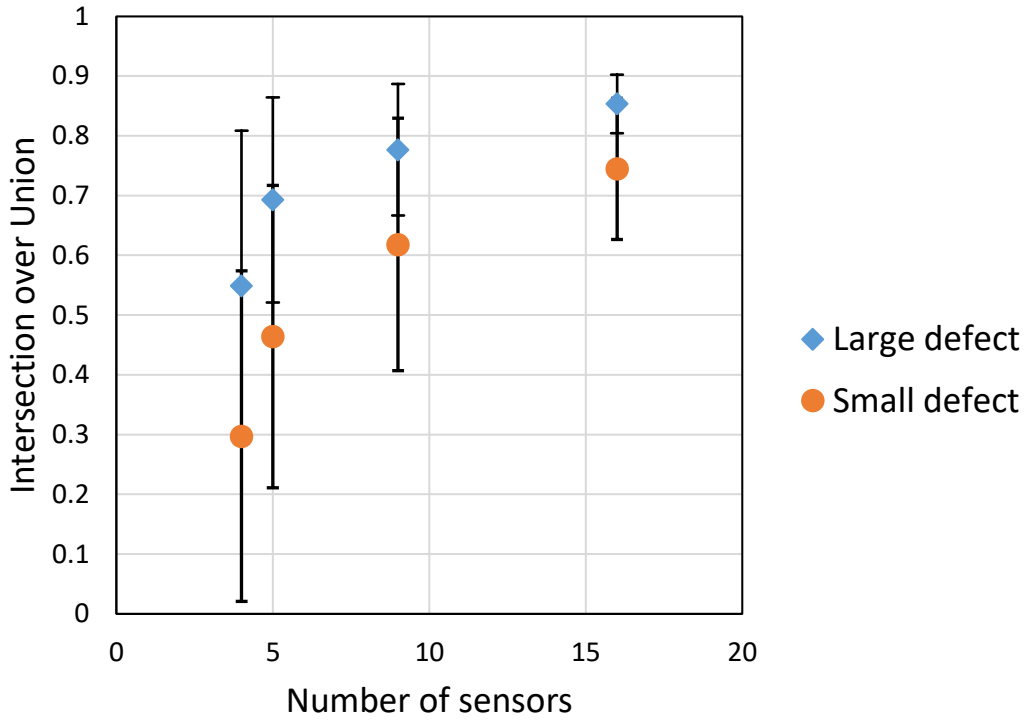


IoU = 0.71
NRMSE = 0.30



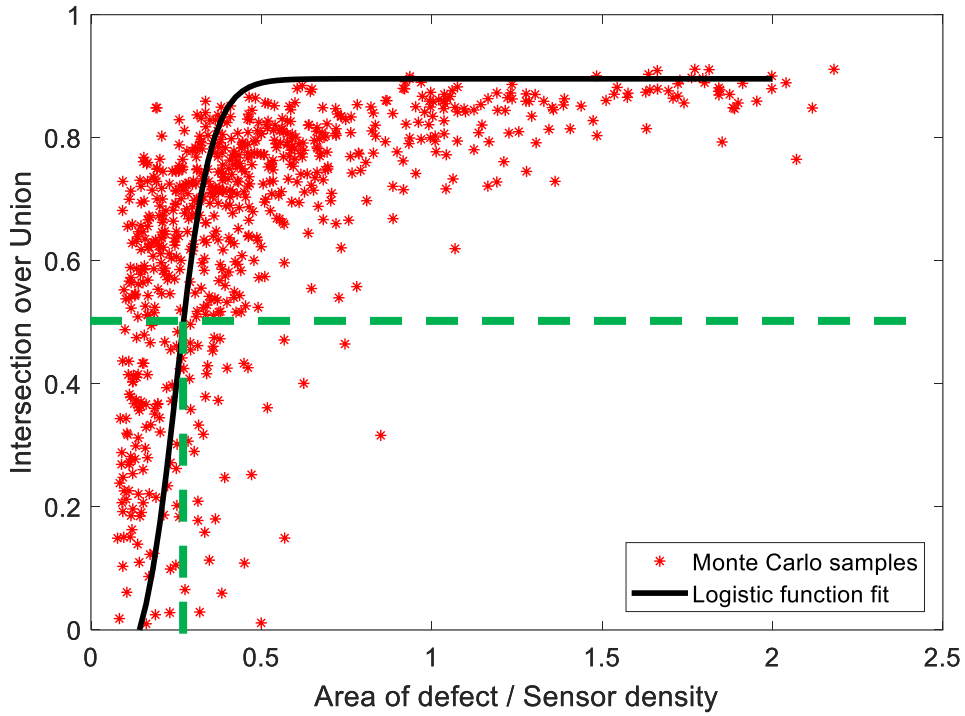
Minimising number of sensors

- Monte Carlo simulations for local changes of different size:
  - Mould size – 30 cm × 30 cm
  - Different inclusion size
- IoU > 0.5 is counted as “detected”
- 9 sensors arrangement provides good estimation of local variations



Minimising number of sensors

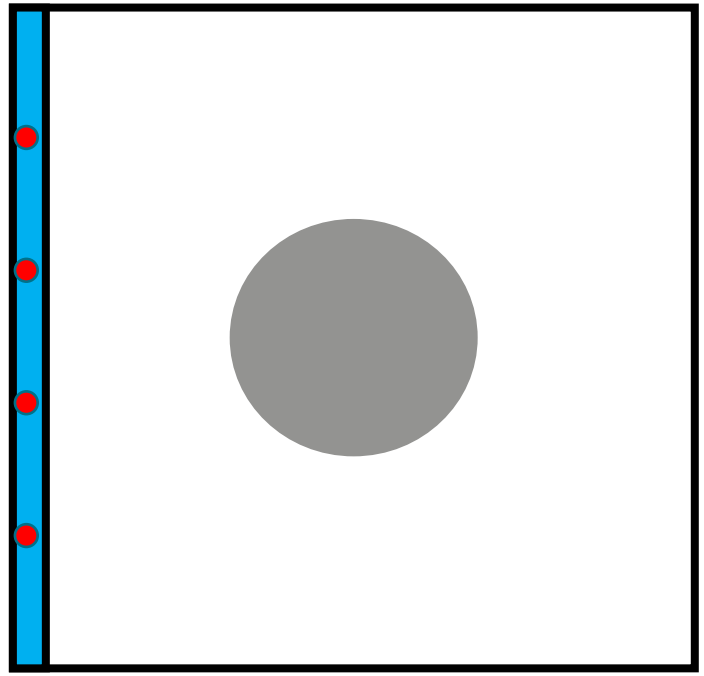
- Monte Carlo simulations for local changes of different size:
  - Mould size – 30 cm × 30 cm
  - Different inclusion size – normalised by sensor density
- IoU > 0.5 is counted as “detected”
- Critical sensor density is around 0.25×(Area of inclusion) sensors/m^2



Logistic function: $f(x) = \frac{1}{1+e^{-k(x-x_0)}}$

Estimating race-tracking (RT) strength

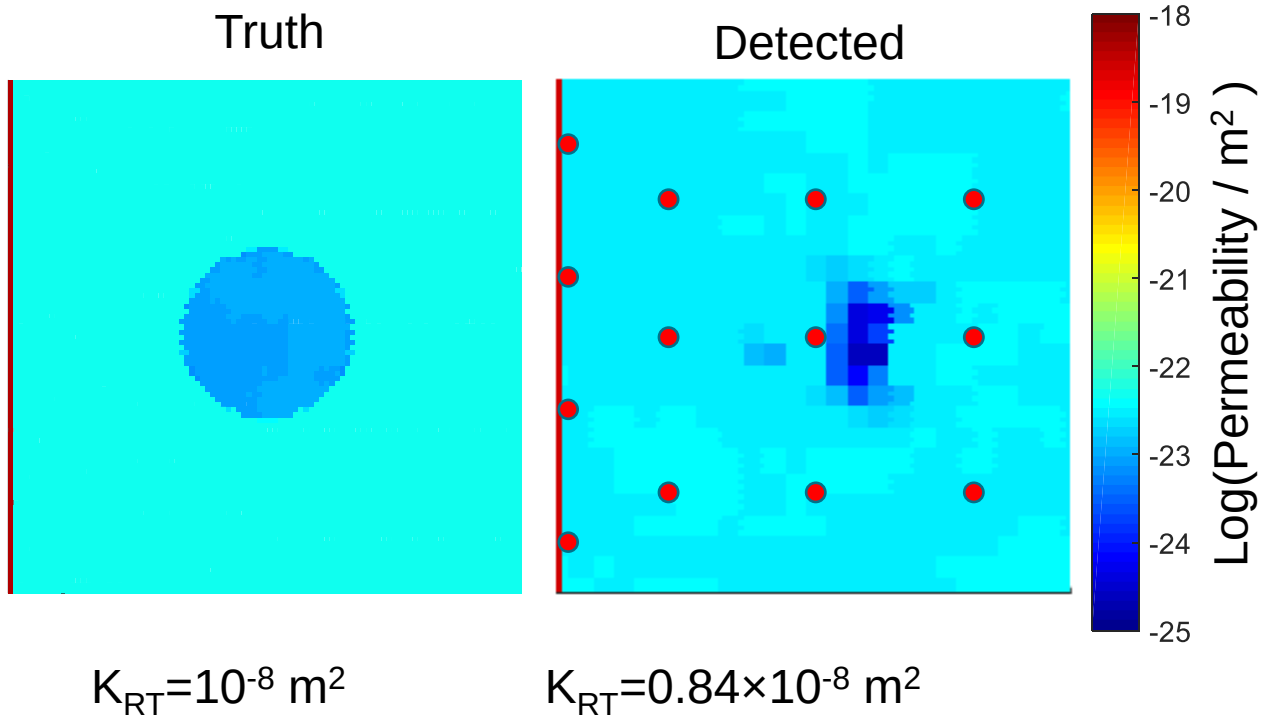
- Race-tracking (RT) has predetermined position but unknown “intensity”
- RT with constant intensity along its length was parameterised with additional parameters
- Extra sensors added at the edge to increase reliability of RT detection



RT on one of the sides: $K_{RT}=10^{-8}$ m^2
Inclusion: $K_{inc} = 10^{-10}$ m^2
Preform: $K = 10^{-9}$ m^2

Estimating race-tracking (RT) strength

- Race-tracking (RT) has predetermined position but unknown “intensity”
- RT with constant intensity along its length was parameterised with additional parameters
- Extra sensors added at the edge to increase reliability of RT detection
- RT is detected with good accuracy



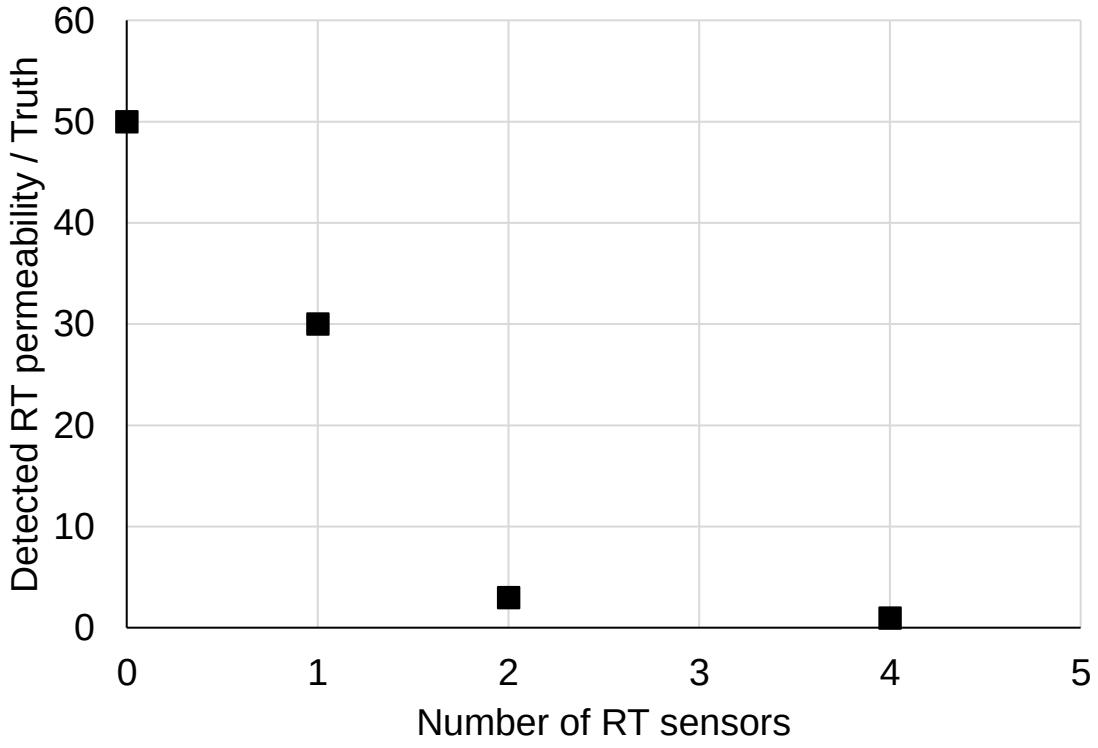
$K_{RT}=10^{-8}$ m²

$K_{RT}=0.84\times10^{-8}$ m²

Predictions used 3×3 sensors + 4 additional sensors at the RT edge

Estimating race-tracking (RT) strength

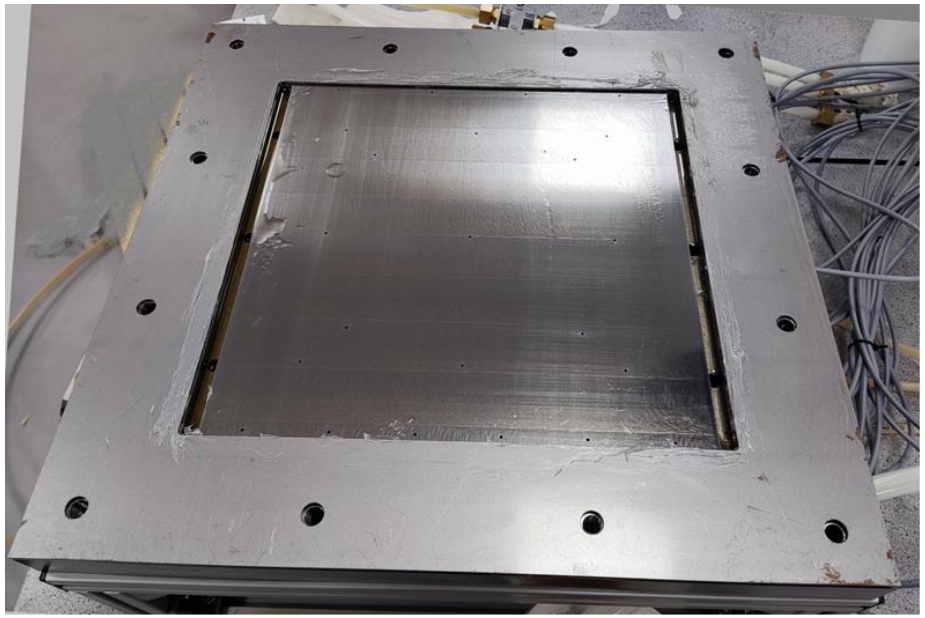
- Race-tracking (RT) has predetermined position but unknown “intensity”
- RT with constant intensity along its length was parameterised with additional parameters
- Extra sensors added at the edge to increase reliability of RT detection
- RT is detected with good accuracy – 2 sensors is enough if only RT is of interest



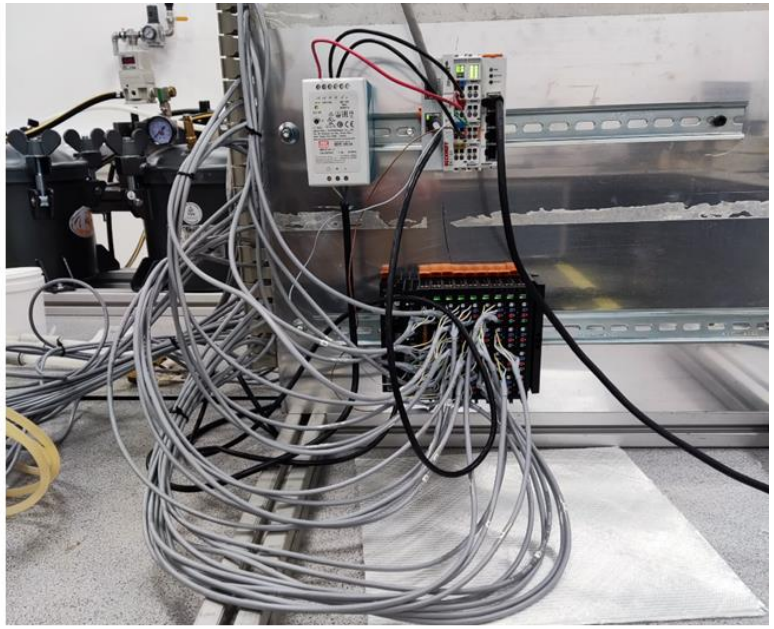
Experimental work

- Instrumented tool with 23 pressure sensors was created:
  - Linear injection
  - Sensors arrangements: 2×2, 2×2+1, 3×3
  - RT arrangements: 4 sensors, 6 sensors
  - DAQ – Beckhoff PLC

Instrumented tool

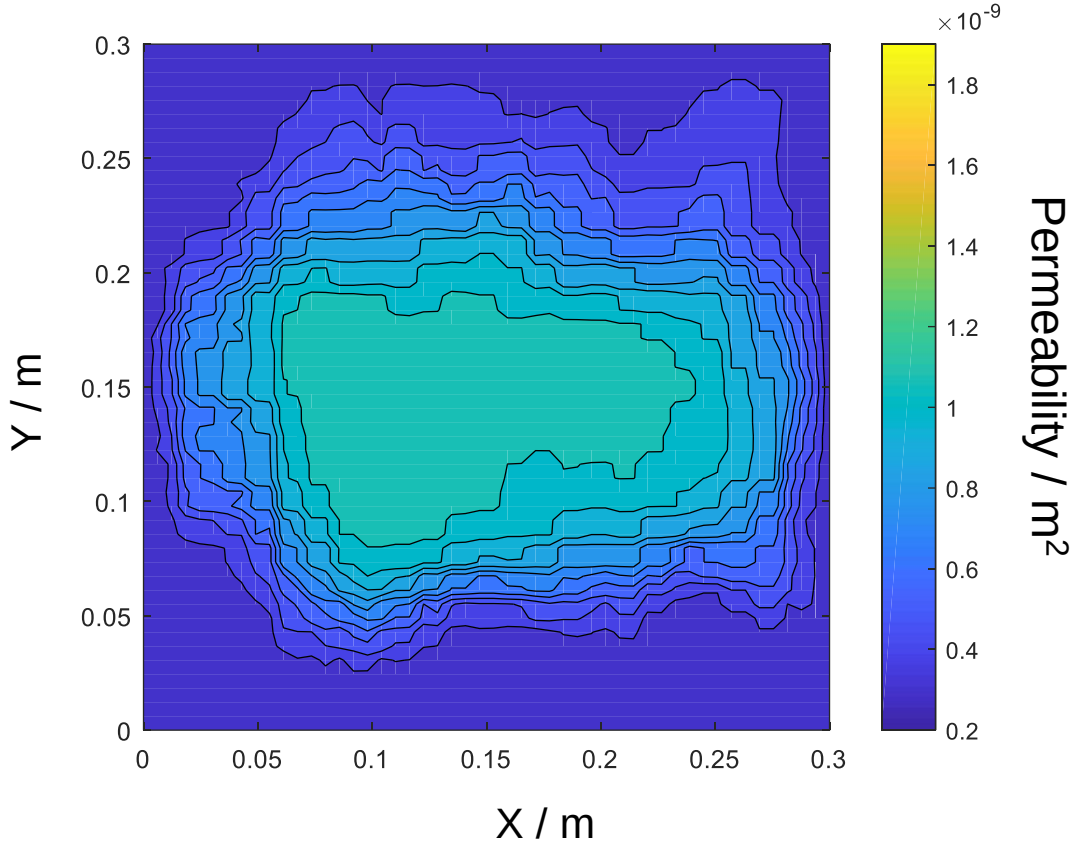


Data acquisition system



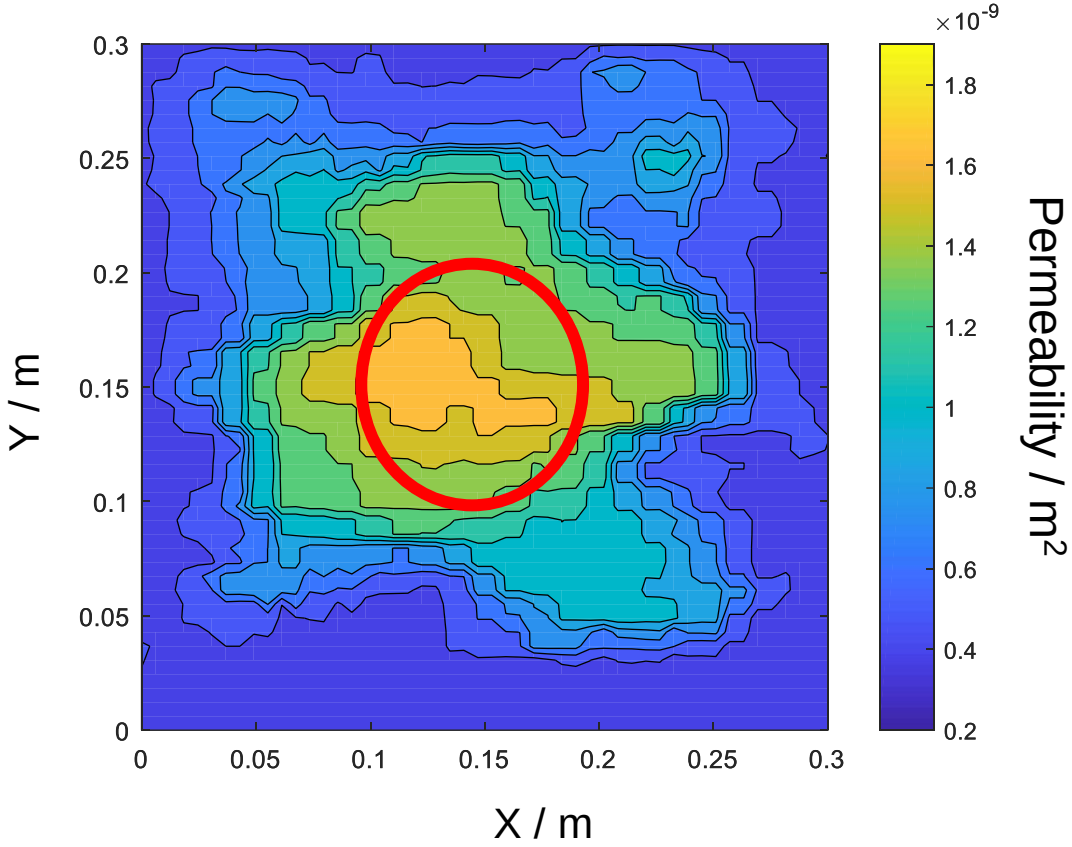
Experimental work – estimating mould deflection

- Uniform preform – non-woven glass fibre mat
- 9 sensors used for estimating “nominal” mould deflection
- Mould deflection is consistent with our expectations



Experimental work – inclusion in the centre

- Hole in the centre of the preform (circle R=4 cm, removing two layers)
- 9 sensors used for detection
- Preliminary results show that model needs to reflect the experiment closely e.g. exact inlet pressure profile needs to be used



Conclusions

- Local non-uniformities can be inferred using relatively small amount of data
- Predicted local properties of the preform will be used for NDE and advanced local process control
- Extensive experimental programme for validating the approach is in progress

Acknowledgements
This work was supported by the Engineering and Physical Sciences Research Council, UK, through the EPSRC Future Composites Manufacturing Research Hub [EP/P006701/1].