A CFD-augmented machine-learning approach for the classification of nasal pathologies

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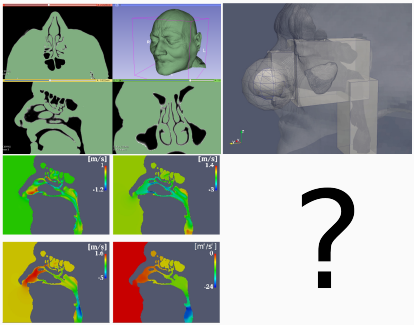
The workflow: form CT scan to...

1. Segment the CT scan
2. Build a volume mesh
3. Compute a CFD solution (DNS, LES, RANS)



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Resort to Machine Learning

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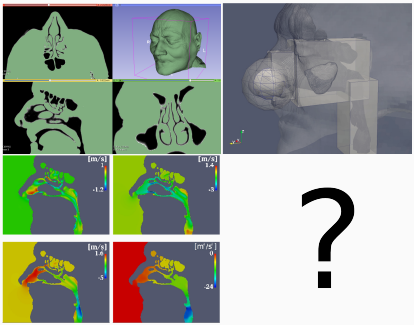

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Resort to Machine Learning

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Need for a dataset!

Dataset's requirements

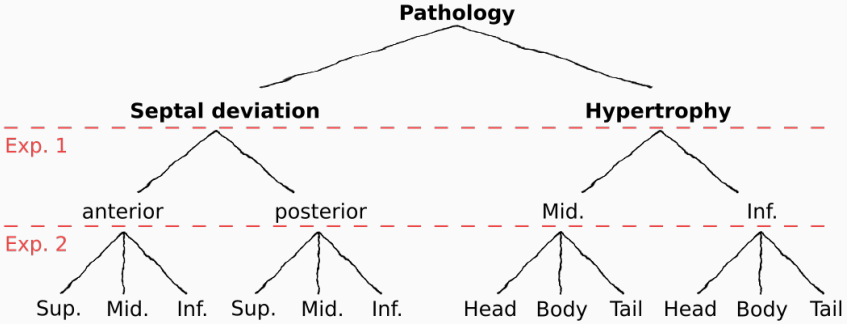
- Use real anatomies
- The same pathology for different patients
- Avoid ambiguity of labels

Building the dataset

1. Define a set of pathologies with ENT surgeons
2. Pick one healthy patient
3. Inject the pathologies (one or more at the time, with different severities)
4. GO TO 2

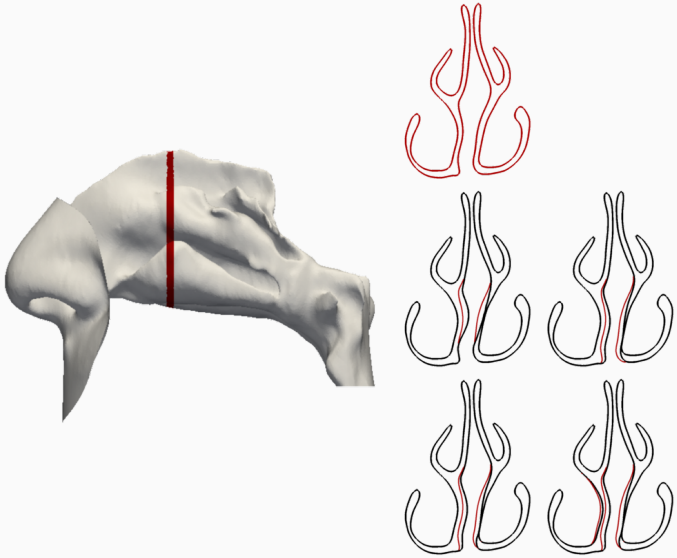
Define the pathologies

Septum
Middle Turbinate
Inferior Turbinate



7 healthy patients – 270 unique geometries

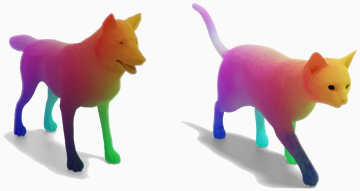
The cost of $(\textit{virtual surgery})^{-1}$



Consistent process - Functional maps

Is there a way to *propagate* the information?

- Computational geometry tool
- Generalization of Fourier basis on surfaces
- Basis: eigenfunction of the Laplace-Beltrami operator
- Compare *real valued function* on surfaces

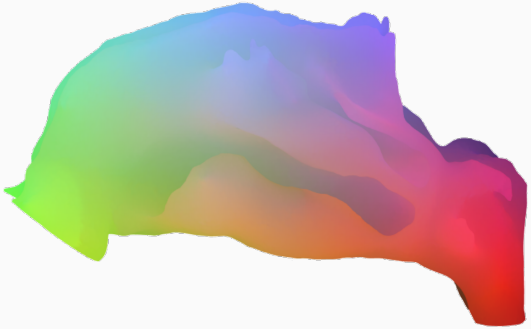


$$T_F \approx \phi_{\mathbf{N}} \ \mathbf{C} \ \phi^{+}_{\mathbf{M}}$$

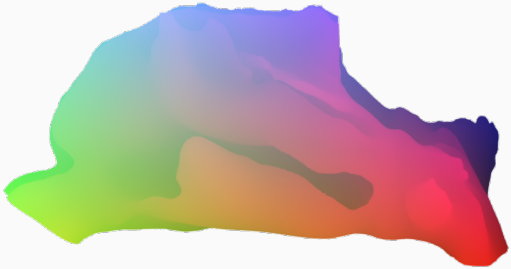
Ovsjanikov M., *et al*. Functional maps: a flexible representation of maps between shapes. ACM Transactions on Graphics 2012

Functional maps

Source

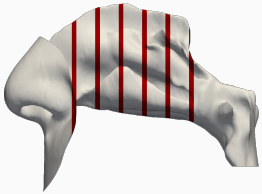


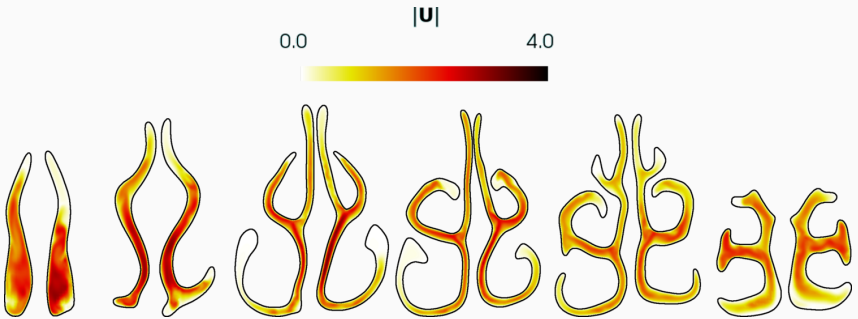
Target



The CFD setup

- Meshes of around 13 Millions cells without sinuses
- LES simulations, WALE turbulence model
- Constant flow rate 266.66 ml/s
- 0.6 s simulated (excluding transient)





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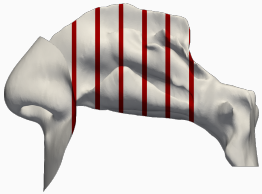

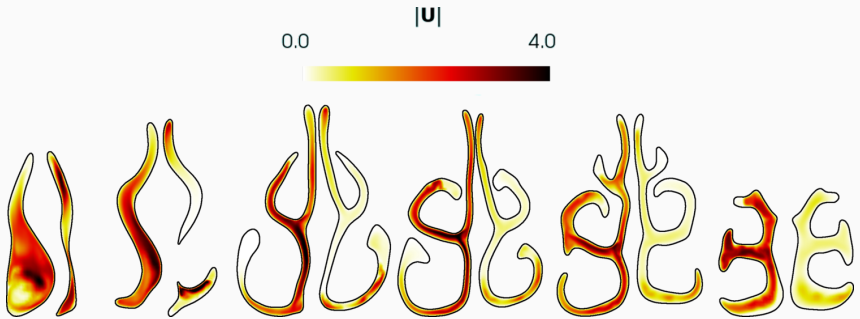

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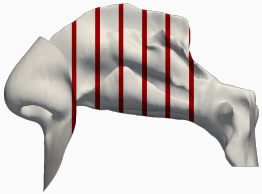

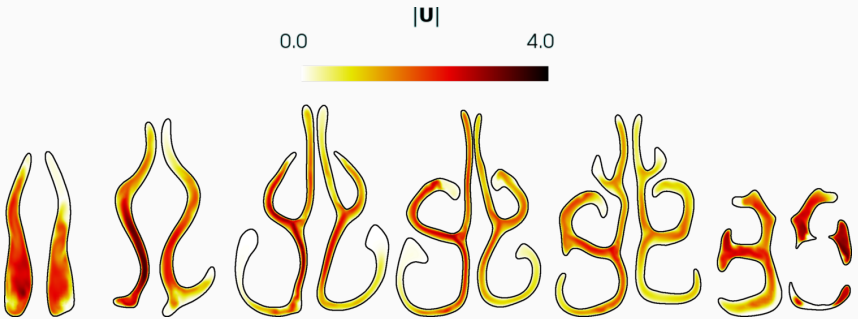

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The classification problem

The task:

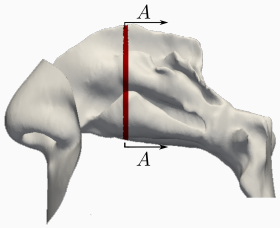
Classify 28 pathologies from 270 LES into 2 (exp. 1) or 4 (exp. 2) classes.

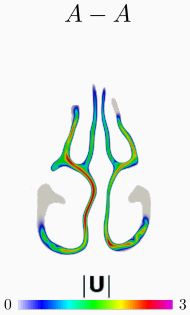
Challenges:

- Each CFD carries around 2 GB of information
- Need for feature engineering!

Feature engineering example: Regional Averages

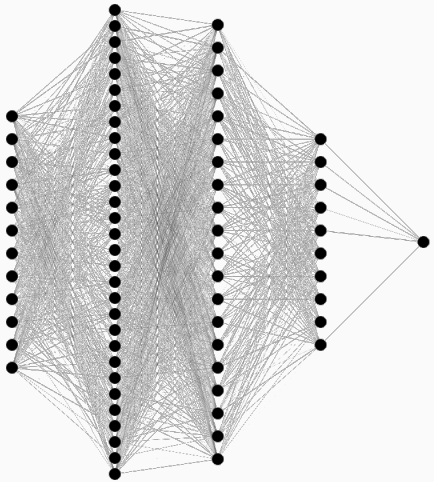
- Extract several slices of the domain
- Average the flow variables in the single fossa





Prediction model: Neural Network

- Input layer 12 nodes
- Hidden layer: 30, 20, 10
- Loss function: Cross-entropy
- Backpropagation: Levenberg-Marquardt
- Output layer: 1 node (binary), 4 nodes (multiclass)



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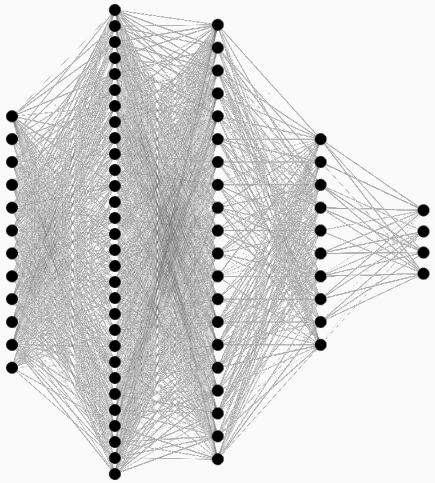

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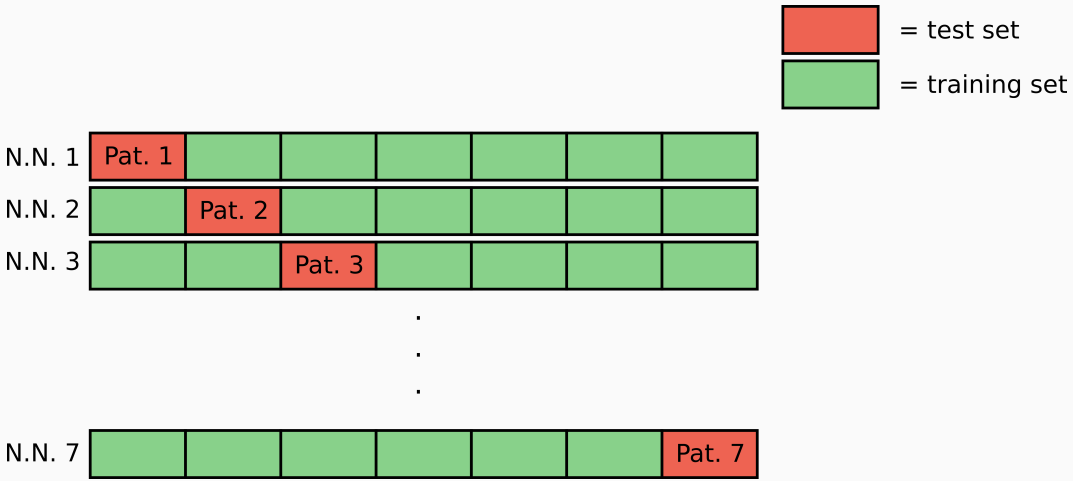
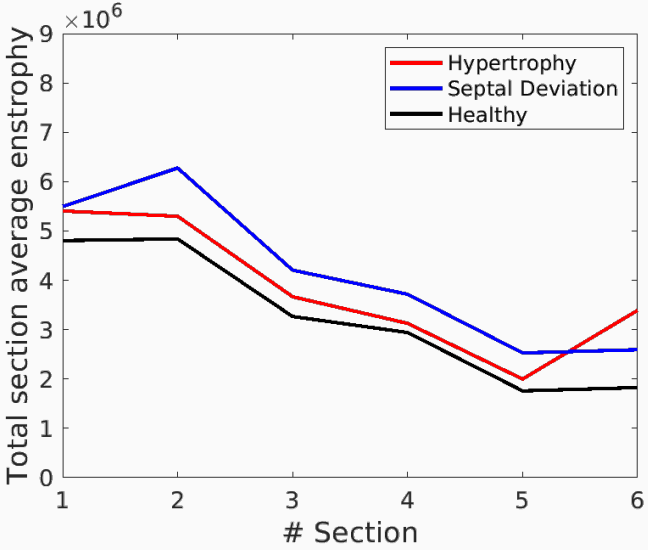
How we test the dataset



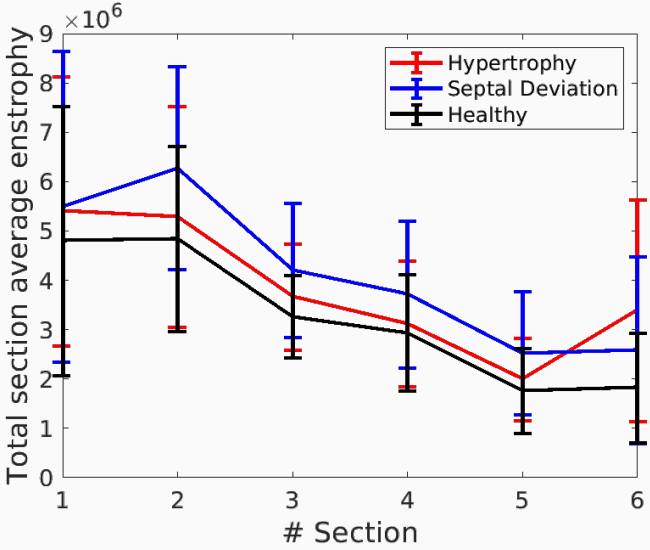
Results

# classes	Dataset size	Feature	Accuracy
2	270	$\lvert\mathbf{U} - \mathbf{U}_{\perp}\rvert$	0.85
4	154	$\lvert\mathbf{U} - \mathbf{U}_{\perp}\rvert$	0.76

What is the NN seeing?



What is the NN seeing?



Final remarks

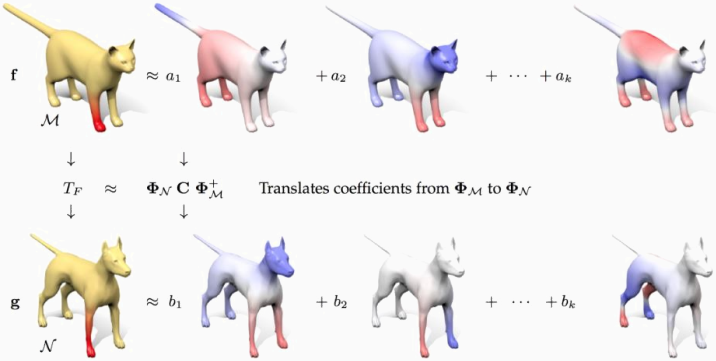
- First step to apply a ML approach on the nose problem
- CFD data used as input of ML algorithm to obtain a medical label
- 2GB of information converted into 12 significant numbers
- Geometry parameterization is a crucial step
- Need for real patient testing

Laplace-Beltrami basis

Eigenfunctions of the Laplace-Beltrami operator:

$$\Delta\Phi_i = \lambda_i \Phi_i \qquad \Delta(f) = -div\Delta(f)$$

- Generalization of Fourier bases to surfaces
- Ordered by eigenvalues and provide natural scale



How to measure the error of a map?

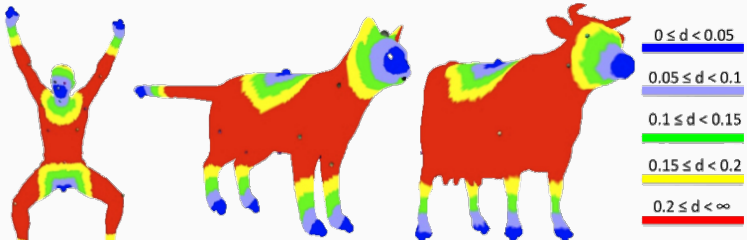
Given:

$$f : \mathcal{M} \to \mathcal{N} \text{ and } f_{True} : \mathcal{M} \to \mathcal{N}$$

Geodesic error defined as:

$$Err(f, f_{True}) = \sum_{p \in M} d_{\mathcal{N}}\Big(f(p), f(p_{True})\Big)$$

Where $d_{\mathcal{N}}\Big(f(p), f(p_{True})\Big)$ is normalized by $\sqrt{Area_{\mathcal{N}}}$

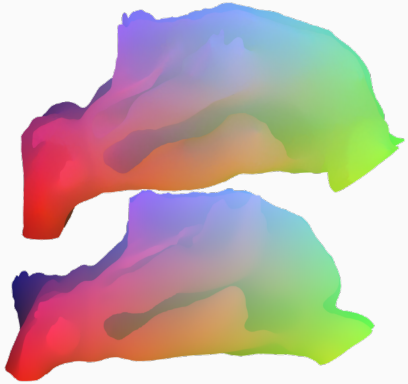


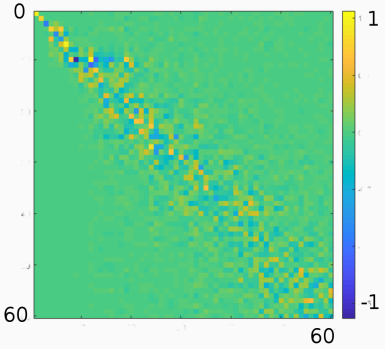
How to compute the map - The pipeline

Given a pair of shapes $\mathcal{M}, \mathcal{N}$:

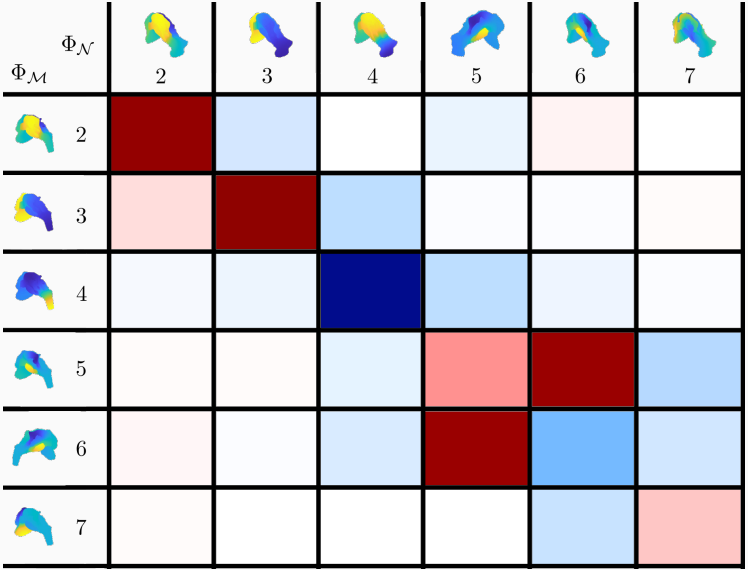
- Compute the first ~ 100 eigenfunctions of Laplace-Beltrami operator: $\Phi_{\mathcal{M}}, \Phi_{\mathcal{N}}$
- Compute descriptor functions (e.g. Wave kernel signature, landmarks, etc.) on $\mathcal{M}$ and $\mathcal{N}$. Express them in $\Phi_{\mathcal{M}}, \Phi_{\mathcal{N}}$ as columns: A, B
- Solve $C_{opt} = argmin_C ||CA - B||^2 + ||C\Delta_{\mathcal{M}} - \Delta_{\mathcal{N}} C||^2$
  $\mathcal{M}$, $\mathcal{N}$: diagonal matrices of eigenvalues of LB operator
- Convert the functional map C_{opt} to a point to point map Π.

Mapping the nose

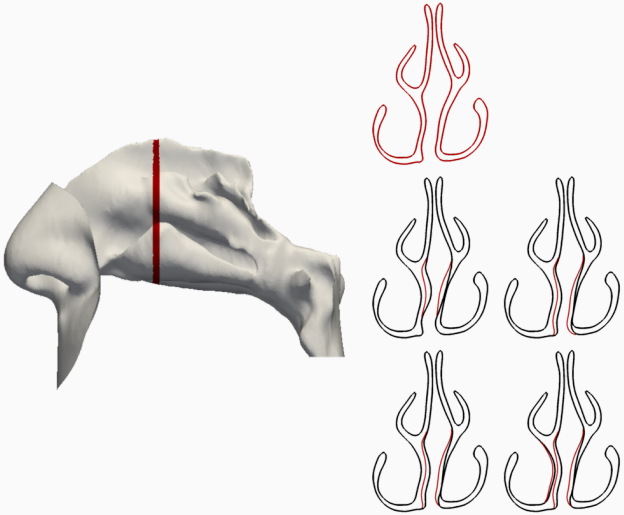




Laplace-Beltrami on the nose

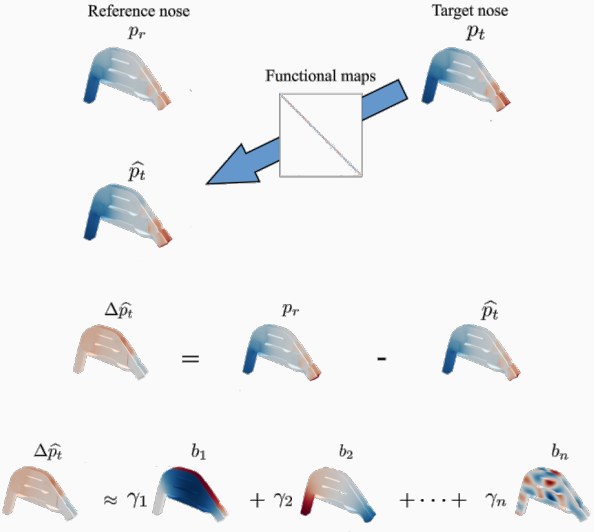


Building pathologies with the doctors - 4 iterations



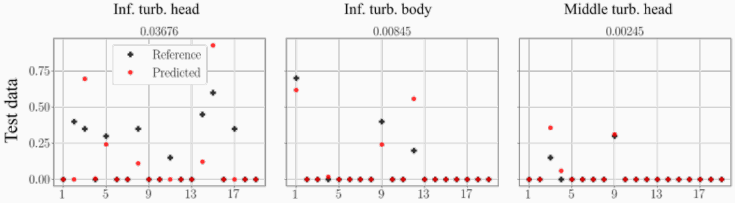
Building pathologies with the doctors - What is on iteration

Mapping thin cans



Classifying thin cans

Geometrical features



Fluid dynamics features