Image-based Meshing; OpenFOAM export for ScanIP

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Mesh Generation

Mesh generation – most complex and time-consuming task in CFD analysis.

- Quality of mesh directly affects quality (existance) of solution
- Substantial challenges in driving (complex) mesh generation packages
- Substantial investment of (trained) user time
- Problems if geometry unknown or difficult to characterise

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Image-Based Meshing

Developed initially in computational biomechanics. Biomedical problems are

- Geometrically complex
- Difficult to measure/describe
- Patient-specific

Medical image techniques (MRI, CT) generate 3d information about patient as stack of 2d images. Challenge is to create geometry, mesh from this *automatically*.

Simpleware founded by Dr Philippe Young to develop techniques for CSA – worked to develop CFD output (originally Fluent mesh format; now OpenFOAM).

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MRI

Magnetic Resonance Imaging – works by exciting proton spin + detecting photons emitted by decay back to ground state

- Measures proportion of H atoms in sample
- Good for distinguishing soft tissues
- Samples must contain water (can be introduced artificially)

University of Exeter; access to MRI scanners at PCMD, RDEHT

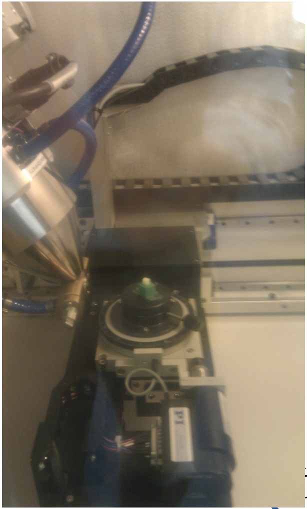
CT, μ-CT

Computerised Tomography – advanced form of X-ray photography; sample rotated between X-ray source and detector to capture 2d images at different orientations. Inverse modelling to generate 3d structure (as stack of images)

- Material contrast based on X-ray absorbtivity
- Good penetration of dense samples (problems if wide range of densities)
- Not so good with soft tissue
- μ-CT – small scale, high resolution

μ-CT facility

Recently invested in μ-CT machine at Exeter. $160\mathrm{keV}$, 3 $\mu\mathrm{m}$ max resolution.



Approaches

Both CT and MRI produce 3d data as stacks of 2d images. Need to generate geometry/mesh from this. Two possible approaches can be used;

CAD-based Use edge-detection algorithms to generate bounding surfaces – pass to existing mesher for mesh generation.

Voxel-based Work with image stack voxels; generate volumetric mesh directly from these.

We use voxel-based methods. Advantages; faster, more robust, greater automation possible.

Basic principles

Voxel-based approach :

1. Identify and mark voxels forming domain(s) of interest – *segmentation* into *mask(s)*
2. Create base Cartesian mesh using Marching Cubes algorithm
3. Truncate base mesh at edge of mask to form boundary
    - resulting surface export for ALM
    - base mesh export as computational mesh
    - use boundary triangulation for alternative mesh generation

Step 3 can include surface smoothing; algorithm assures conforming boundaries between domains.

ScanIP

Image processing and segmentation code. Provides tools for manipulating the image stack and defining regions by marking voxels (segmentation):

Data Processing – crop, pad, rescale etc.

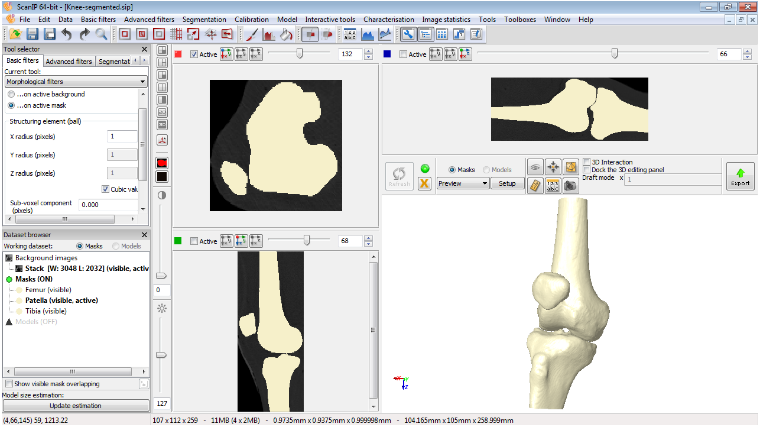
Image Processing – various basic and specialised filter operations, eg. recursive Gaussian, skeletonisation, metal artifact reduction.

Segmentation – threshold, floodfill, confidence connect region growing, manual painting.

Morphological filters – Erode, Dilate, Open, Close – apply to images and to masks.

Boolean Operations on masks

ScanIP


ScanIP 64-bit - [Knee-segmented.sip]
File Edit Data Basic filters Advanced filters Segmentation Calibration Model Interactive tools Characterisation Image statistics Tools Toolboxes Window Help
Tool selector
Basic filters
Advanced filters
Segmentat
Current tool:
Morphological filters
...on active background
...on active mask
Structuring element (ball)
X radius (pixels)
Y radius (pixels)
Z radius (pixels)
Cubic val
Sub-voxel component (pixels)
0.000
Dataset browser
Working dataset:
Masks
Models
Background images
Stack [W: 3048 L: 2032] (visible, activ
Masks (ON)
Femur (visible)
Patella (visible, active)
Tibia (visible)
Models (OFF)
Show visible mask overlapping
Model size estimation:
Update estimation
Active
132
66
68
127
Refresh
Preview
Setup
3D Interaction
Dock the 3D editing panel
Draft mode
Export
(4,66,145) 59, 1213.22
107 x 112 x 259 - 11MB (4 x 2MB) - 0.9735mm x 0.9375mm x 0.999998mm - 104.165mm x 105mm x 258.999mm

Further processing

ScanIP can output STL surfaces based on truncating base hex mesh – output for ALM, external meshing.

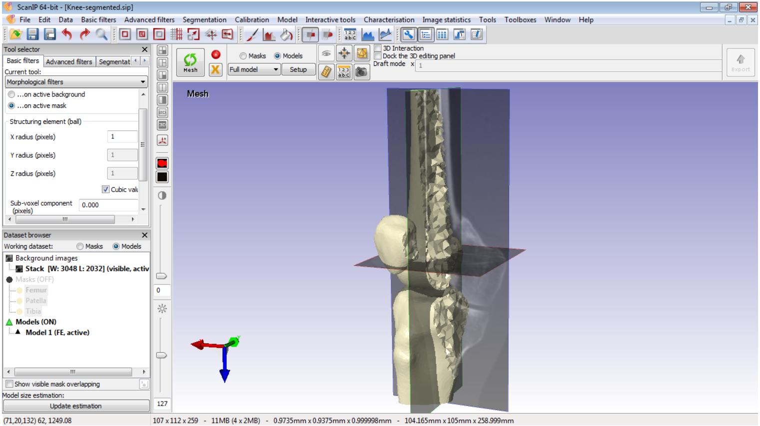
Can also be combined with other Simpleware tools :

+CAD Further manipulation of image stack by voxelisation of imported CAD elements.

+FE – Proprietry mesh generation code. Two meshing algorithms :

- +FE-Grid Defines grid by truncation of base hex mesh
- +FE-Free Uses Delaunay triangulation based on computed surfaces.

ScanIP+FE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Current tool:
Morphological filters
...on active background
...on active mask
Structuring element (ball)
X radius (pixels) 1
Y radius (pixels) 1
Z radius (pixels) 1
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Sub-voxel component (pixels) 0.000
Dataset browser
Working dataset: Masks Models
Background images
Stack [W: 3048 L: 2032] (visible, activ
Masks (OFF)
Femur
Patella
Tibia
Models (ON)
Model 1 (FE, active)
Show visible mask overlapping
Model size estimation:
Update estimation
Mesh
Masks Models
Full model
Setup
3D Interaction
Dock the 3D editing panel
Draft mode
Export
Mesh
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127
(71,20,132) 62, 1249.08
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ScanIP+FE

- Capable of meshing multiple domains with conforming interfaces
- User controlled smoothing of surfaces
- Generate all-tet, mixed hex/tet meshing
- +FE-Grid – highly robust mesher, fast
- +FE-Free – more complex meshing algorithm, automated/user controlled feature-based mesh refinement
- Boundary Layer meshing under development

OpenFOAM export option now available.

Application Examples

Rest of talk – various case studies demonstrating range of applications for the technology.
Test cases;

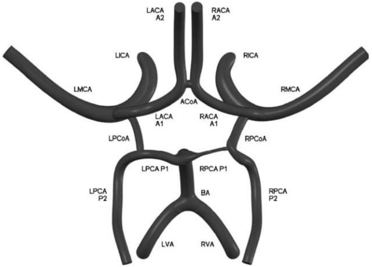
1. Flow in Circle of Willis
2. Dog Nose geometry
3. Engine Manifold
4. Diesel Particulate Filter

Circle of Willis

Structure of arteries supplying brain

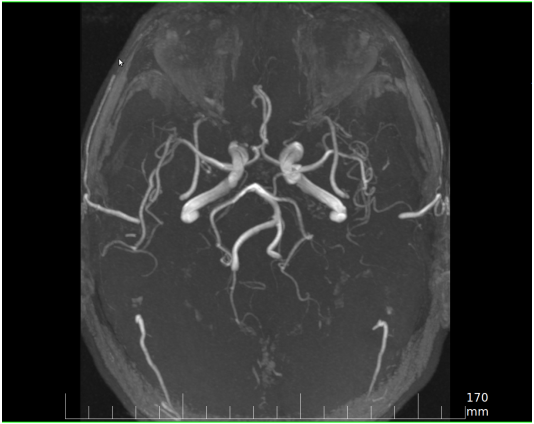
Carotid, basilar arteries merge in Circle; afferent arteries supply brain

Very patient-specific; interest in stroke research

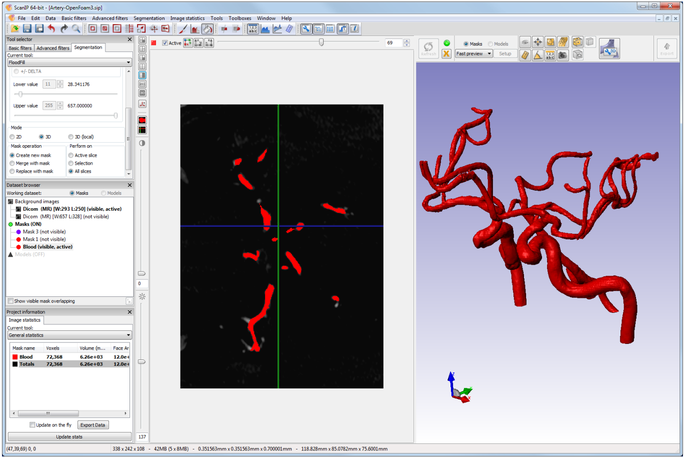


Project to investigate flow in CoW for healthy and stroke patient cases – UofE, RDEHT Stroke Research unit.

Original scan



Threshold/floodfill segmented mask



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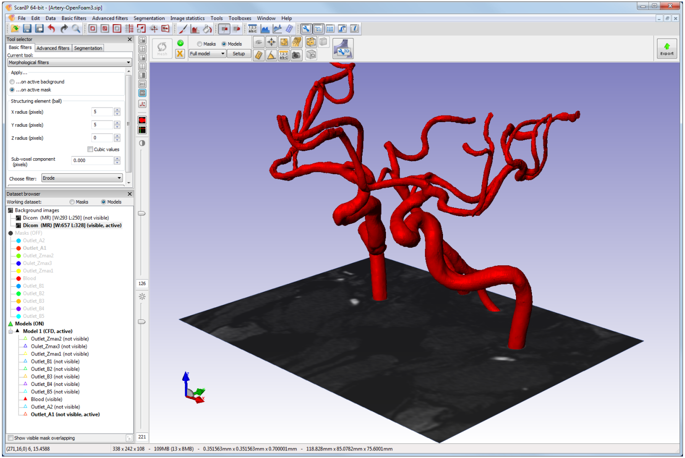
Geometry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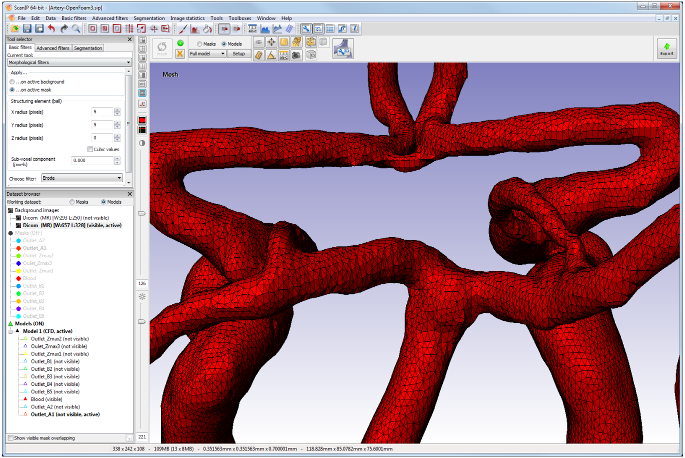
Tool selector
Basic filters Advanced filters Segmentation
Current tool:
Morphological filters
Apply...
...on active background
...on active mask
Structuring element (ball)
X radius (pixels) 5
Y radius (pixels) 5
Z radius (pixels) 0
Cubic values
Sub-voxel component (pixels) 0.000
Choose filter: Erode
Dataset browser
Working dataset: Masks Models
Background images
Dicom (MR) [W:293 L:250] (not visible)
Dicom (MR) [W:657 L:328] (visible, active)
Masks (OFF)
Outlet_A2
Outlet_A1
Outlet_Zmax2
Oulet_Zmax3
Outlet_Zmax1
Blood
Outlet_B1
Outlet_B2
Outlet_B3
Outlet_B4
Outlet_B5
Models (ON)
Model 1 (CFD, active)
Outlet_Zmax2 (not visible)
Oulet_Zmax3 (not visible)
Outlet_Zmax1 (not visible)
Outlet_B1 (not visible)
Outlet_B2 (not visible)
Outlet_B3 (not visible)
Outlet_B4 (not visible)
Outlet_B5 (not visible)
Blood (visible)
Outlet_A2 (not visible)
Outlet_A1 (not visible, active)
Show visible mask overlapping
Masks Models
Full model
Setup
Export
126
221
(271,16,0) 6, 15.4588
338 x 242 x 108 - 109MB (13 x 8MB) - 0.351563mm x 0.351563mm x 0.700001mm - 118.828mm x 85.0782mm x 75.6001mm

Meshed Geometry



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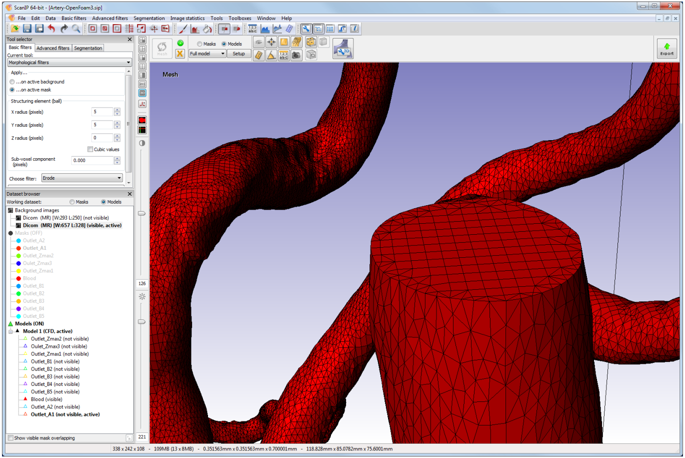
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Outlet_Zmax2 (not visible)
Oulet_Zmax3 (not visible)
Outlet_Zmax1 (not visible)
Outlet_B1 (not visible)
Outlet_B2 (not visible)
Outlet_B3 (not visible)
Outlet_B4 (not visible)
Outlet_B5 (not visible)
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Outlet_A1 (not visible, active)
Show visible mask overlapping
Mesh
Full model
Setup
Export
338 x 242 x 108 - 109MB (13 x 8MB) - 0.351563mm x 0.351563mm x 0.700001mm - 118.828mm x 85.0782mm x 75.6001mm

OpenFOAM Simulation

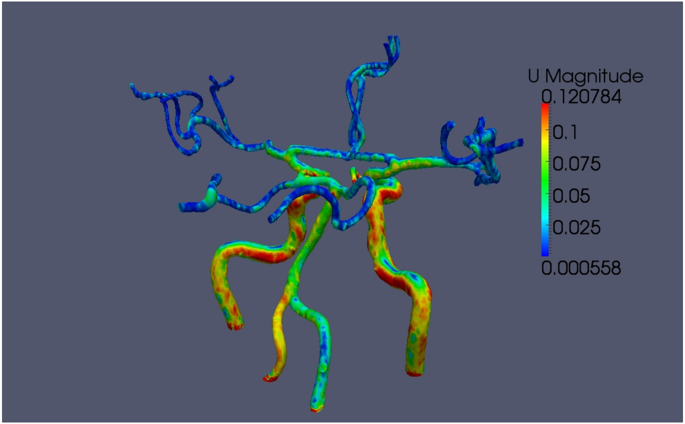
Data from healthy 50-yr old volunteer – MRI data capture used.

+FE-Grid mesher exports native OpenFOAM output as `polyMesh` file set. Boundary patch definition inside ScanIP (mask painting).

Inlet conditions – experimenting with sinusoidal wave inlet using `GroovyBC`, physiological inlet using `mapped`

+FE-Free mesher also used to compare results

Typical CFD results



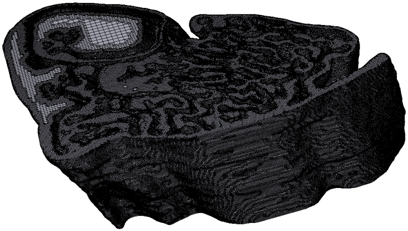
Canine Nose

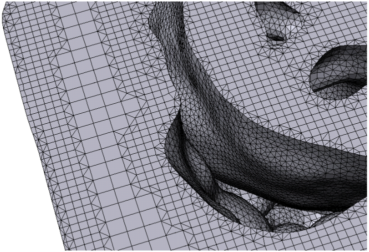
Dataset from Prof Eric Paterson (PSU) – very complex geometry to mesh.

Meshing accomplished with +FE-Grid, +FE-Free (different coarsenesses) and beta version of boundary layer mesher

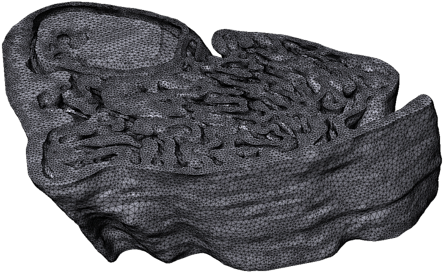
Mesher	# cells	Mean in-out aspect ratio	Worse than 0.1
+FE-Grid	6.9M	0.737	0 (0%)
+FE-Free (-50 coarse)	922k	0.708	284 (0.0308%)
+FE-Free (-25 coarse)	2.16M	0.735	278 (0.0128%)

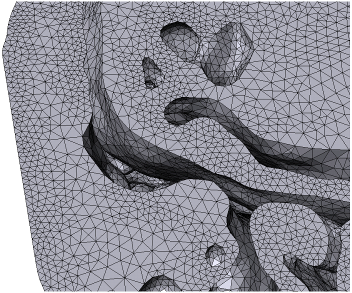
+FE-Grid



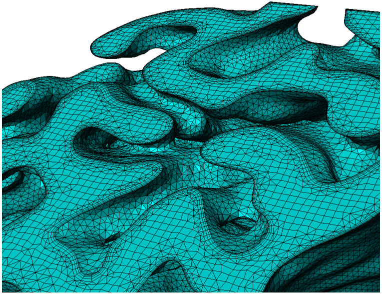


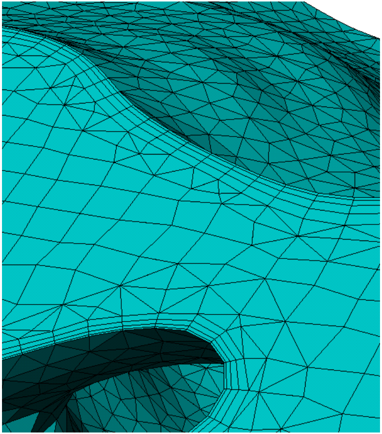
+FE-Free





Boundary Layer Meshing





Other uses

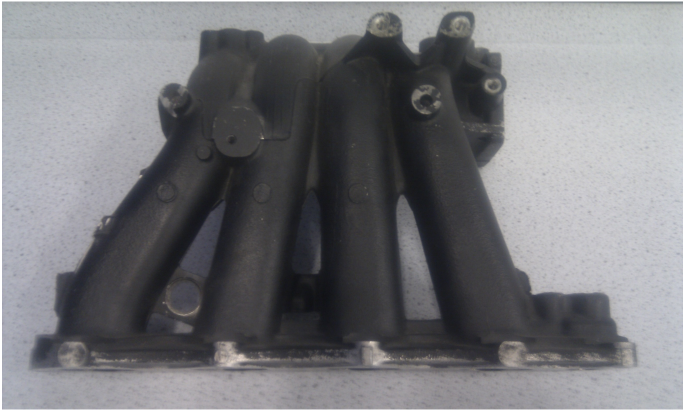
Methodology can be used wherever we have complex (unknown) geometry, but also an object to scan.

Other examples include :

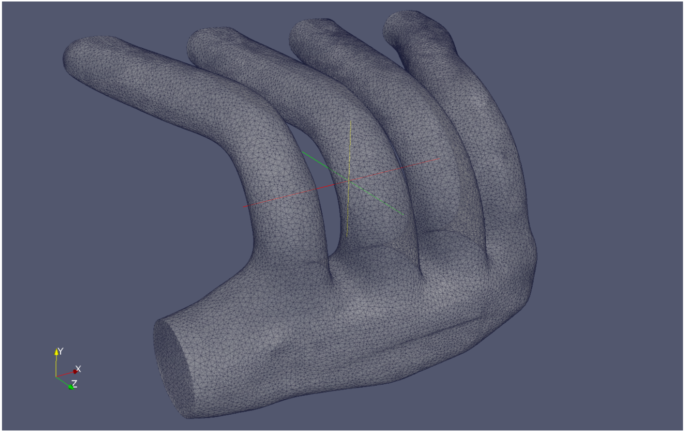
- Biological – pine cone pollination, graptolites
- Engineering – reverse engineering complex geometries
- Microstructural flows in filters/packed beds

Example: Engine Manifold. CT scan performed

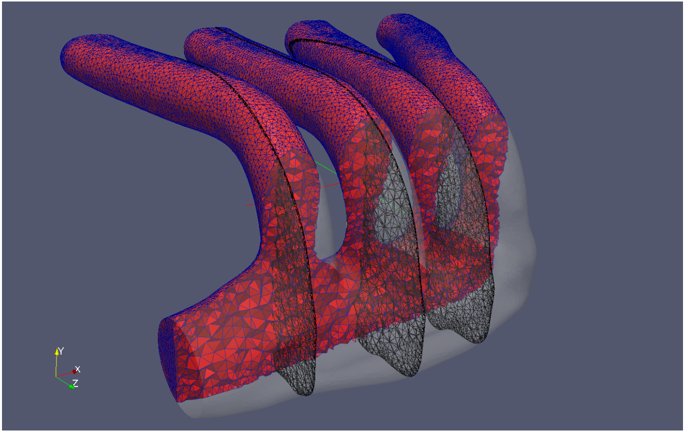
Engine manifold



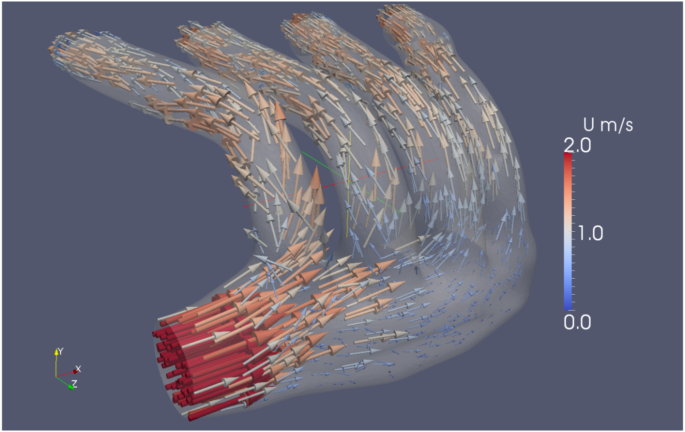
Surface Mesh



Internal Mesh (+FE-Free)



CFD results



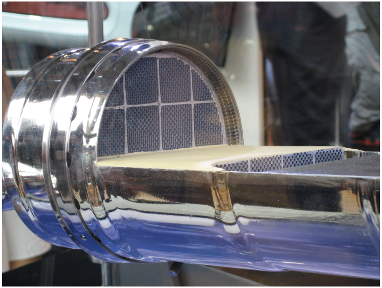
DPF analysis

DPF – important for removing particulates from exhaust – driven by legislative requirements.

Ceramic filter comprising fused particles (microstructure) and multi-channel geometry (macroscale)

μ-CT scan to determine microscale

OpenFOAM simulation – `simpleFoam`, range of turbulence models, laminar, different differencing schemes.



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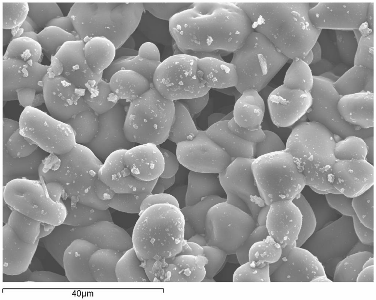
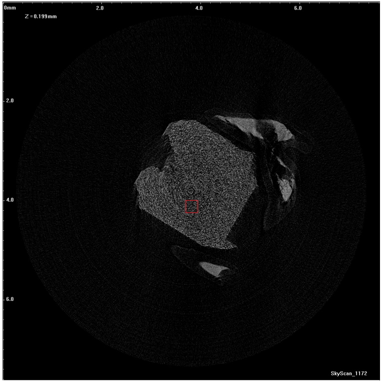
Microstructure

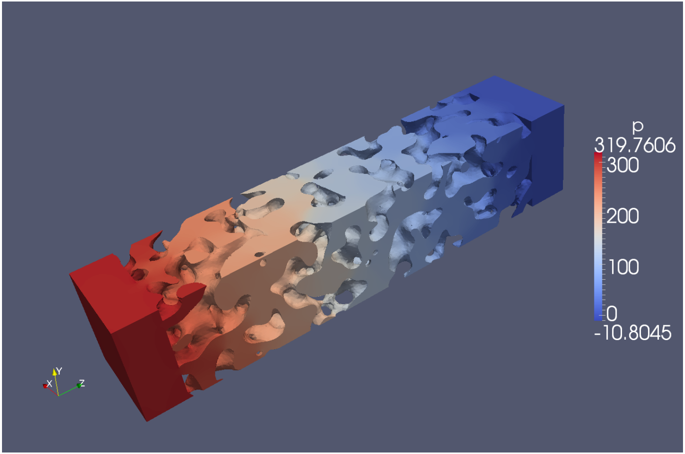
μ-CT scan $\rightarrow$

Electron Micrograph $\downarrow$

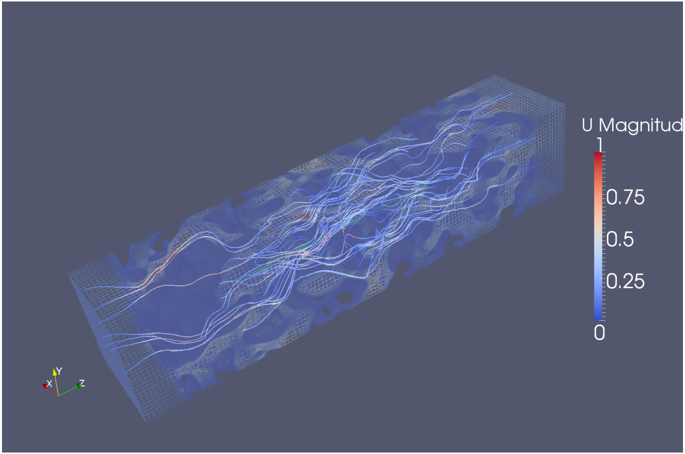




Pressure



Streamlines



Summary

- Image-based meshing a valuable tool
  - for any situation where you have a complex geometry and an object to scan
- ScanIP+FE powerful tools for creating meshes for CCM and CFD
- Native OpenFOAM export implemented

Company website; http://www.simpleware.com/

Thanks to : Prof Eric Paterson (PSU),
Richard Knights (DPF work)

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