National Physical Laboratory

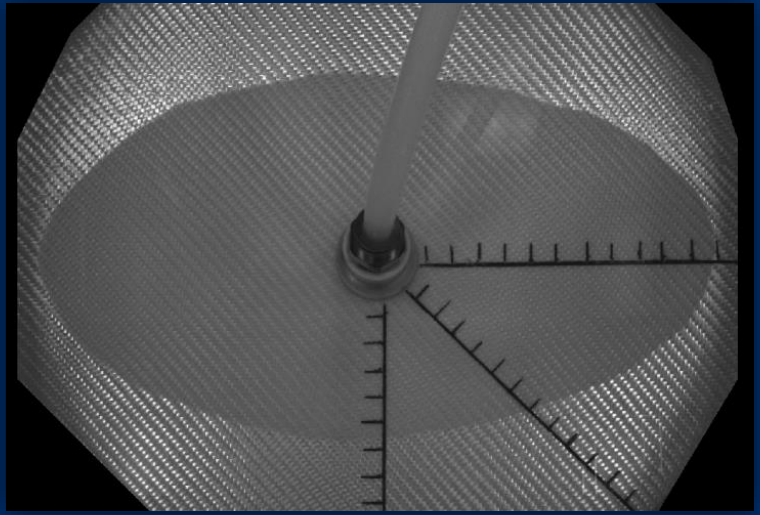
Utilising Machine Vision for Automatic Flow Front Detection of Textile Permeability Measurements

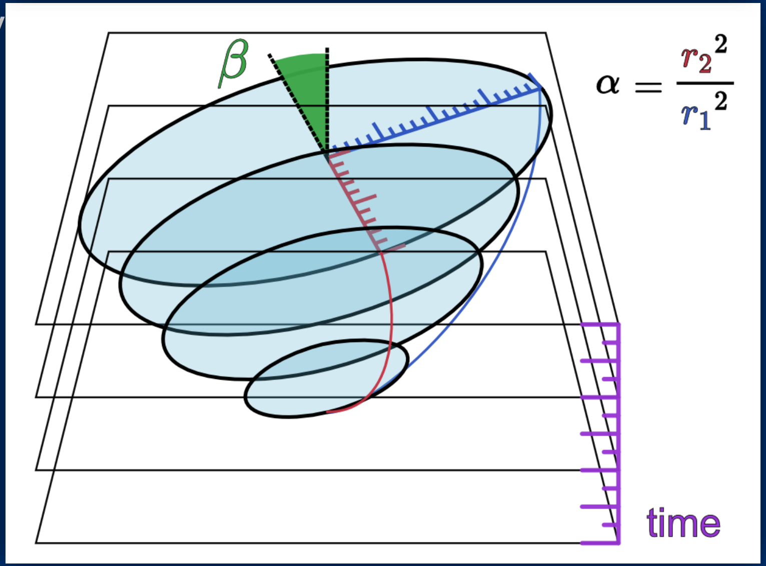
Jamin D . S. Vincent, Piotr J. Geca,

Ana X. H. Yong, Stefanos Giannis.

Introduction

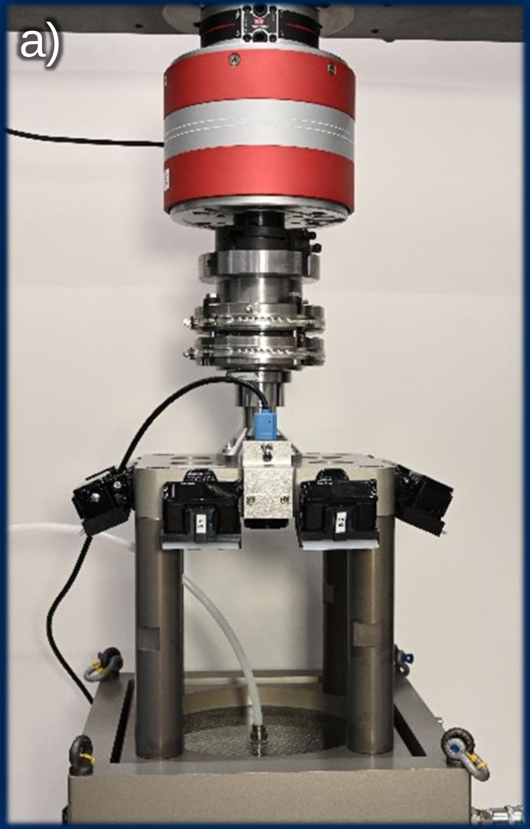
- Currently, radial flow testing is performed across institutions using a wide range of sensing modalities and modelling methods. NPL's rig is designed to allow human operator to visually acquire the flow front. This is followed by J.R. Weitzenböck's modelling process.
- The upcoming ISO standard (ISO/DIS 4410) introduces E. Fauster's paraboloid model as the recommended geometric model approximation of radial flow in time.
- The process of implementing and validating the new modelling paradigm has been combined with switching from manual point measurement of flow front, to extensively automated machine-vision (MV) solution.
- The presented results are based on series of validation tests comparing measurements obtained using the current NPL methodology and the new method.



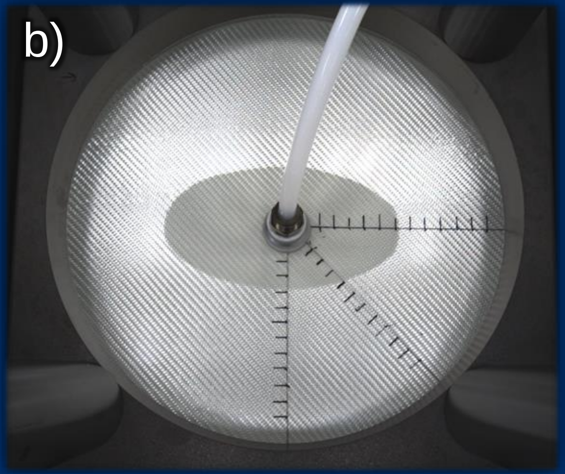


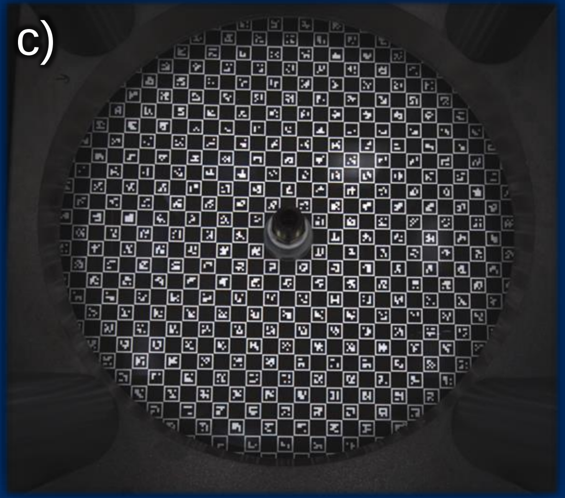
Experiments and data acquisition

- Permeability tests were performed on the in-plane radial flow rig at the NPL (a) with minor modifications to facilitate machine vision: polarized illumination reduces glare and camera’s working distance was increased to capture entire window.
- Testing was performed on Hexcel twill weave (2/2) woven glass fibre fabric.
- Silicone oil was used as test fluid with an injection pressure of 2 bar (abs).
- The images were recorded at the rate of 1 fps using a 5 mm focal length machine vision camera.
- Manual acquisition of flow front distance is based on setpoint benchmarks (b) placed under the viewing window
- MV acquisition of flow front is based on calibration board (c) placed under the window before test fabric is placed in the same location

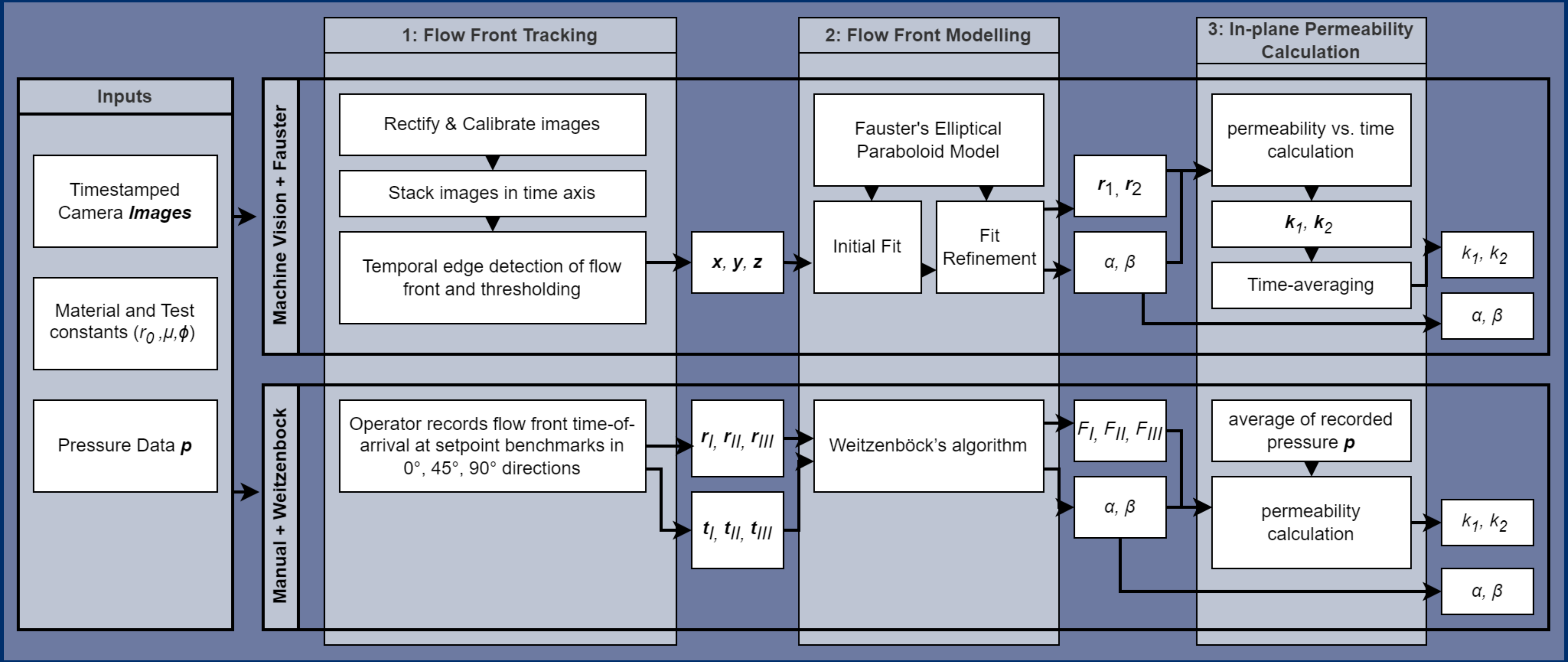


In-plane permeability rig at NPL



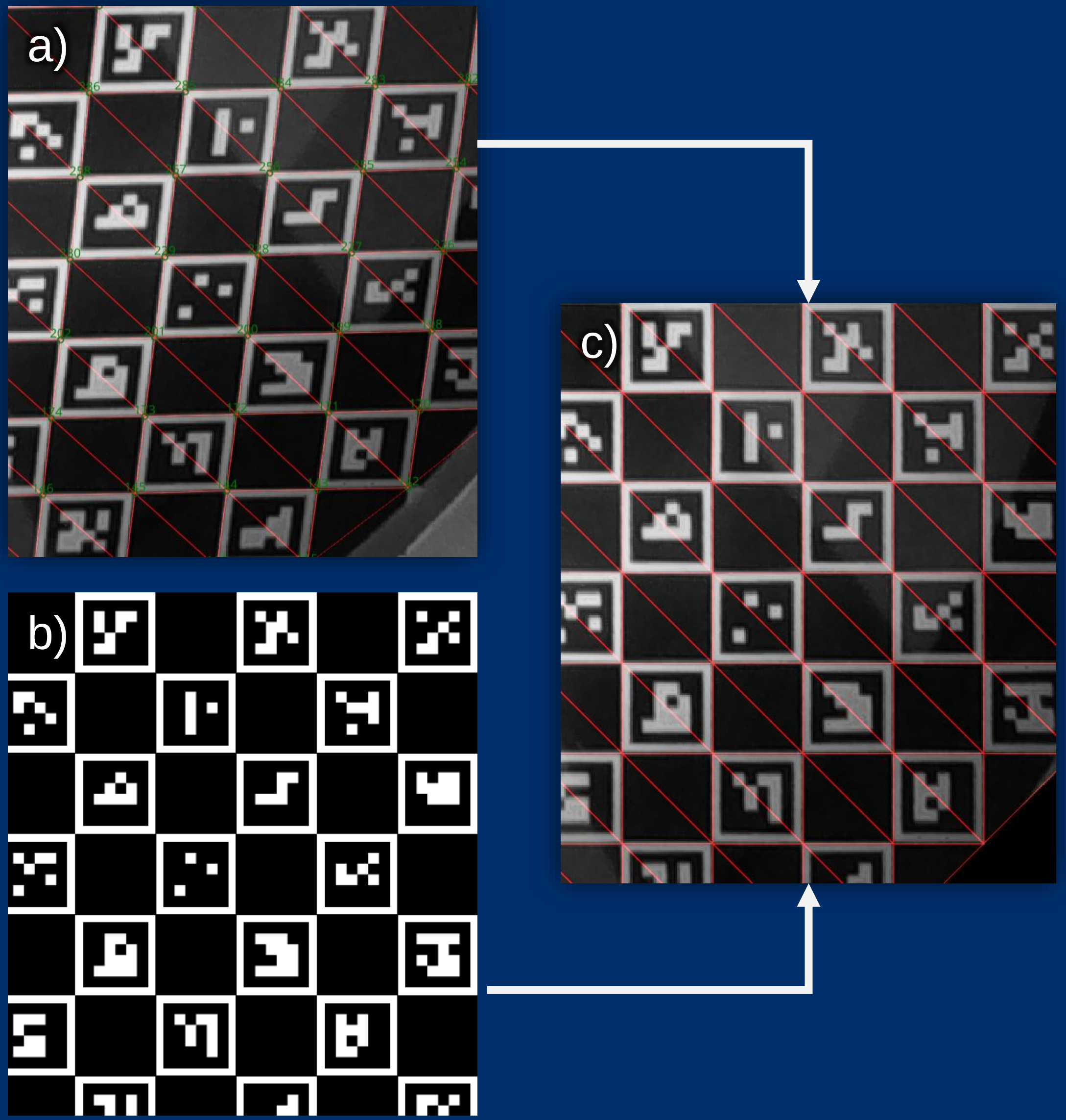


Current and new methods



Machine Vision: Calibration and rectification

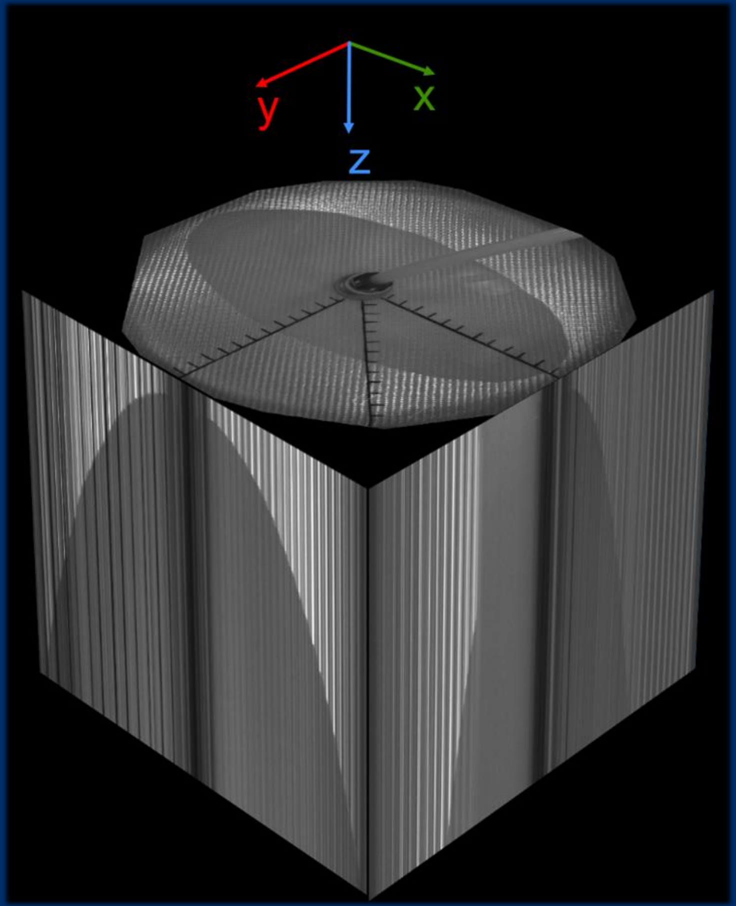
- The process of rectification transforms the contents of test images onto orthogonal grid. Based on known nominal dimensions of the calibration board, uniform pixel/mm scaling is applied to the image at the same time.
- Visible corners of the checkerboard are identified and located with subpixel precision using OpenCV library.
  2D mesh is generated using acquired points and Delaunay triangulation.
- The rectification transformation is calculated as piecewise affine function mapping each triangular mesh region onto corresponding region on nominal grid, producing rectified image.
- The process is highly automated and robust. A new calibration image is taken every time rig is assembled.



Machine Vision: 3D Coordinate frame

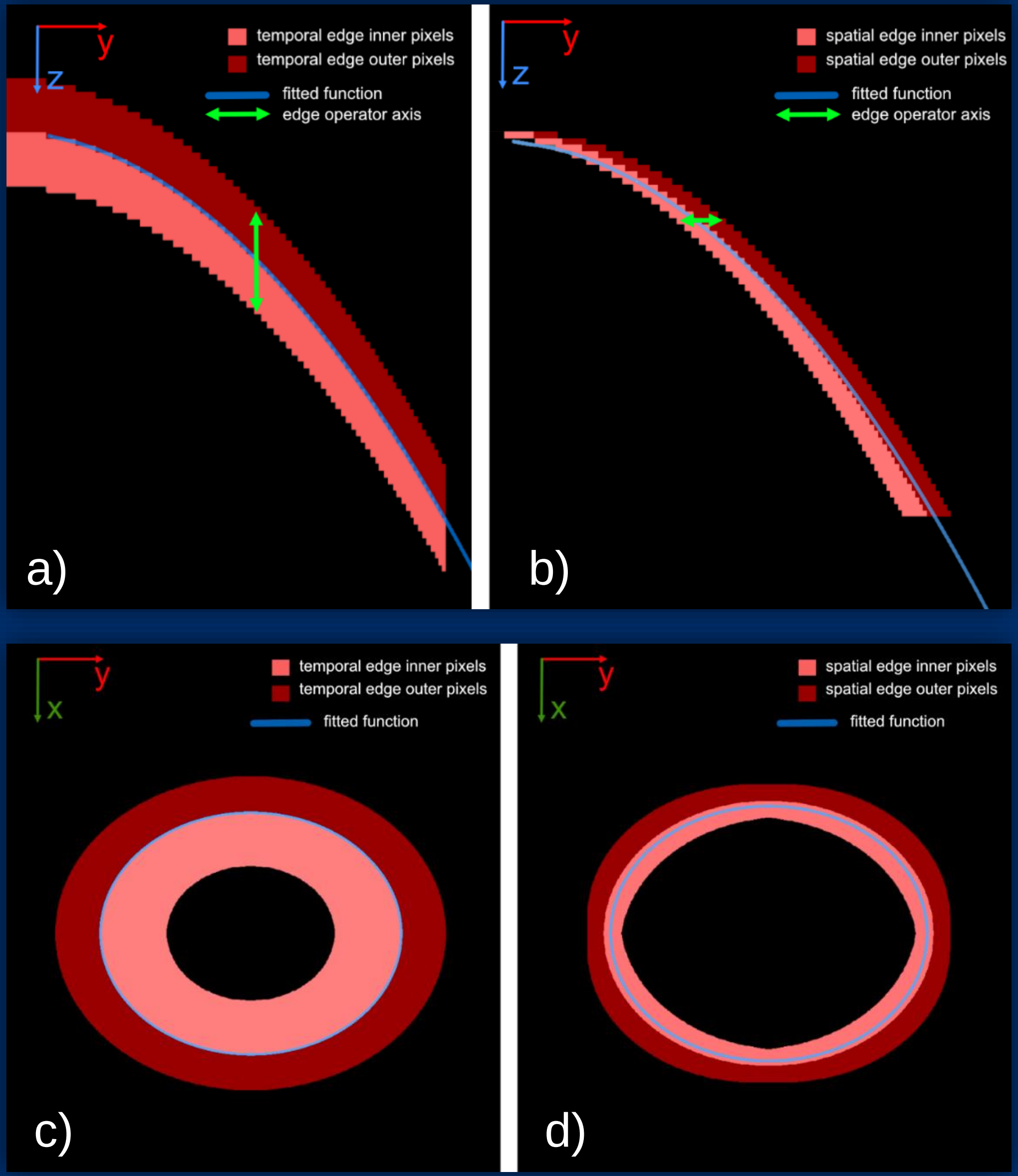
NPL

- E. Fauster's model operates on the principle of combining spatial model of radial flow - ellipse, with temporal model - parabola. The model can be viewed as a 3D surface composed of 2D images stacked in temporal dimension.
- Manipulating test images in form of 3D array facilitates efficient processing and compressed storage.
- When viewed in cross-section using z axis, the parabola patters of flow progress vs time is apparent.
- Allowing operator to visualize the data both ways improves understanding on the result of model fitting operation.



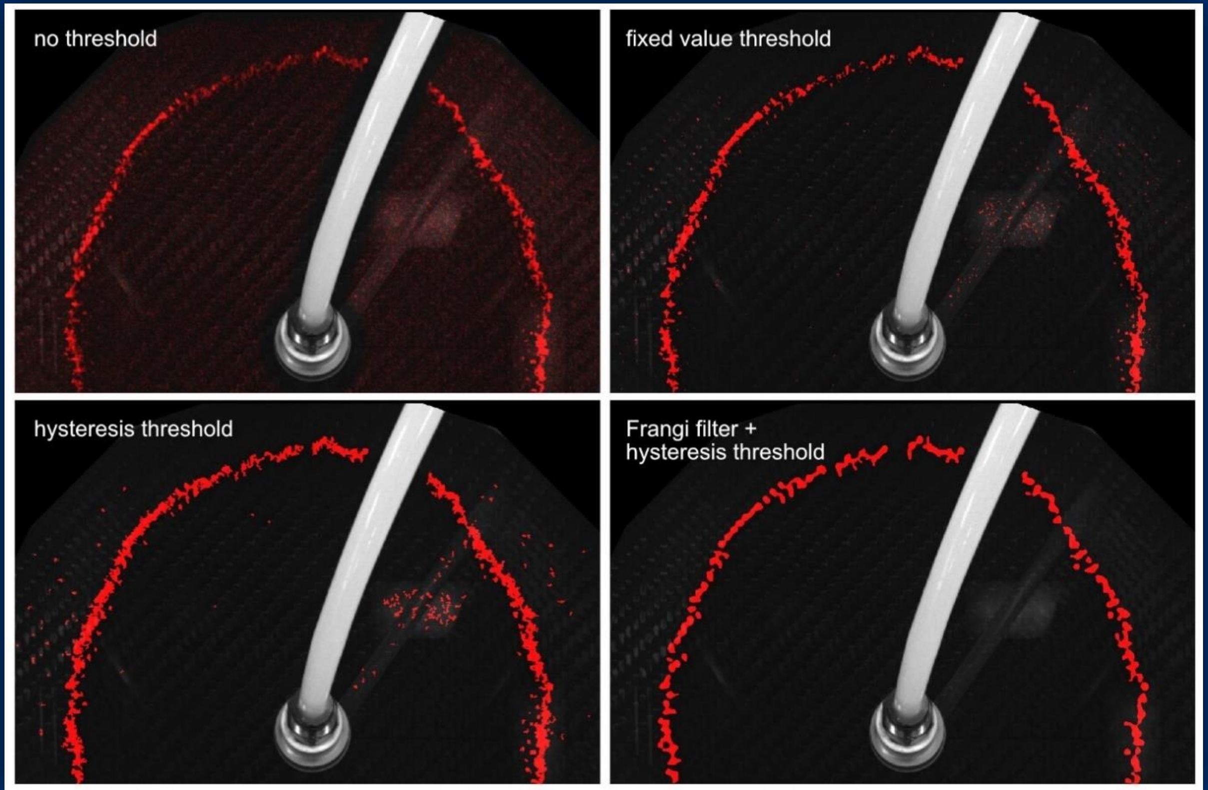
Machine Vision: Temporal edge detection

- Edge detection operations, which are the basis of flow tracking, are best performed in the temporal axis.
  (see z axis in Figures a-d)
- Gaussian Gradient Magnitude (GGM) was used as the edge detector, applied in z axis of the image stack only.
- An important property of pixels labelled through temporal edge detection is that they are located symmetrically about the edge position in z axis. As the Fauster's model is fitted based on z-axis error, the symmetry guarantees accurate fit in idealized case. This is in contrast to spatial edge of the ellipse, which yields a biased fit. The effect is made visible by applying algorithm to synthetic image with exaggerated sigma of the GGM detector.



Machine Vision: Flow front tracking

Flow front tracking on twill weave carbon

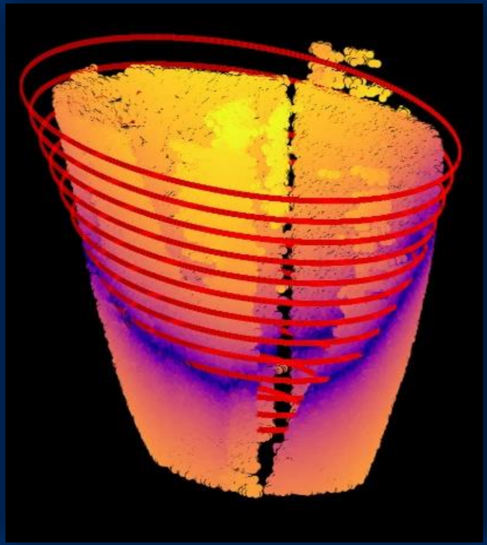


- The flow edge detection step must be followed by thresholding operation separating true edge signal from noise and spurious detection.
- Without use of contrast-enhancing dyes, the contrast offered by resin-saturated region can be very poor, especially for naturally dark materials such as carbon fibre.
- The thresholding algorithm operates on output of the temporal edge detector. Temporal edge detector itself functions as background-subtracting algorithm, effectively responding to frame-to-frame changes in image brightness.
- Value of pixels belonging to the elliptical shape is enhanced through Frangi vesselness filter, which boosts edges forming continuous segments. Noise is de-emphasized.
- Finally, hysteresis threshold captures low-value pixels linked to high-value pixels in continuous segment.
- The algorithm functions very well even in cases challenging to human operator.

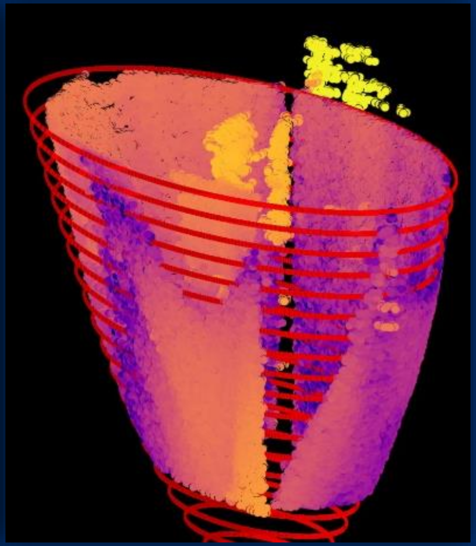
Flow front model fitting

- By nature of the MV based flow tracking, noise and spurious signal can appear in the image some distance from true edge. Tuning MV flow tracking to prioritize noise rejection comes at cost of rejecting valid signal in difficult-to-track cases.
- Numerical model fitting using least-squares loss over-emphasize points distant from fitted model. Model fitting can be made robust against noise by using a 'short-sighted' loss function such as Cauchy loss.
- Full fitting process uses the following steps:
  i. Initial fit is obtained using Singular value decomposition (SVD) algorithm and least squares loss.
  ii. The Initial fit is then refined using Trust Region Reflective (TRF) algorithm and Soft l1 loss. TRF explores solutions within bounds, which are set by multiplying initial fit coefficients by generous tolerance factors.
  iii. Last stage of refinement uses TRF algorithm with Cauchy loss
  iv. Finally, model coefficients are adjusted to enforce the convention of k_1 denoting the highest in-plane permeability and r_1 the major radial extent.

Fitting to set of data with spurious detection (case before improvements to flow tracking)



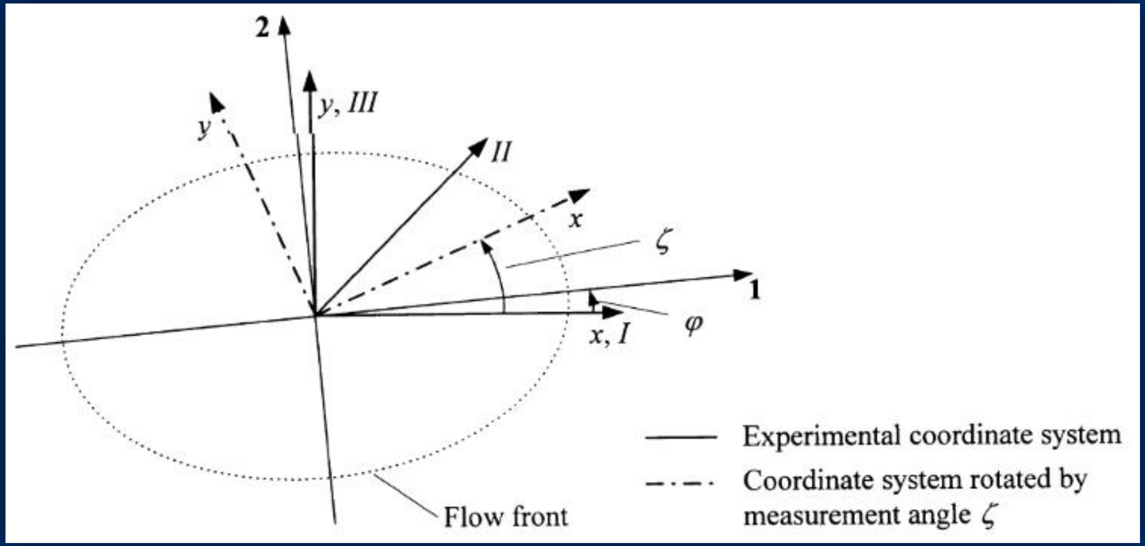
Initial SVD fit. Model intersects the shell corresponding to flow edge in time.



Refined fit with Cauchy loss. Distant points not part of the shell are de-emphasized, fit to rest of points is much improved.

Weitzenböck's method

- Based on Darcy's law of two-dimensional flow in porous media.
- Calculates principal permeability and orientation of principal axis based on measurements from three directions.
- Direction Ⅰ and direction Ⅲ is similar to x and y axes of the cartesian coordinate system and direction Ⅱ represents a 45° axis between direction Ⅰ and Ⅲ. 1 and 2 represents the principal coordinate system.
- A constant inlet pressure is considered throughout the experiment.

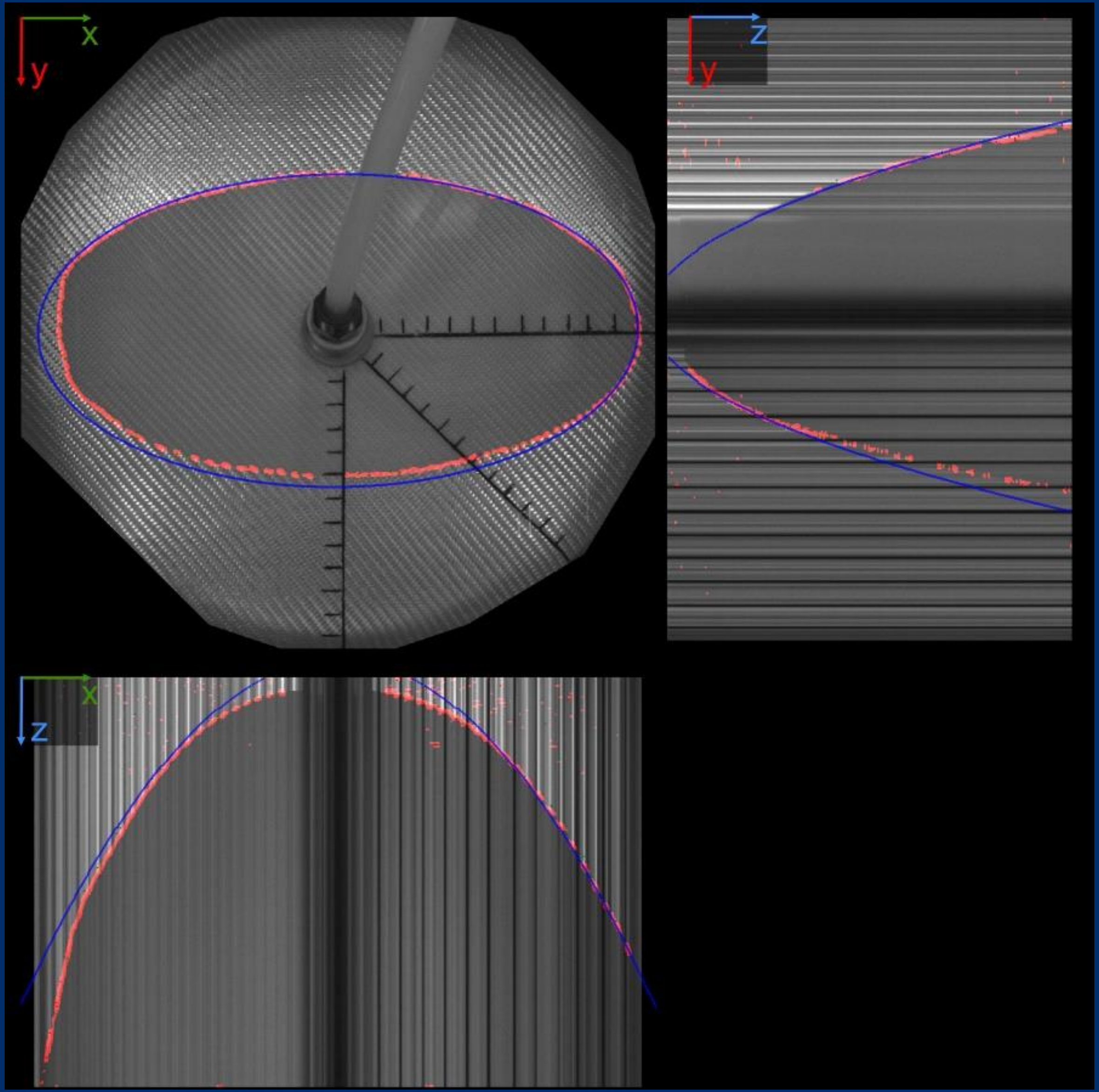


Source: J.R Weitzenböck, R.A Shenoi, P.A Wilson, *Radial flow permeability measurement. Part B: Application*, Composites Part A: Applied Science and Manufacturing, Volume 30, Issue 6,1999, Pages 797-813,ISSN 1359-835X.

Permeability calculation and interpretation

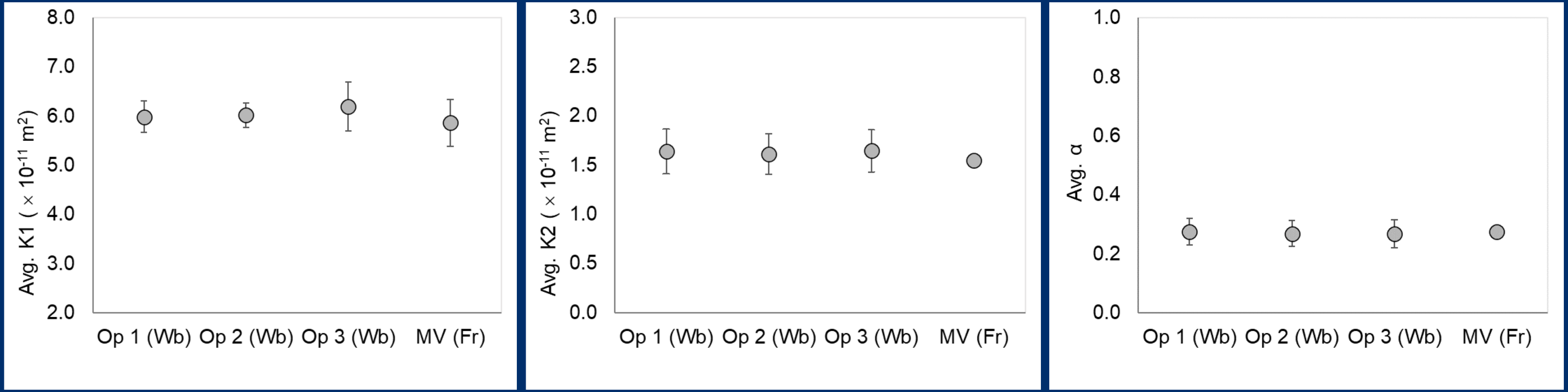
NPL

- Compared to Fauster's, Weitzenböck's model places more assumptions on the test data. Specifically, that flow achieved a steady state with constant *k* and that flow was initiated at exactly *t*=0. Real-world data was seen to deviate from those assumptions. Fauster's model allows for fitting to find time offset and assumes *k* is changing with test time.
- With permeability changing with test time, the averaging method and valid data range chosen for final *k* calculation has impact on the test results. We followed new ISO-recommended algorithm but will continue investigating the effects it has on the results.
- Weitzenböck's model additionally cannot accommodate flow front tracking solutions capable of measuring in more than 3 prescribed directions. Fauster's model is flexible regarding distribution of the datapoints
- In our assessment, we agree that Fauster's model should eventually supersede Weitzenböck's, but NPL must quantify the effect it will have on the produced results and that requires a greater volume of tests recorded using both methods.



Results

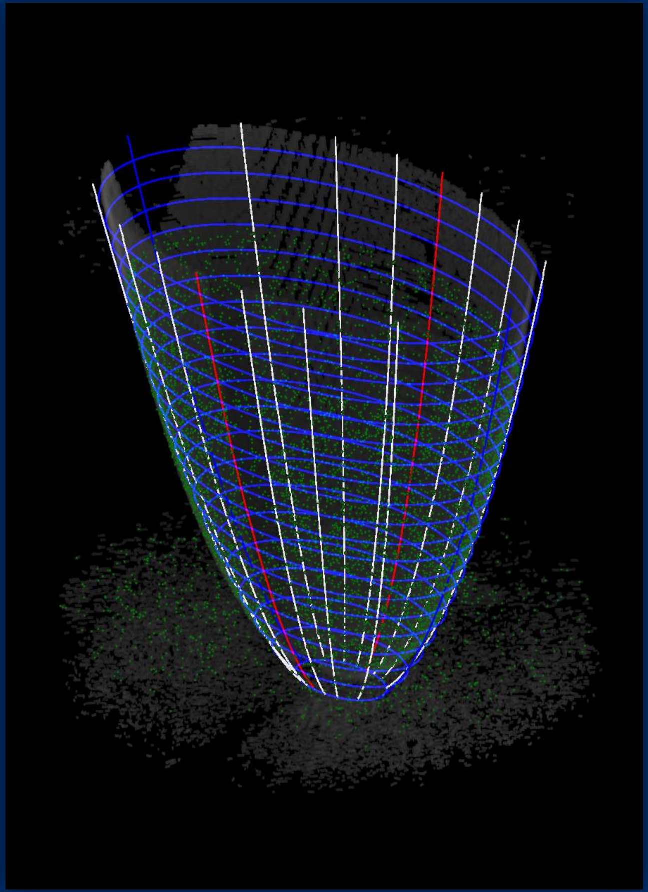
- The results generated by MV+Fauster’s model against manual calculation using Weitzenböck’s method with three different operators and the average K1 & K2 values from the software were 3.5% & 5% lower than the average K1& K2 permeability calculated from the manual method.
- This is due to the difference in averaging functions used by Fauster’s model and Weitzenböck’s method. Also, the tested fabric exhibits a minor asymmetry which can contribute to the discrepancy in the permeability values



Conclusions

NPL

- Data acquisition using machine vision and Fauster's model fitting synergize. Fauster's model, when fitted using robust methods, effectively filters noise and spurious detections. This allows flow tracking to prioritize signal acquisition, leading to good flow tracking even in very challenging materials. In internal tests, we found the MV algorithm working on range of materials with minimal tweaking.
- The tests results generated by the automated procedure show good agreement with ones obtained using established procedures, based on manually acquired data. The high amount of variance inherent in radial flow tests means that a greater number of tests is necessary to quantify the new method's contribution to measurement uncertainty.
- Robust model fitting based on Cauchy loss introduces additional layer of robustness against localized flow deviations from model impacting the test results. However, in cases of systematic error in form of ellipse asymmetry, fit will prioritize one side over a more averaged result.
- Because of the fundamentally different modelling and calculation steps used to obtain averaged permeability, direct comparison between current and new methodologies is challenging.
- We aim to collaborate with partner institutions to acquire image recordings from alternative radial flow rigs. We believe that the MV+F method's robustness makes it possible to deploy on rigs not designed for MV from ground up, as is NPL's.



NPL

National Physical Laboratory

npl.co.uk