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OPTIMAD engineering

COST, COMPLEXITY AND UNCERTAINTY IN AERODYNAMIC SHAPE OPTIMISATION: A NEW OPPORTUNITY FOR HPC

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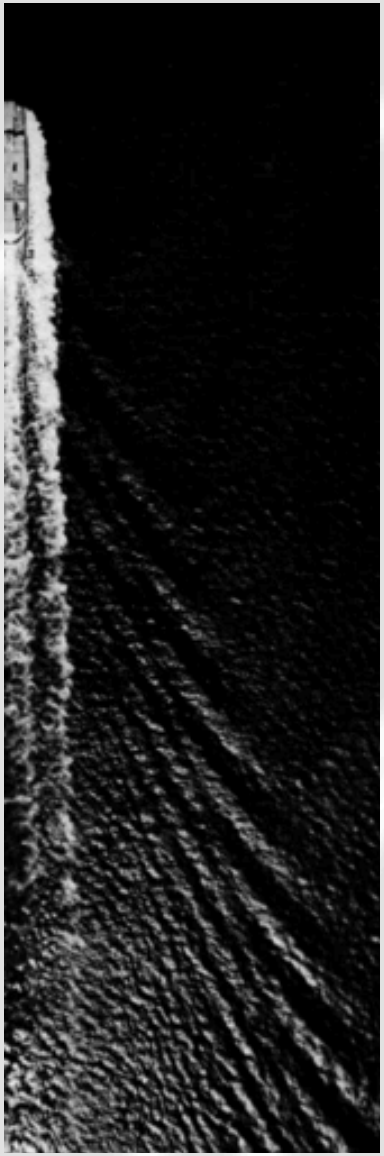
HPC enabling of OF @CINECA, 26/03/2015

Outline



1. **Practical problems in shape optimization**

2. **Enabling of large scale aerodynamic shape optimization**

   - **Shape morphing based on FFD and Level-Sets**
   - **ROM based on POD and domain decomposition**

3. **The Fortissimo SOUTH experiment**

Motivation

2 major burdens to aerodynamic shape optimization

1. **Difficult to set-up (Integration)**
    - identification of parameters, parameterization itself etc
    - totally automatized (geometry creation, pre-processing)
    - especially critical if at advanced design

2. **Expensive (Availability)**
    - computing resources sized for analysis
    - licenses CAD, CFD

The optimization context – Information provided by solver

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Evaluate functional (Comparative)

Industry standard

AV1: O(10) presentations

Evaluate gradient (convergence, direction)

Advanced capabilities

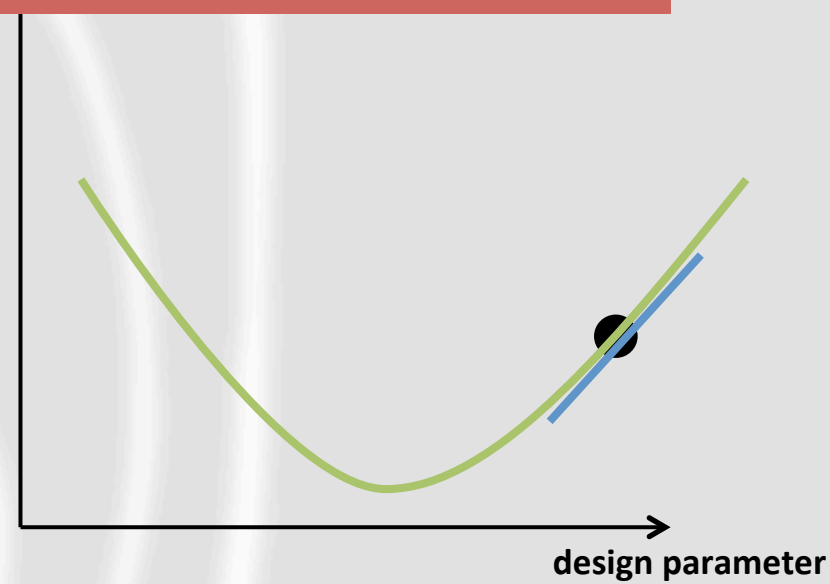
AV1: O(1) presentations

Evaluate Hessian (step, local topology)

Cutting edge

AV1: O(0) presentations

uncertainty: the dark side of CFD
5% error bounds
5% optimization goal



The optimization context – Time & Costs

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cost of real life RANS approx.	**C_{HFM} =2000 cpuh**
# of design variables	**O(10)**
cost of computing	**0.1€/cpuh**
cost of licenses	**0**

2 Level multi-fidelity approach using response surface (neglectable cost) + HFM

global optimization run O(100) - O(1000)	2.e5 – 2.e6 cpuh
computing resources O(10) – O(1000)	2. e2 – 2.e4 h
	1week – 2years -> stop we you have to
	20K€ - 200K€ -> convince your management !!

3 Level multi-fidelity approach using response surface (neglectable cost) + ROM + HFM

cost of Reduced Order Model	$C_{ROM} = \sigma C_{HFM}$
global optimization run O(1000) ROM + O(10) HFM	2.e6 σ + 2.e4 cpuh
necessary saving factor σ O(1month), O(10K€)	**1 – 1/100**

Uncertainty

1. simulation
   - calibration of models
   - hope in “systematic errors” or “conservation of trends”
   - what if your new prototype(!!) performs worse than original??

2. optimal strategy
   - should I use Krigging or ANN?
   - optimal number of initial samples??
   - when should I stop my optimization??
   - best answer we can give today “depends from case to case”

About optimization

- Uncertainty nowadays is mastered by empirical knowledge. Limited basin of validity

- it takes specialized technical staff (like Joel!!)
    i. to build an automatic workflow (geometry??, mesh??, 1month)
    ii. and to do some preliminary investigations (sensitivity, uncertainty) (1.5 month)
    iii. which help you to set up the optimization run (0.5 month)

- very costly (factor 10-100 wrt analysis)

- Automatic shape optimization is used only if strategic

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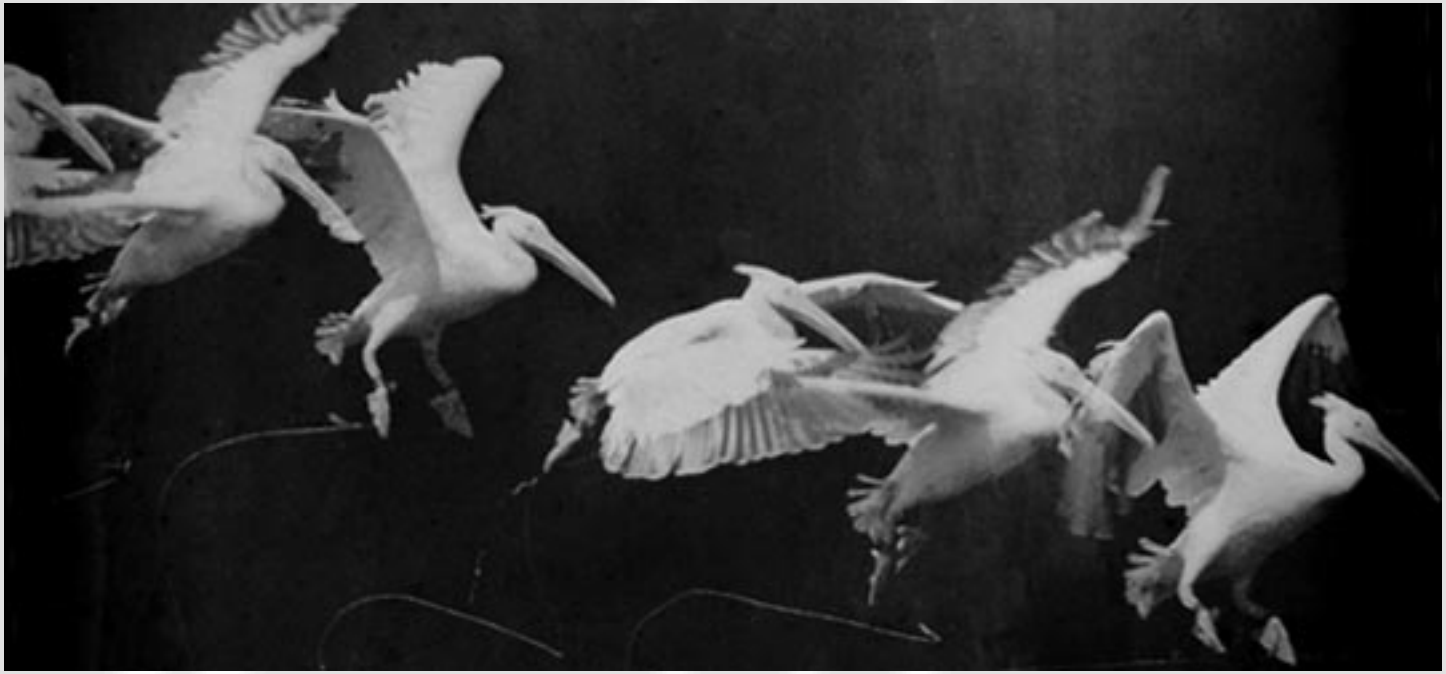


Free-Form Deformation using Level-Sets

Requirements to geometrical engine

Geometry represented as surface triangulation (CAD neutral)

1.parameterization of complex geometries

Free-Form Deformation developed by Desideri et al @INRIA

adaptive parameterization (multi-level etc)

2.constraints handling

C^0, C^1, C^2 conditions on arbitrary boundaries

no-penetration condition

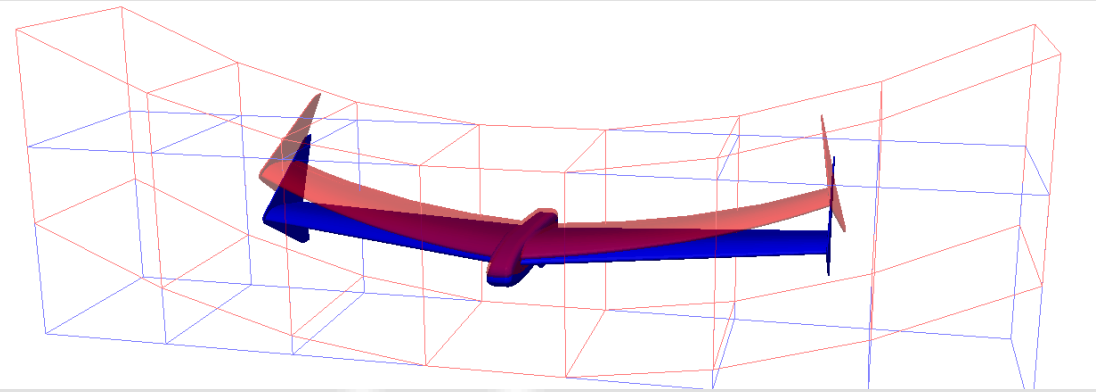
3.features & curvature based surface mesh adaptation

if deformed geometry needs finer surface mesh than original geometry

Constraints via Level-Set information

Free-Form Deformation applies a displacement vector $N_i = S_i + D(S_i)$

difficult to impose regularity conditions on an arbitrary shaped boundary **Γ**



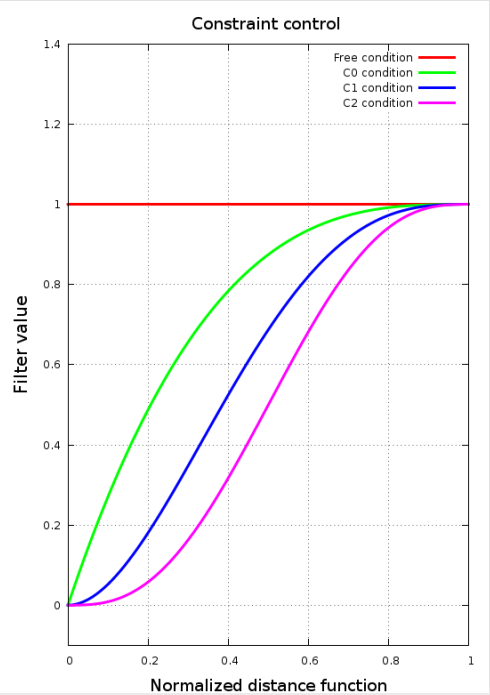
our approach introduces a weight function

$N_i = S_i + w[\ \phi(S_i|\Gamma)\ ]\ D(S_i)$

with $w(0) = 0$ for C^0 condition

with $w(0) = 0$, $w'(0) = 0$ for C^1 condition

with $w(0) = 0$, $w'(0) = 0$, $w''(0)=0$ for C^2 condition



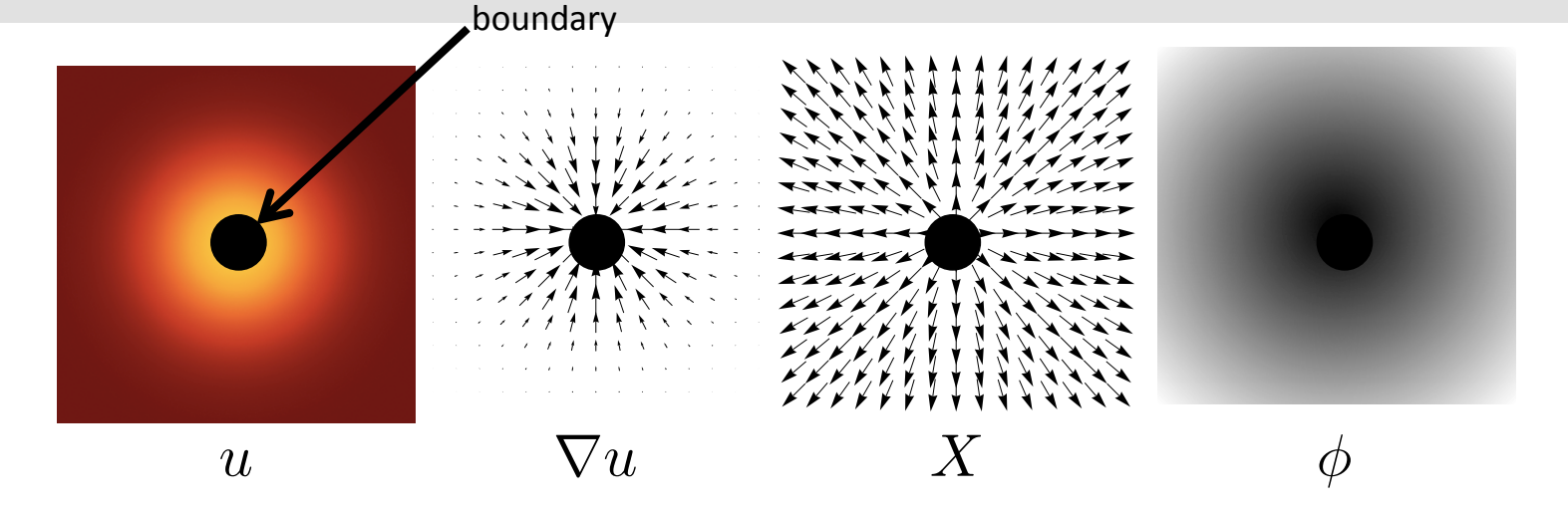
$\phi(S_i|\Gamma)$ must provide topological information

but it is requires that $\phi(S_i|\Gamma)$ is C^0, C^1 and C^2 respectively

Geodesic distance from boundary

resulting function is only C^0, cannot impose higher regularity

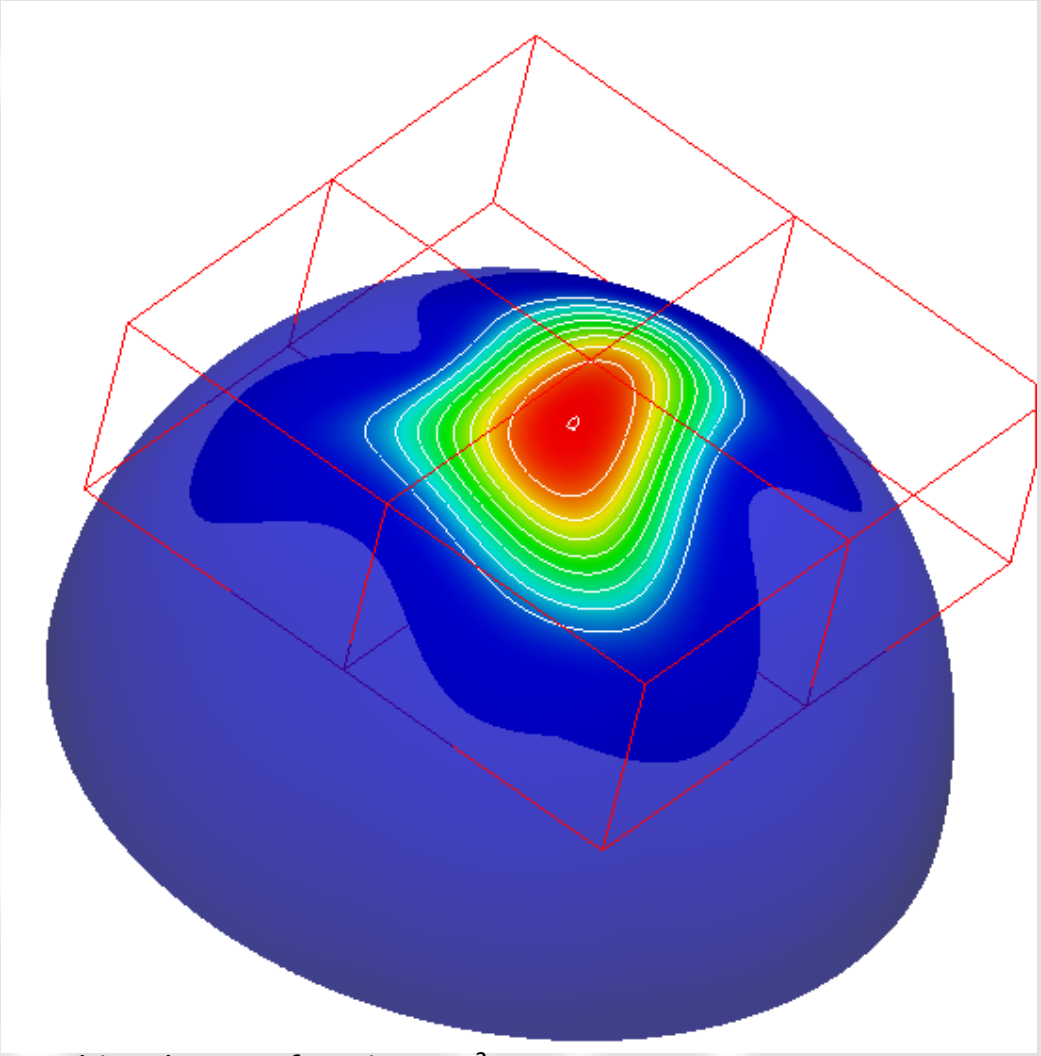
Geodesics based on heat kernel proposed by Crane et al.



1. resovle heat equation $\mathbf{u_{,t} = -u_{,xx}}$ for a given time (parameter for smoothing)
2. calculate **X = -grad u / |grad u|**
3. solve **lap Φ = div grad X**

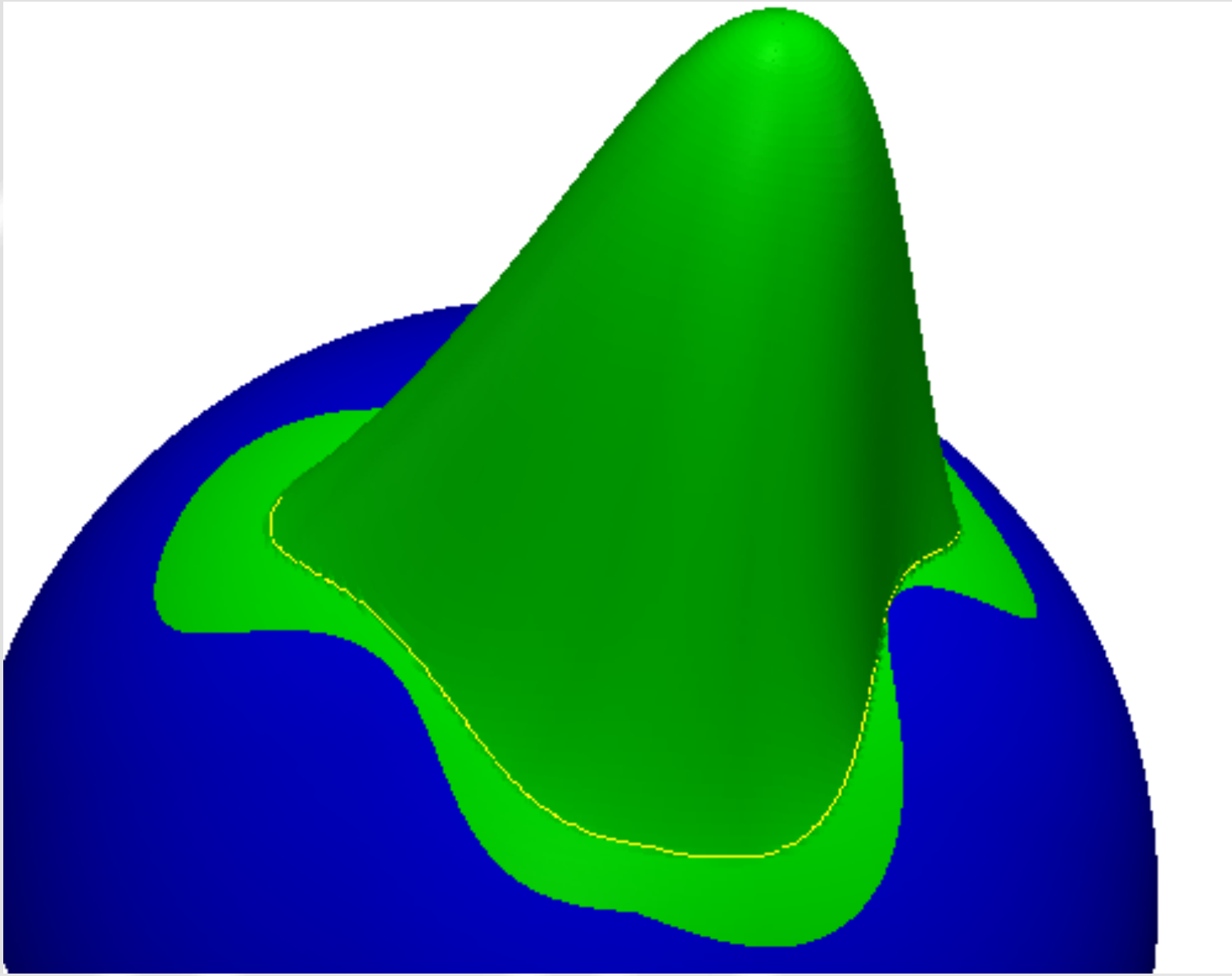
As similar as possible to geodesic distance, but imposes smoothness

Geodesics based on heat kernel proposed by Crane et al.

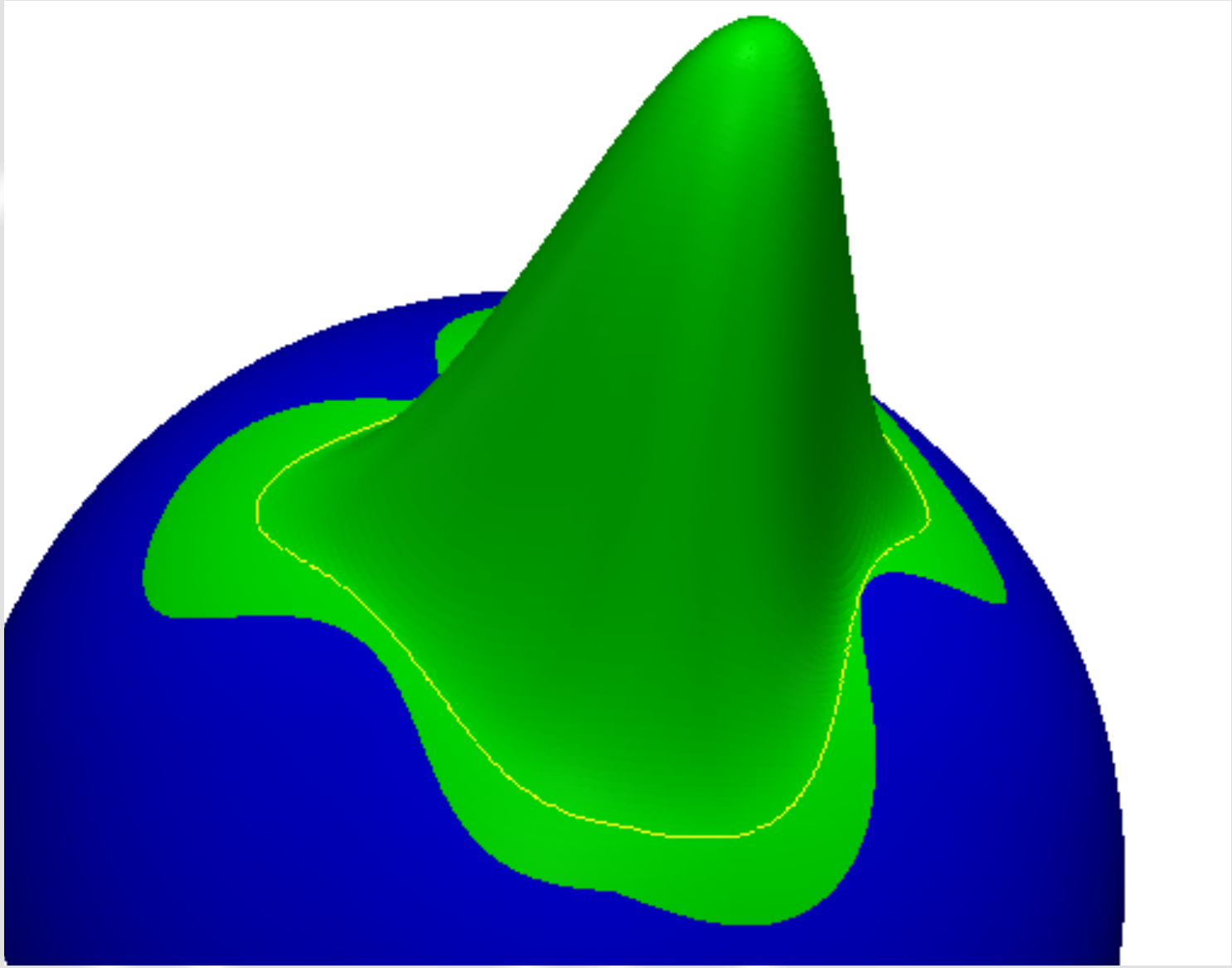


resulting distance function is C^2

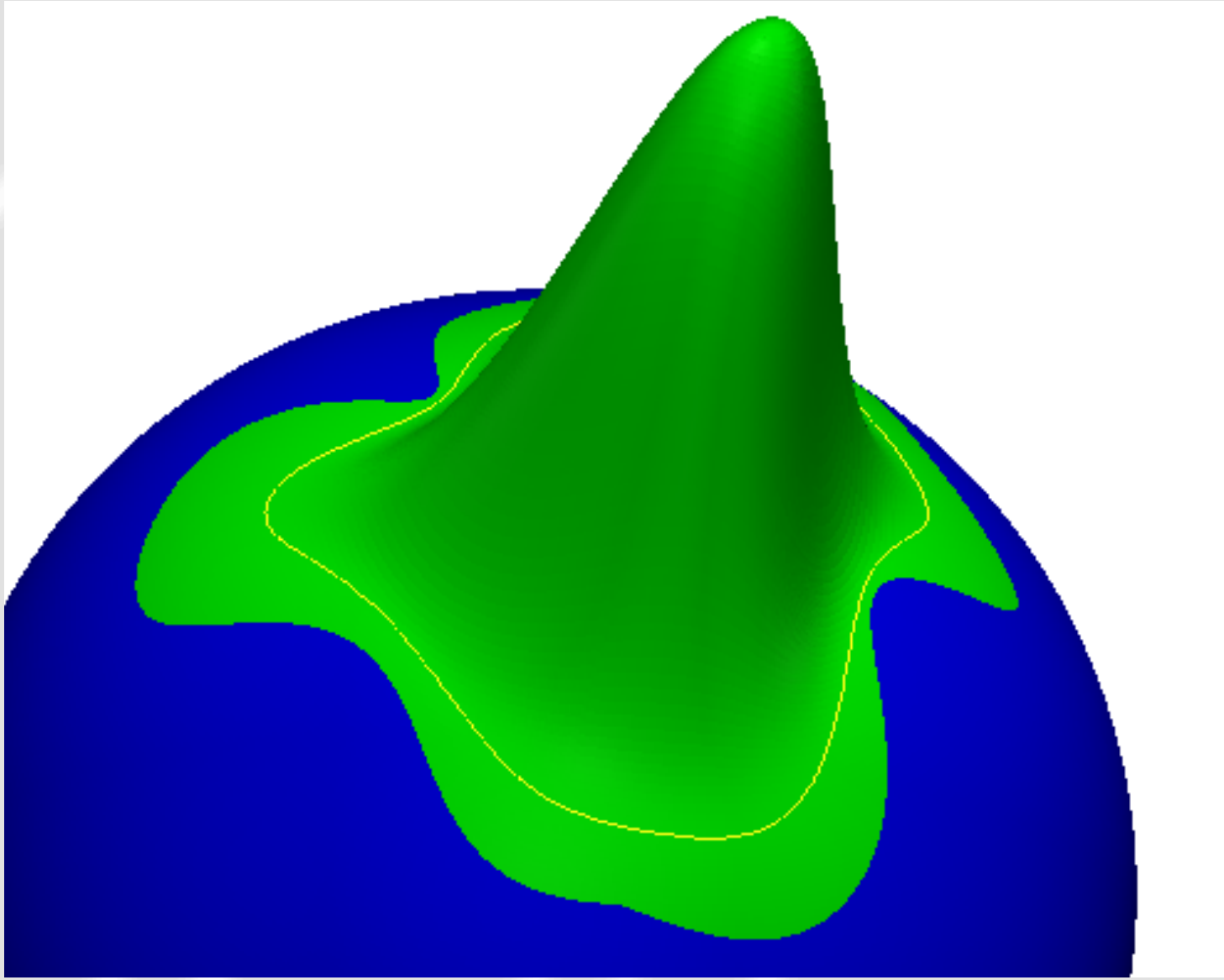
Deformation using C^0 constraint



Deformation using C^1 constraint



Deformation using C^2 constraint



Control of penetration

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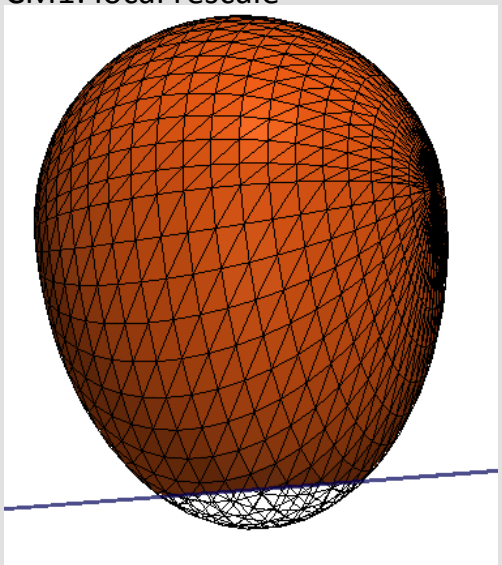
1. User may indicate no-penetration surfaces:
    - surface id
    - distance to be maintained

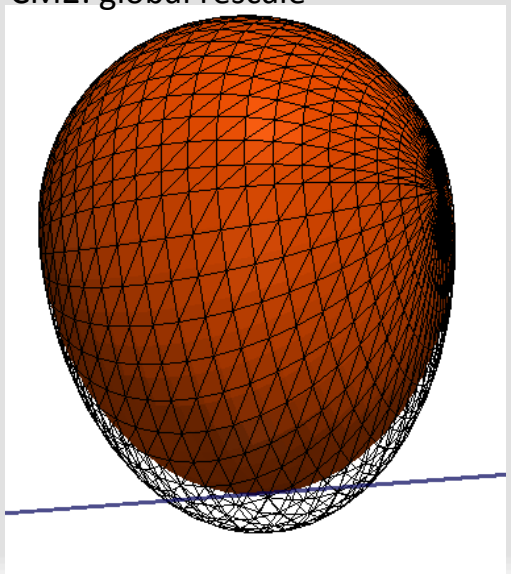
2. Ray-tracing algorithm will calculate maximum displacement for each vertex

3. Two different types of rescaling algorithms available.

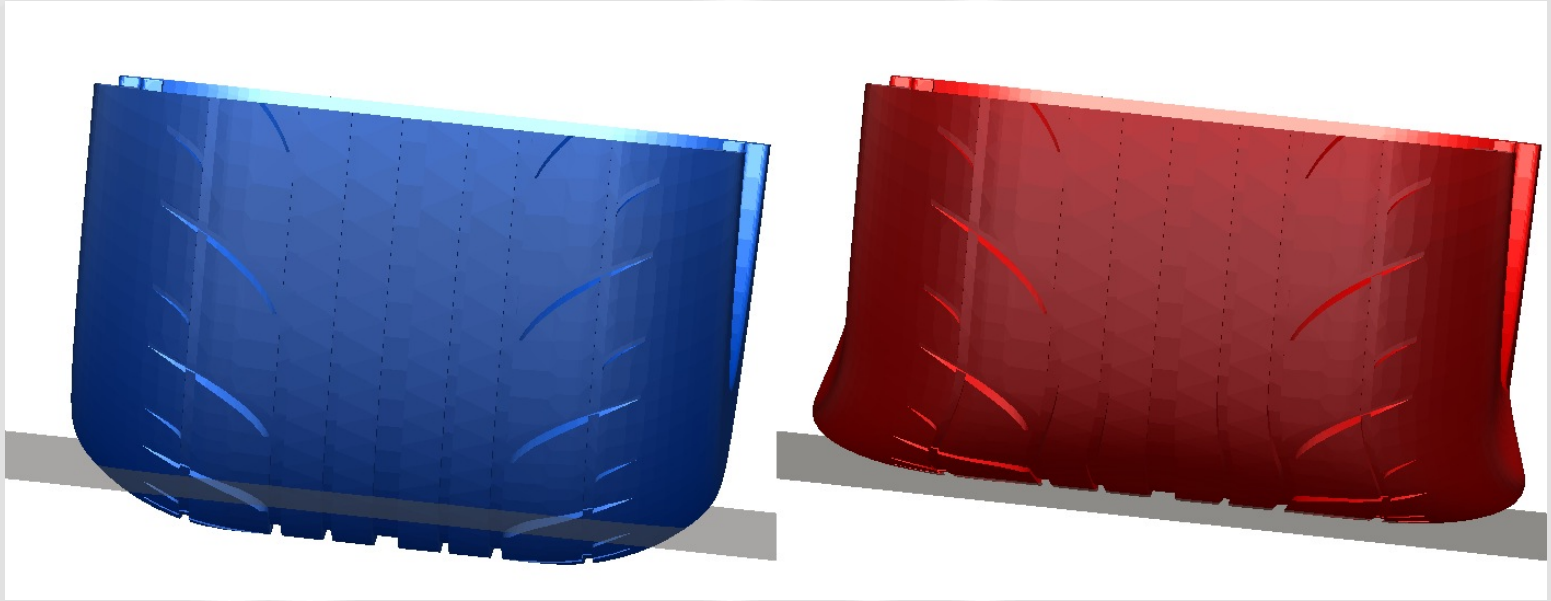
CM1: local rescale



CM2: global rescale

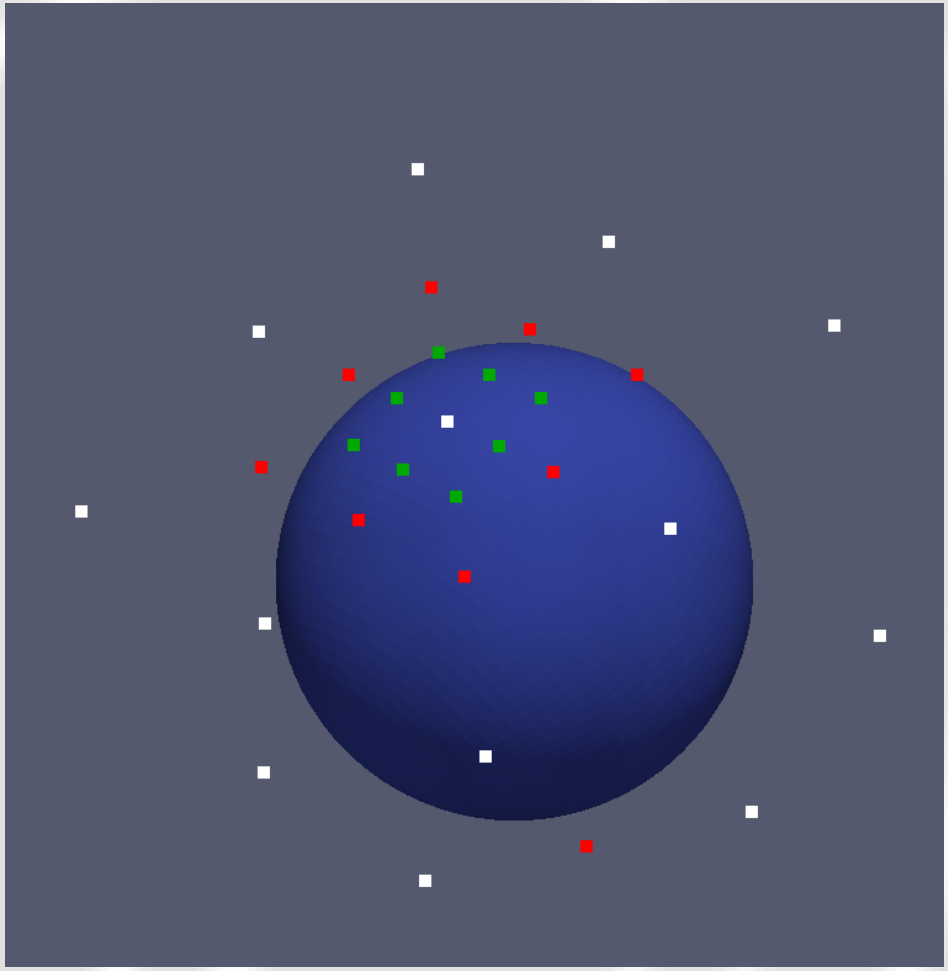


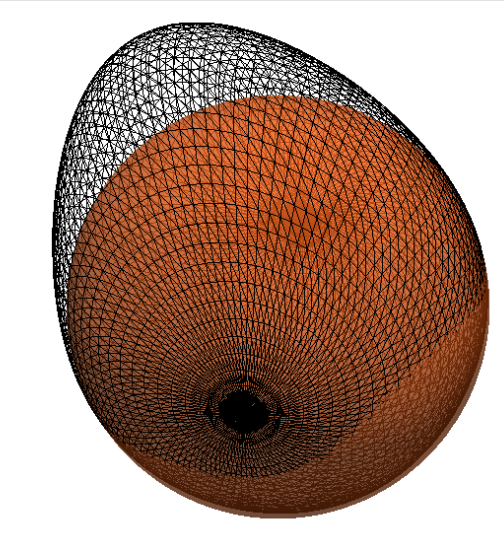
Volume constraints

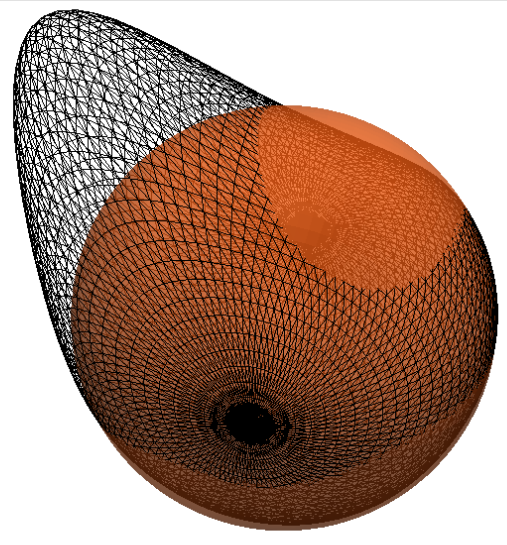


Multi-level parameterization

Goal: Successively refine optimization run by introducing local shape parameters







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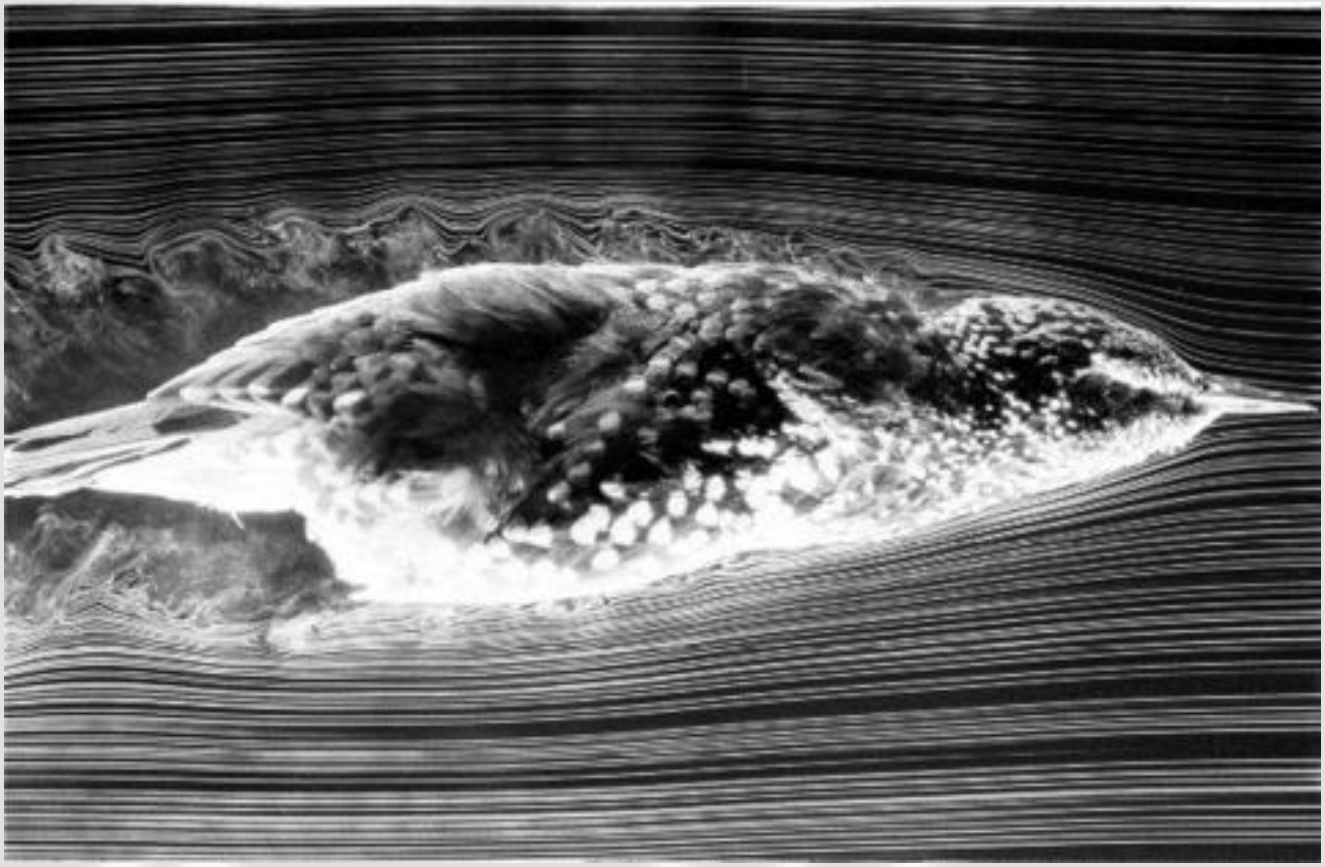

podFOAM: ROM based on POD and Domain decomposition

Sustainable CFD: Domain Decomposition

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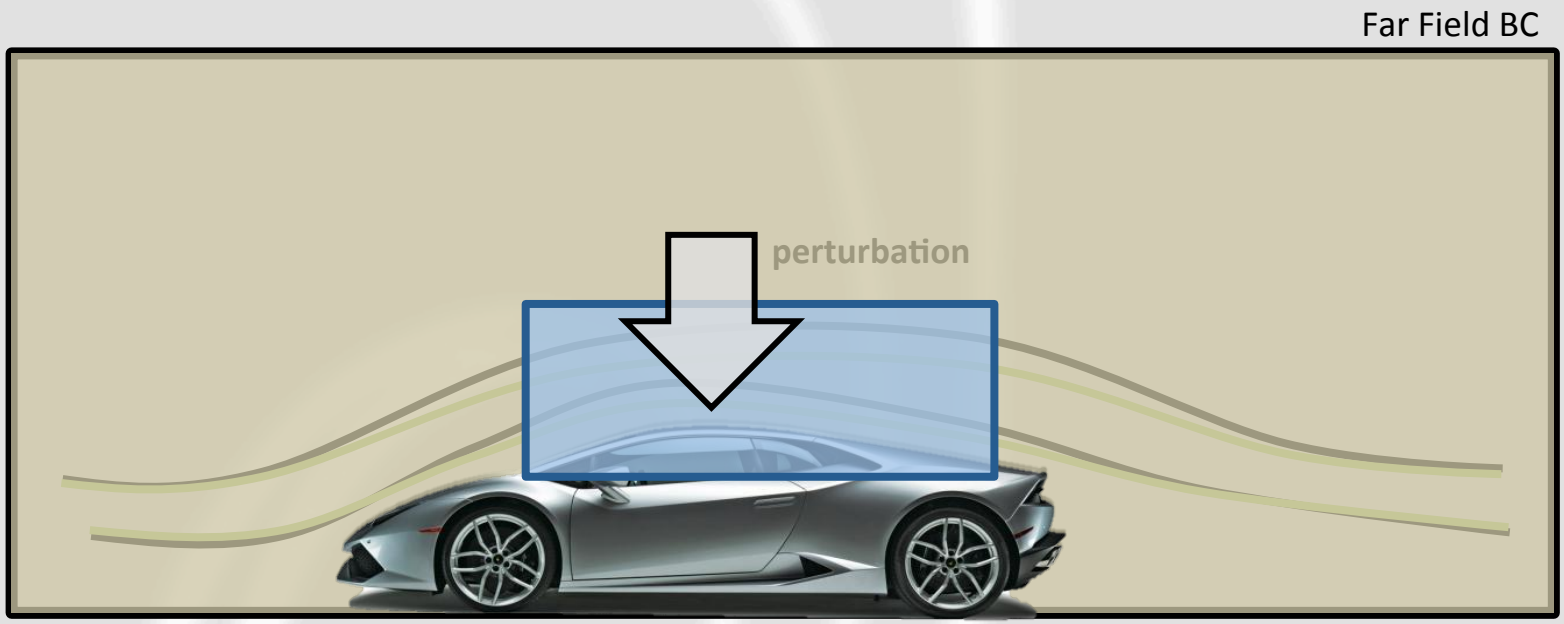
inner zone: use non-linear CFD

outer zone: use simplified model to impose BC to inner zone



Sustainable CFD: Re-Use your data

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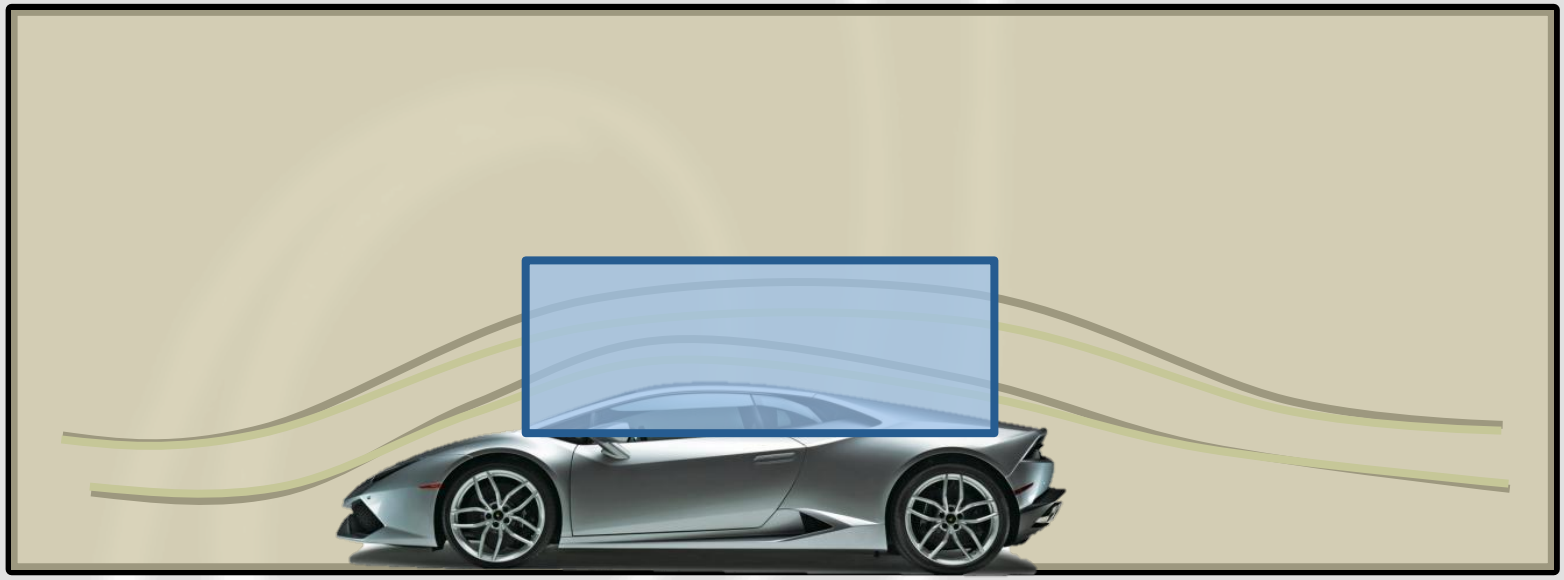
Our assumptions are that

- in the outer zone, the perturbation becomes linear
- the **information needed** for describing the flow field of outer zone, is **already available** in the data stored on your HD

If fulfilled then

- that the new flow field will can be **represented as a linear combination** of the ones on your HD
- **no need to compute**



Sustainable CFD: Re-Use your data: But how?

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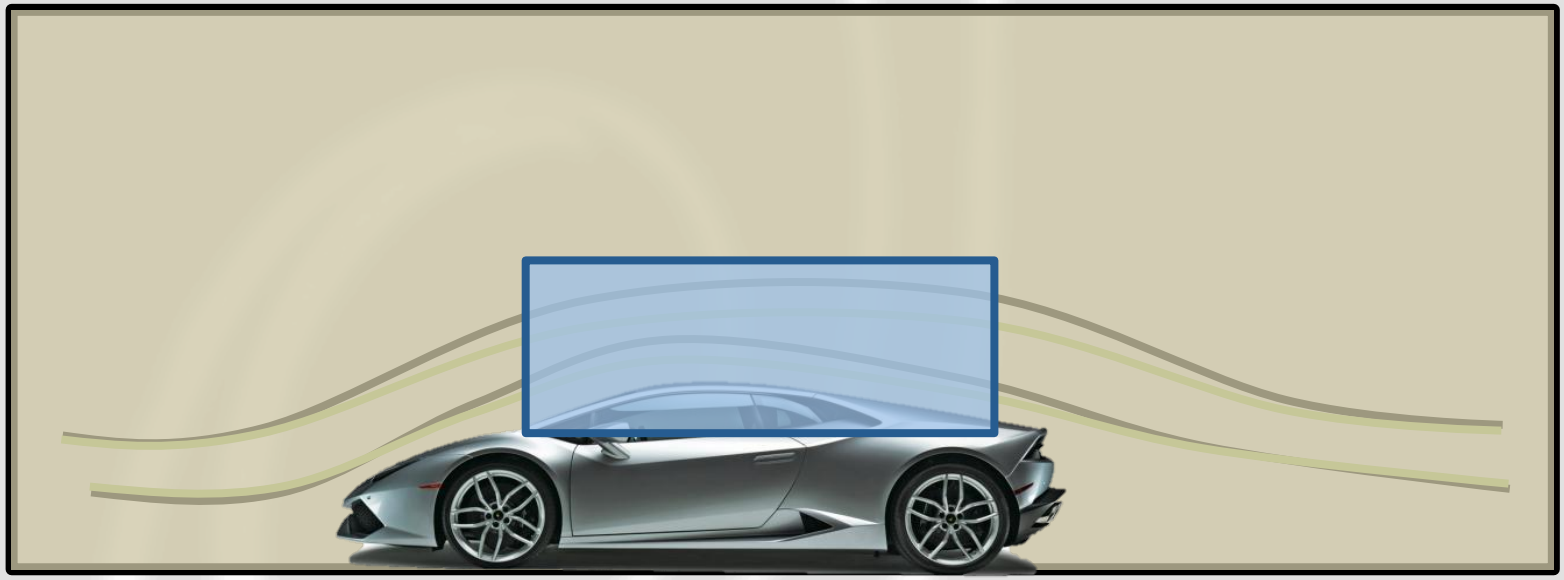
Represent the green zone by Proper Orthogonal Decomposition

- representation of a solution as $\mathbf{u^j_i(x) = \Sigma\, a^j_i\, \Phi_i(x)}$ for i= 0…N
- $\Phi_i(x)$ are orthogonal POD basis, which can be found by solving the eigen-problem of the **snapshot correlation matrix**
- **no series converges faste**r than POD; identification of **coherent structures**; **very few modes** to capture 99% of the energy

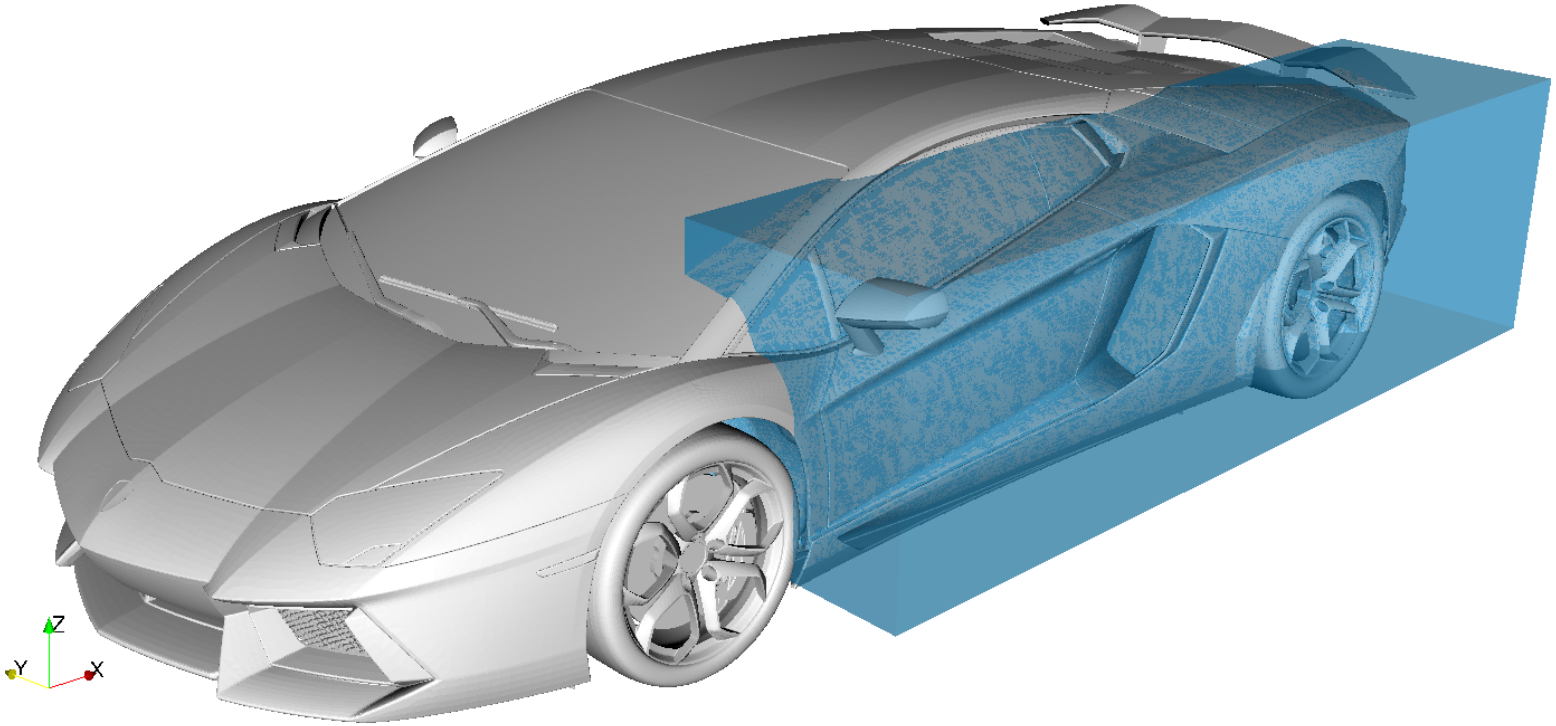
Couple to CFD in blue zone

- through a Least-Squares Problem on the data at the interface
- through a Least-Squares Problem on the residuals at the interface or domain

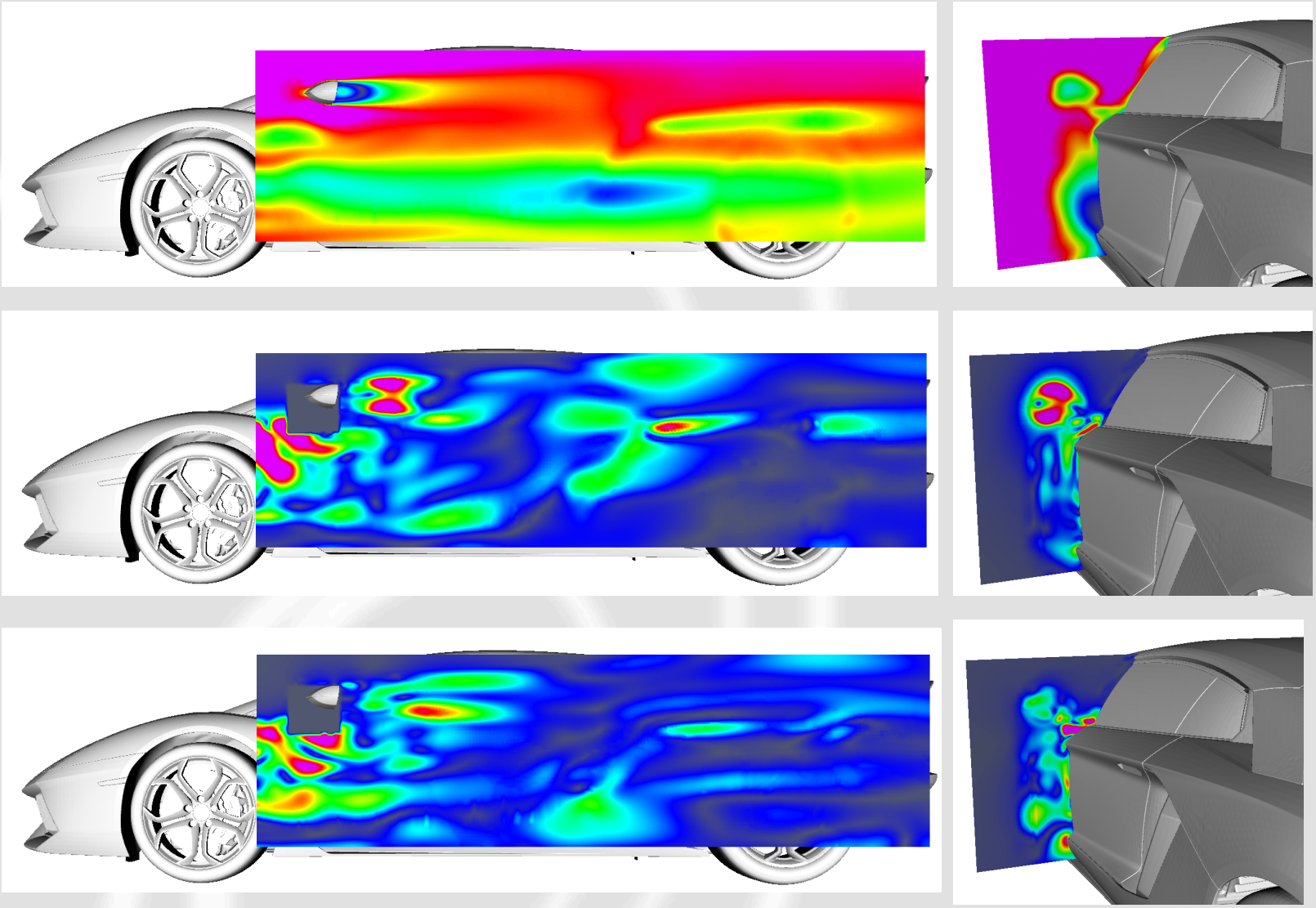


Validation of POD: case 1 mirror

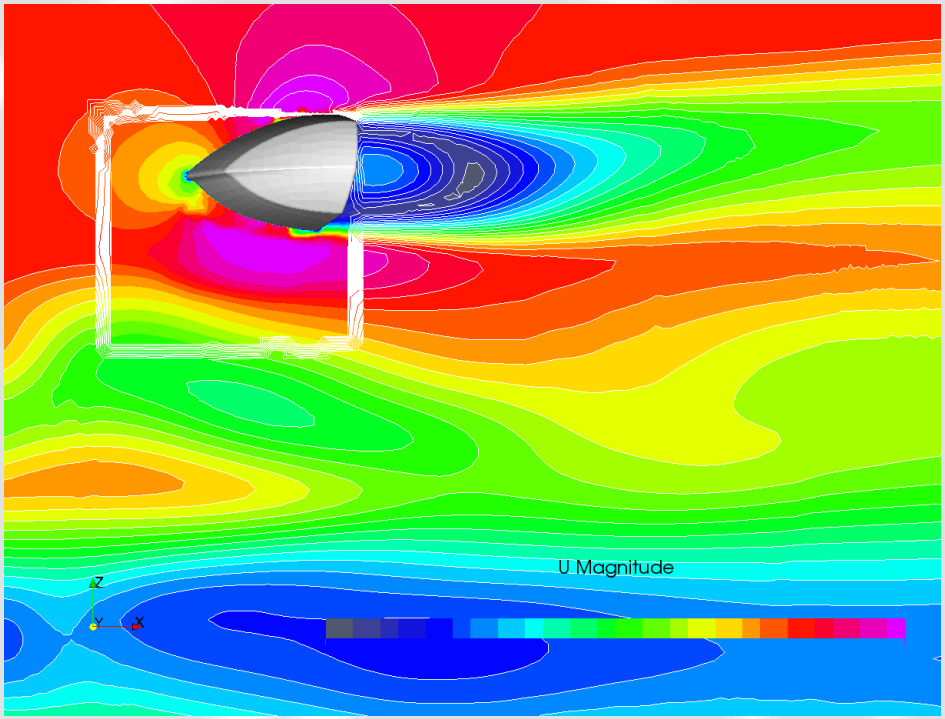
RANS calculations
k-omega TM

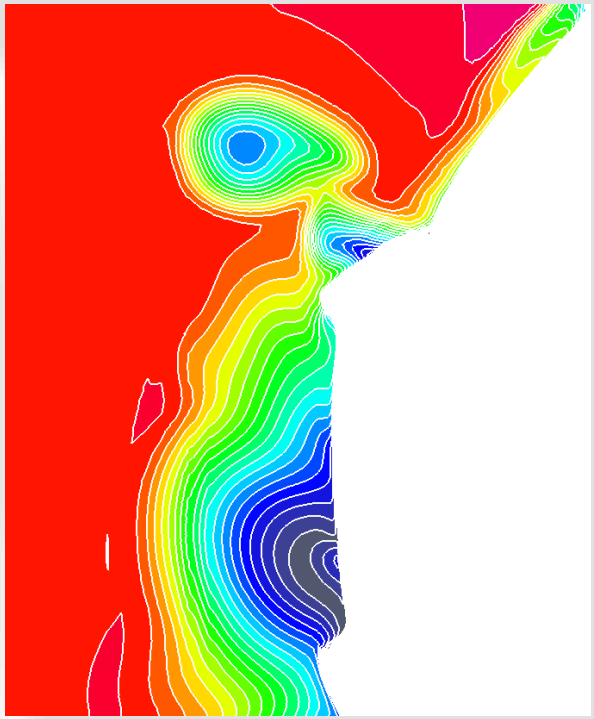


Velocity modes 0, 1, 2



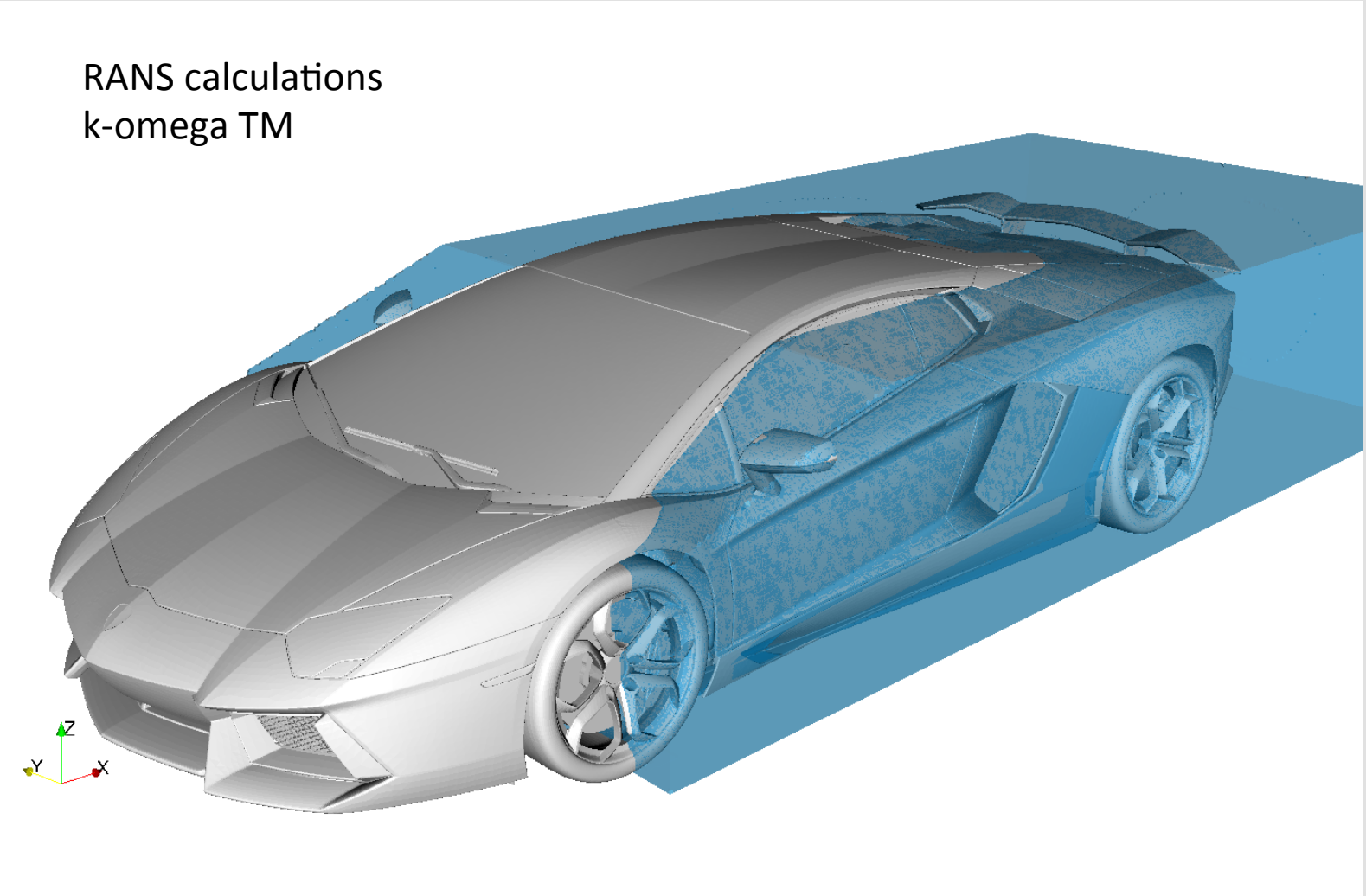
Reproduction of a case included in the database



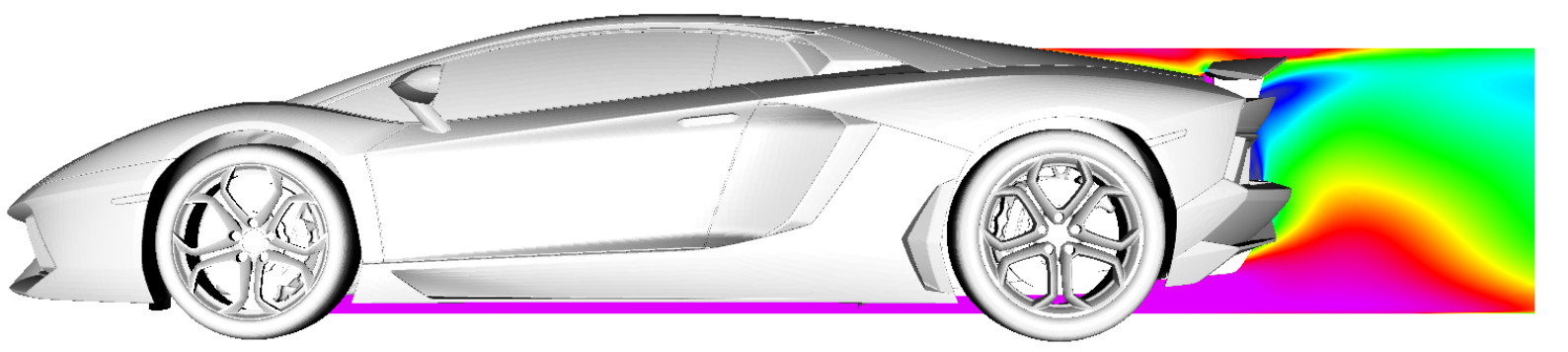


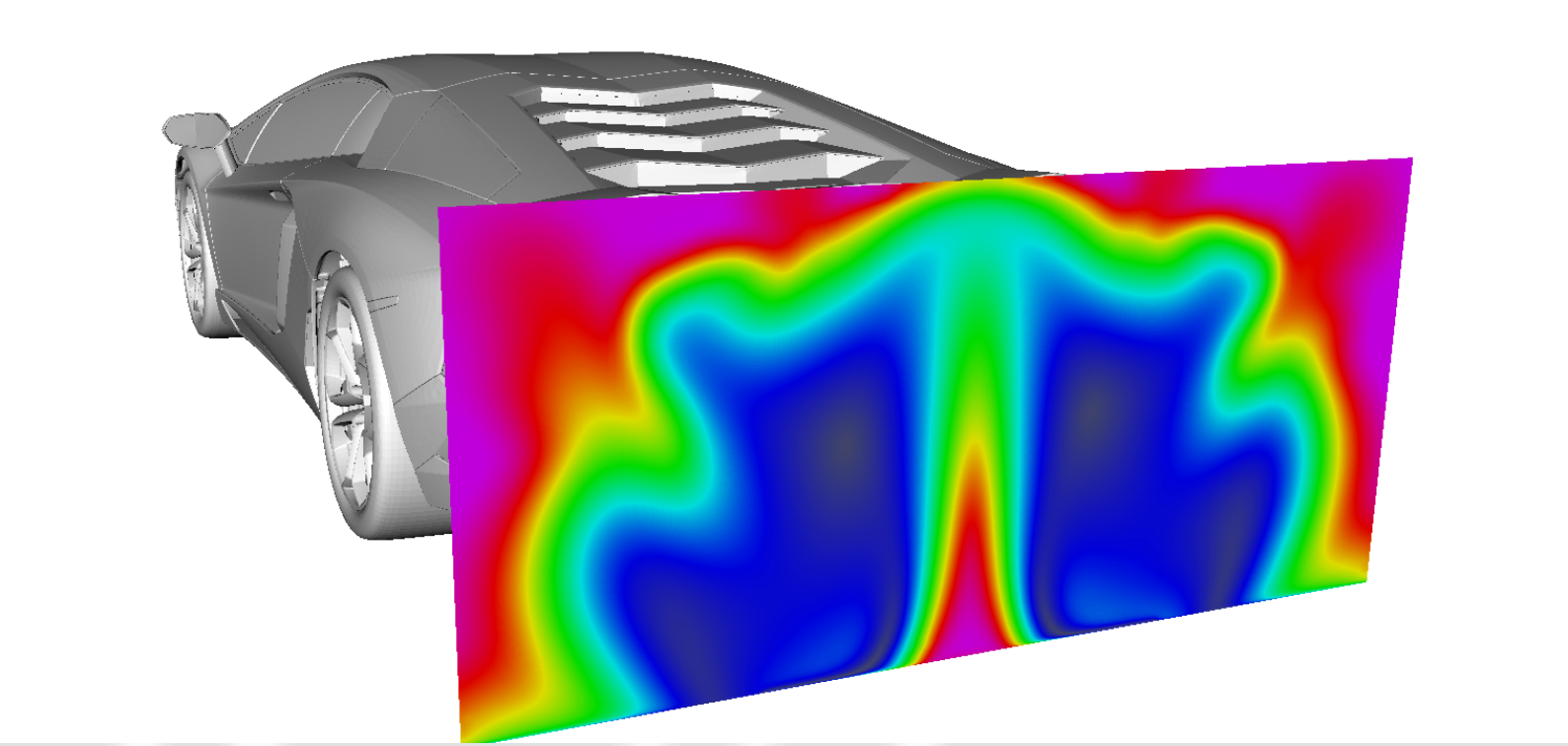
white isolines: ROM, colormap: CFD

Performance of POD: optimization of rear diffusor

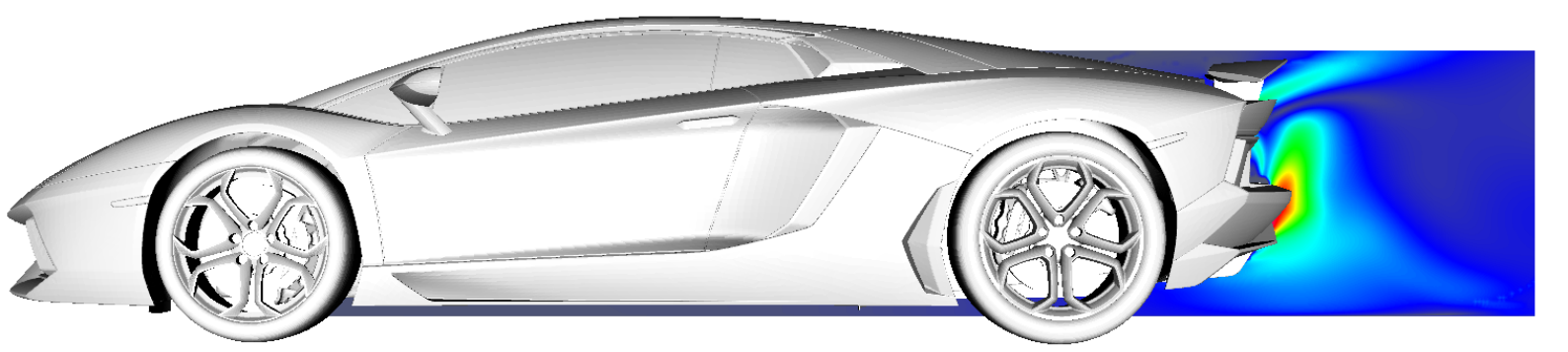


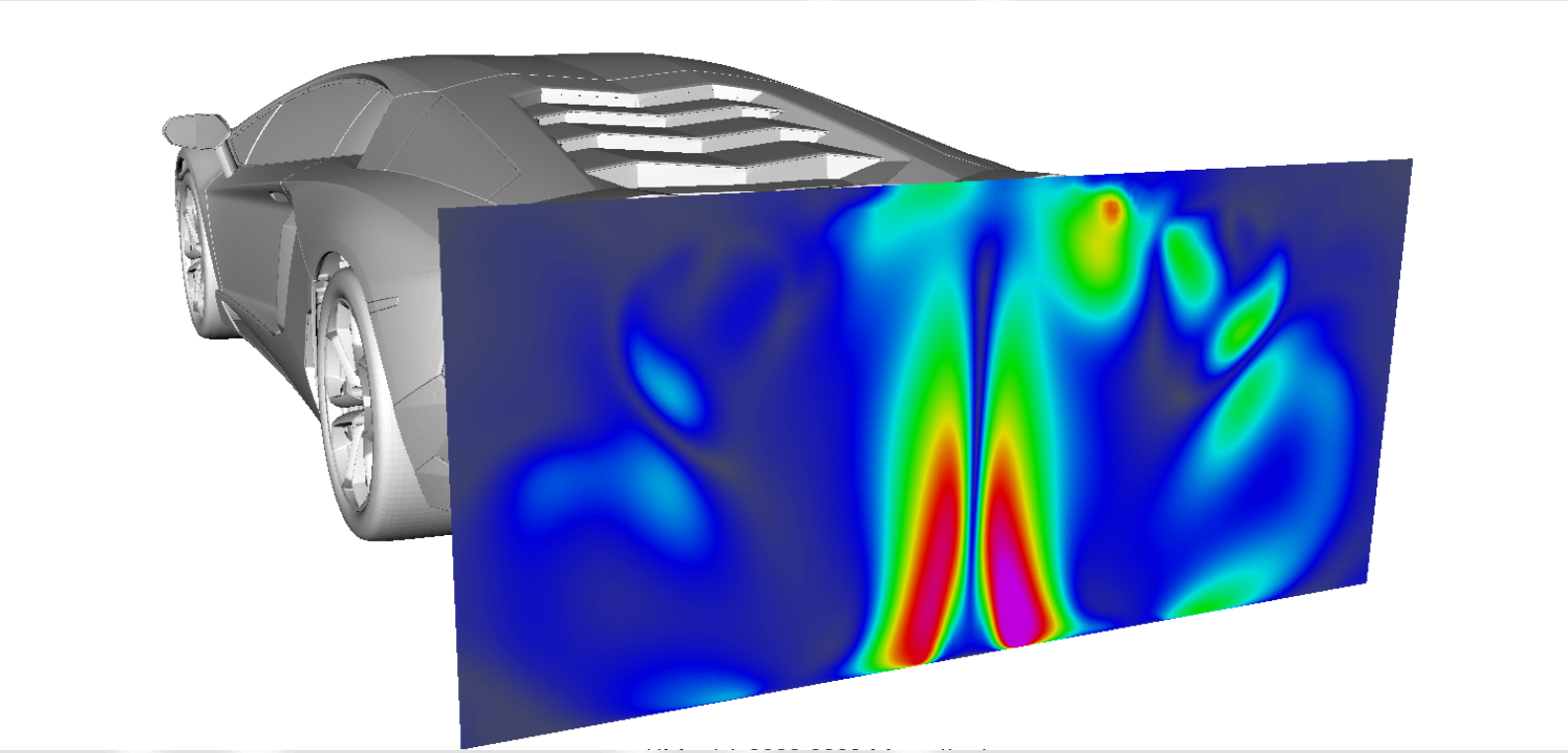
Velocity Mode 0



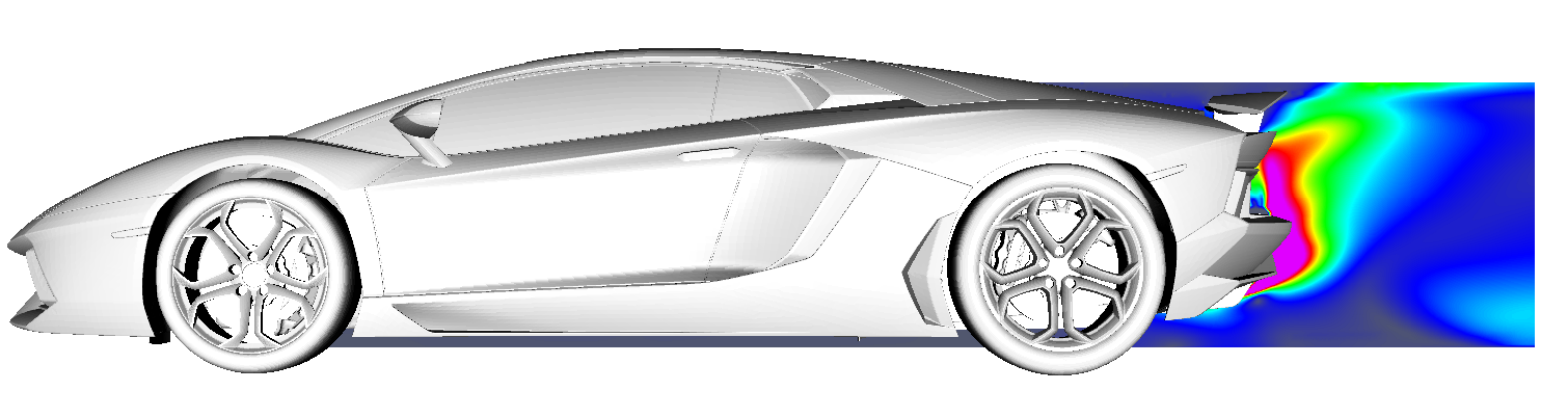


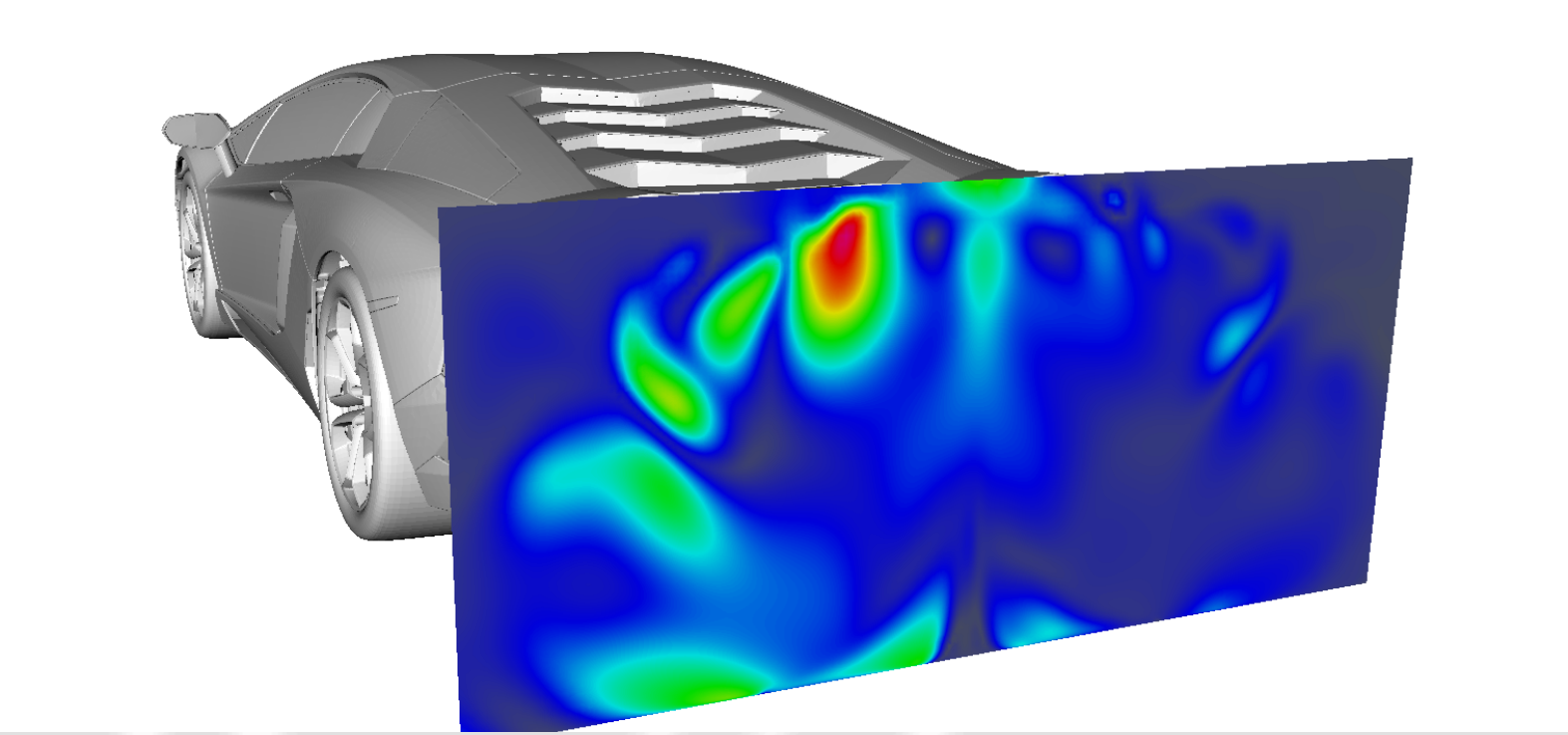
Velocity Mode 1



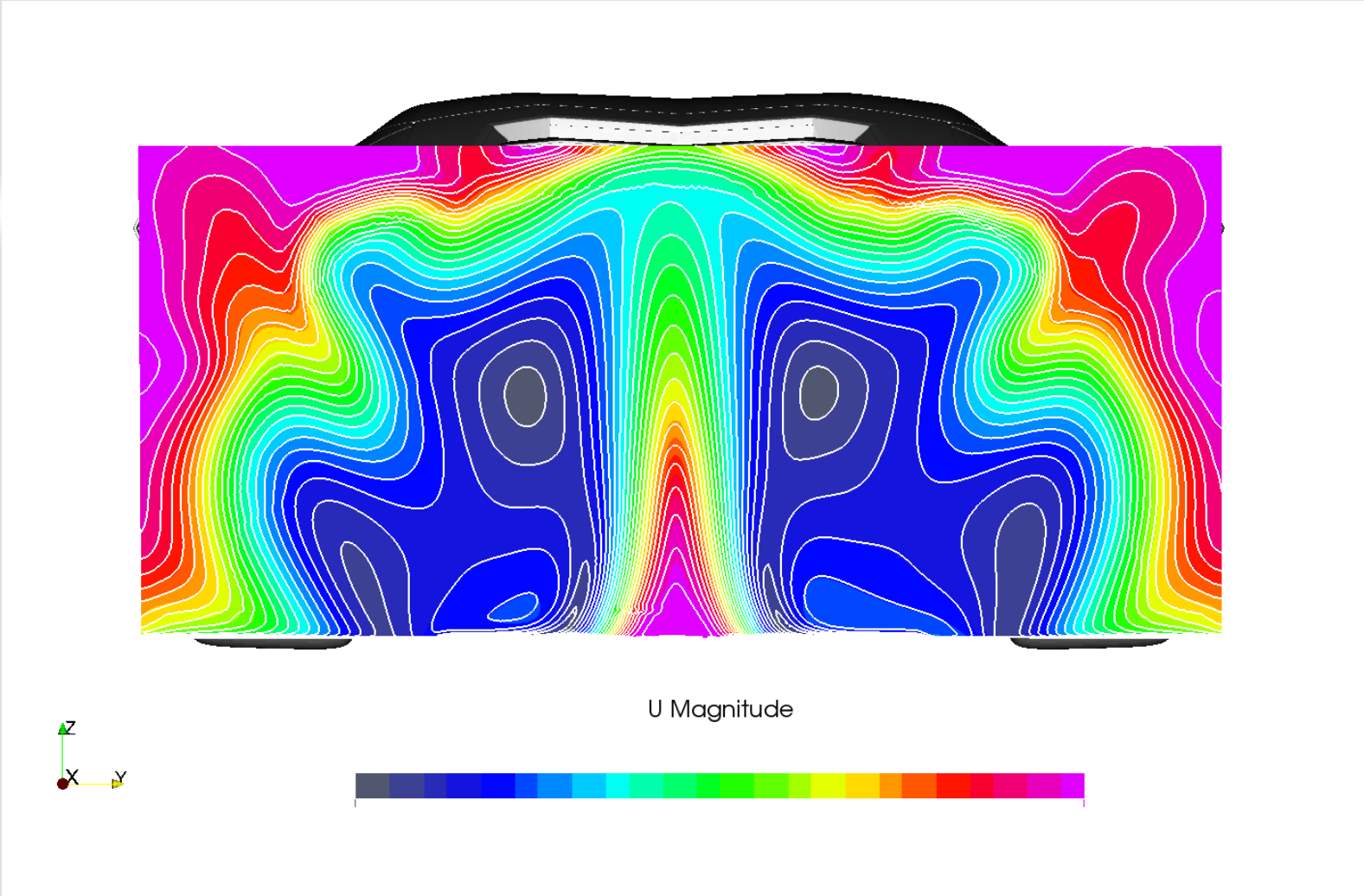


Velocity Mode 2



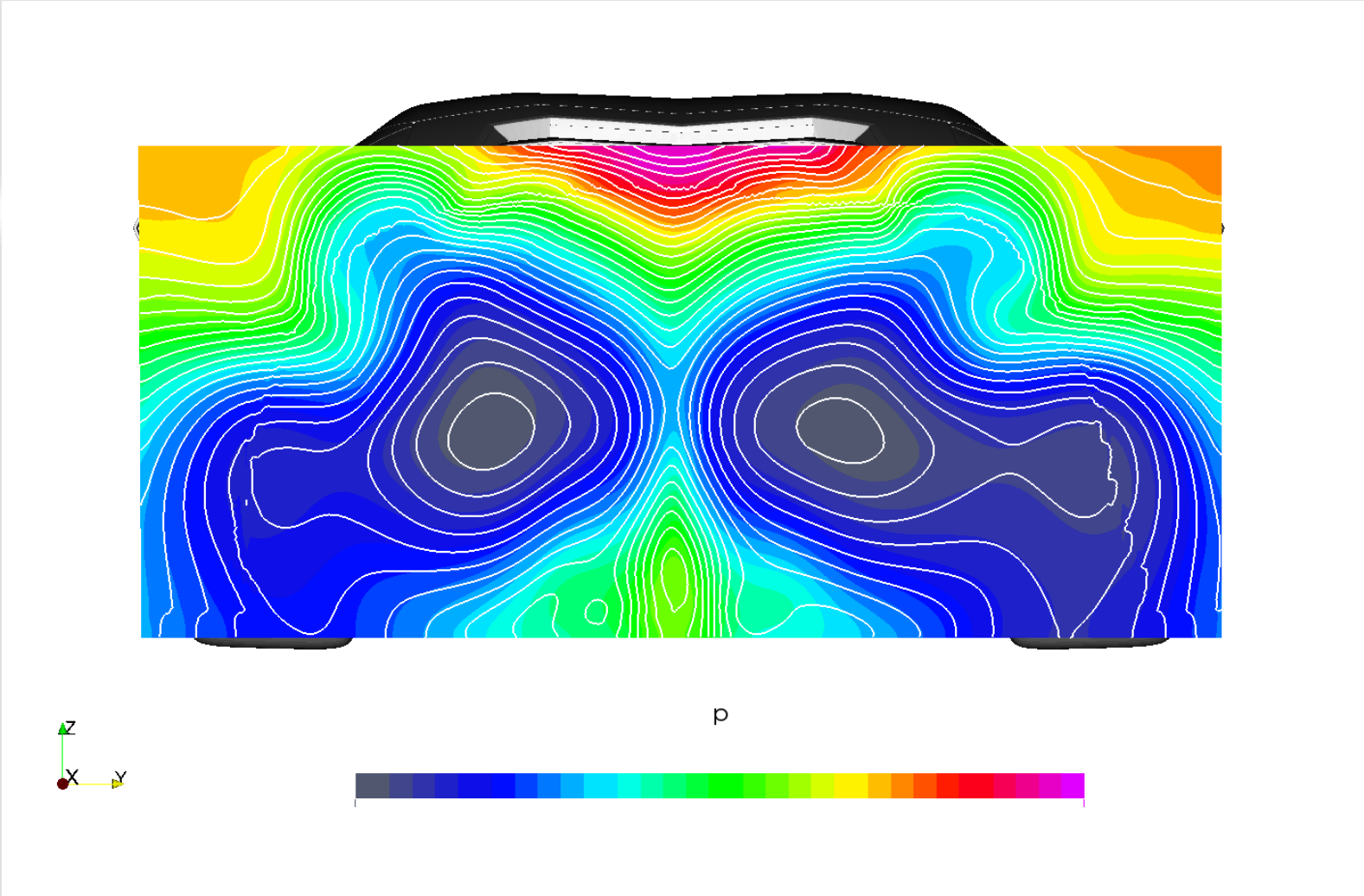


Reproduction of case NOT included in database: velocity



white isolines: ROM, colormap: CFD

Reproduction of case NOT included in database: pressure



white isolines: ROM, colormap: CFD

TC2: Performance Summary

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	original	**hybrid**
cost		
# of grid points	40M - 120M	4M – 9M
iterations	10K	2K
cpuh	1.5K – 2.5K	45 – 75
cost reduction	1	**O(50)**
accuracy		
drag	1.	1.005
lift	1.	0.93*
loss of accuracy	**<1% drag, <10%lift**	

***dependency on grid**

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An outlook: SOUTH experiment within FORTISSIMO

The SOUTH experiment

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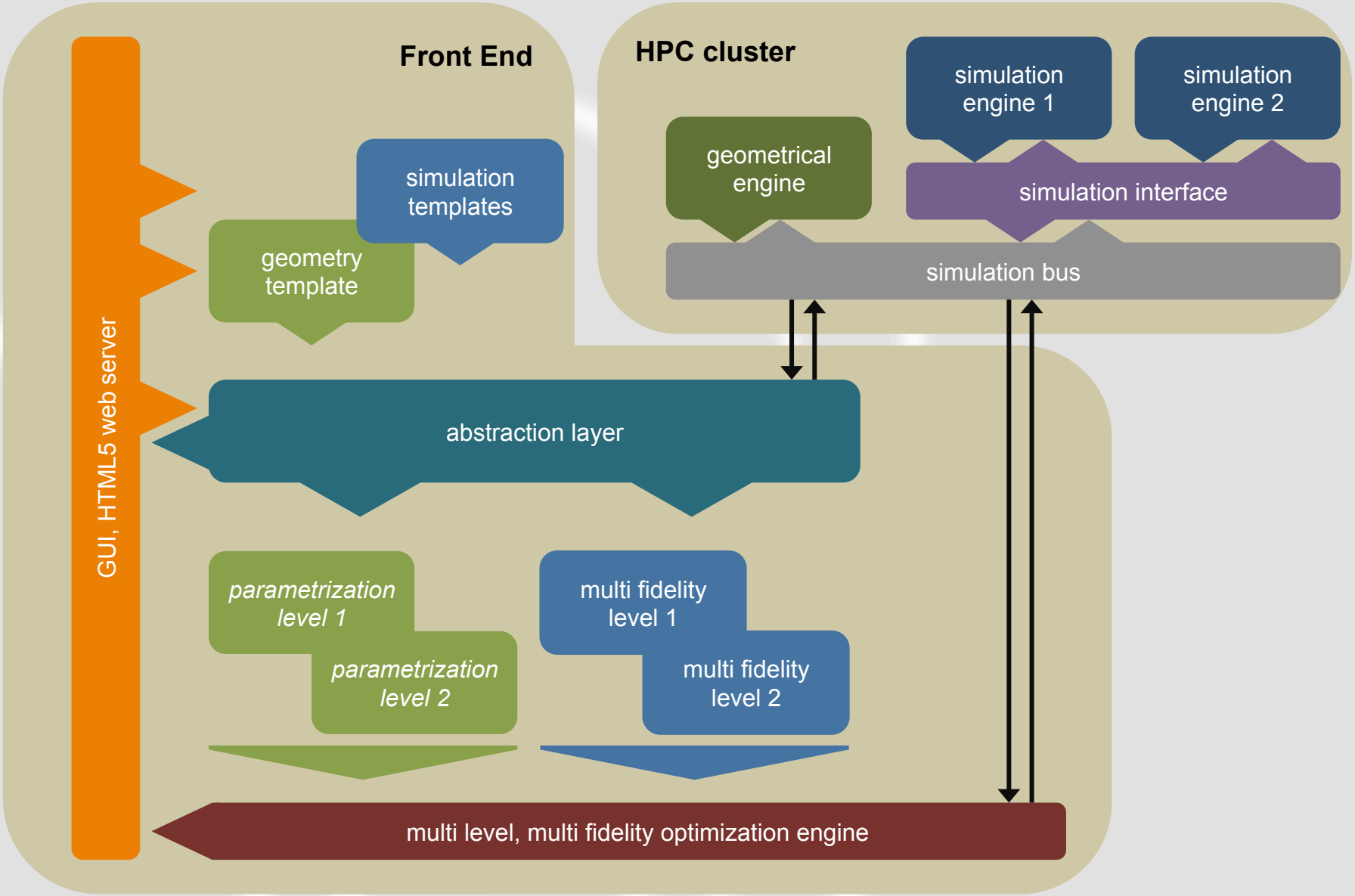
Shape Optimization under Uncertainty through HPC cloudS

- Enable easy setup of optimization runs to SMEs through massive usage of HPC resources.
- Target: Expert user in analysis, un-experienced in optimization
- User provides intuitive information:
    1. time and budget
    2. simulation templates
    3. indication of uncertain and tuneable parameters reference data if available (e.g. wind tunnel)
- automatic setup the optimization run, by exploiting the simulation parameter space through HPC
- Accessible via web using HTML5 protocol, Software-as-a-Service paradigm
- Compatibility with any CAE solution (testing using OpenFOAM)

The SOUTH platform



Contribution per partner

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Optimad	GUI, interaction with geometry	geometrical engine
Univ Strathclyde	abstraction layer	multi level,& fidelity optimization engine
CINECA	GUI, IO, setup of workflow	simulation bus & interface
Lamborghini	templates	specifications & testing

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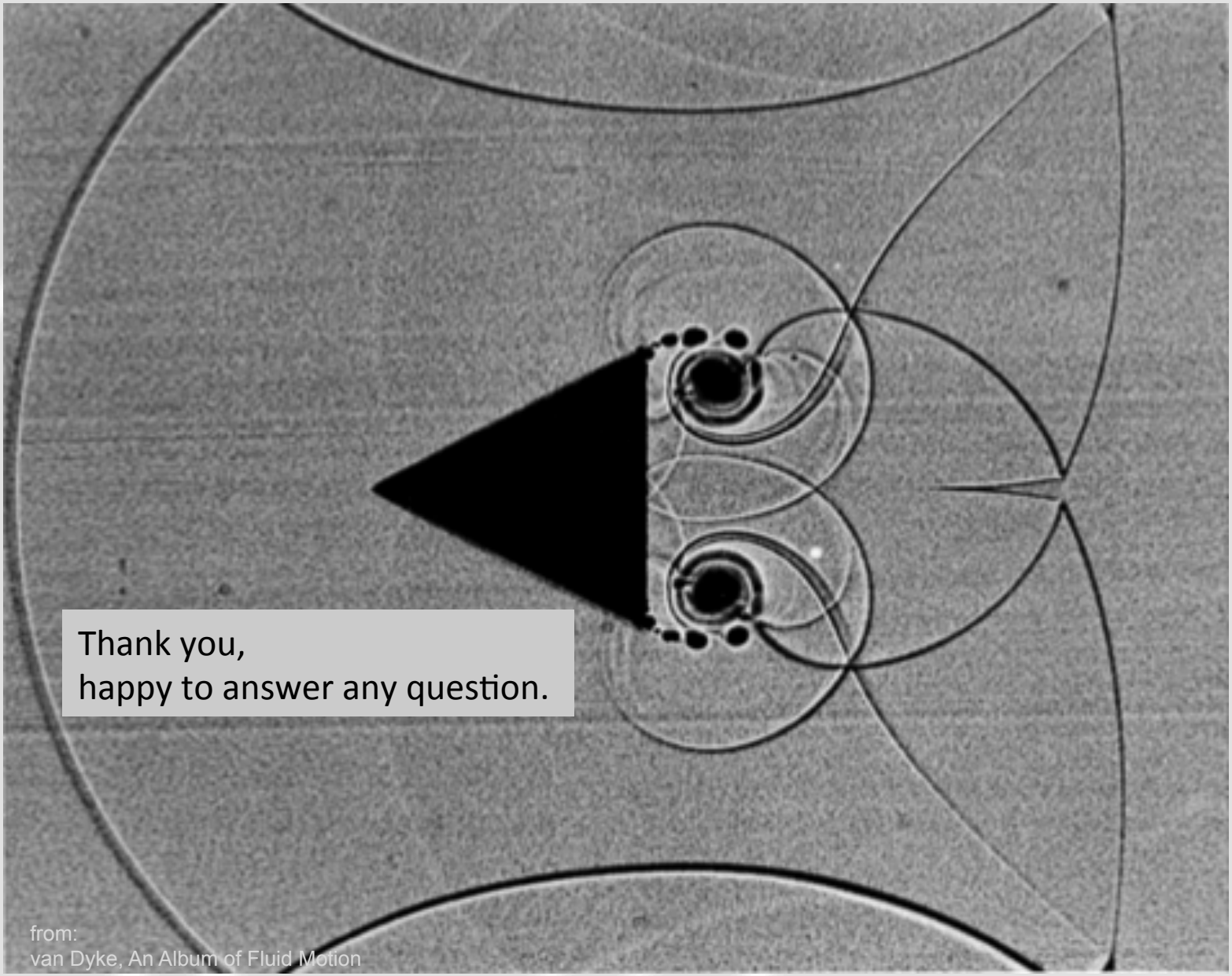

Thank you,
happy to answer any question.

from:
van Dyke, An Album of Fluid Motion