NATIONAL TECHNICAL UNIVERSITY OF ATHENS

Lab. of Thermal Turbomachines -
Parallel CFD & Optimization Unit

Combining an OpenFOAM-based Adjoint Solver with RBF Morphing for Shape Optimization Problems on the RBF4AERO Platform

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The RBF4AERO project

Project details:

- Program: Small or Medium-scale focused research project
- Type of Project: FP7 Cooperation Work Program: Aeronautics and Air Transport (Design and Tools)
- **9 partners** from **5 countries** (Italy, Belgium, Greece, Slovenia and Turkey

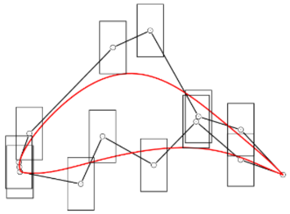
Aim: develop **an integrated numerical platform and methodology** to efficiently face the most demanding challenges of aircraft design and optimization.

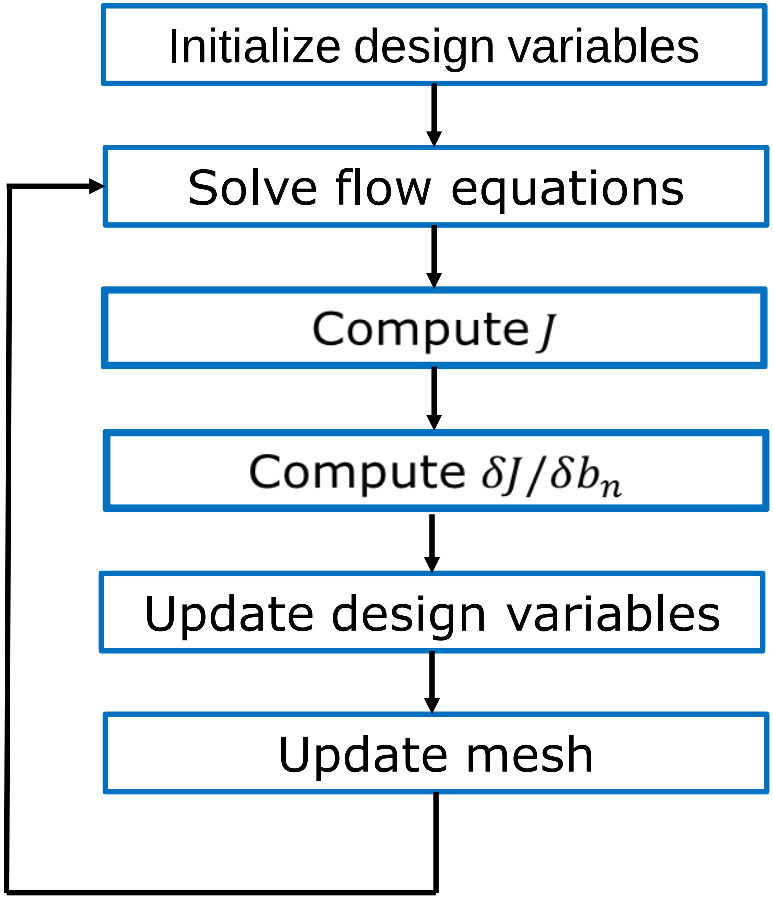
The numerical platform will allow to carry out:

- multi-objective and multi-disciplinary optimization (MOO/MDO)
- ice growth simulation
- FSI
- <u>CFD optimization through adjoint - RBF morphing coupling</u>

Gradient-based shape optimization loop

$$min.\, J(\vec{b}), b_i \in [1, N]$$




Initialize design variables

Solve flow equations

Compute J

Compute $\delta J/\delta b_n$ ⇨ Solution of adjoint equations

Update design variables ⇨ Steepest descent, CG, BFGS, Newton…

Update mesh ⇨ PDE-based, spring analogy, **RBF**…

RBF-based Grid Displacement

- Set of arbitrary control points defined in 3D space, $\overrightarrow{b_i} \in [1, N]$
- Known displacement for all $\overrightarrow{b_i}$ using adjoint-based gradients
- Grid displacement computed through a sum of weighted Radial Basis Functions $\varphi(r)$

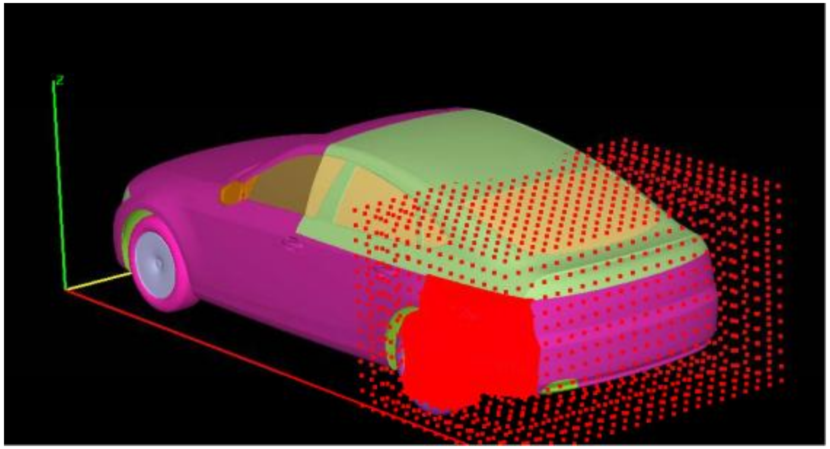
$$\Delta \mathrm{x}_{\mathrm{k}}(\vec{\mathrm{r}}) = \sum_{i=1}^{N} a_i^k \varphi\left(\left|\left|\vec{r} - \overrightarrow{b_i}\right|\right|\right) + h_k(\vec{r}), \mathrm{k} \in [1,3]$$

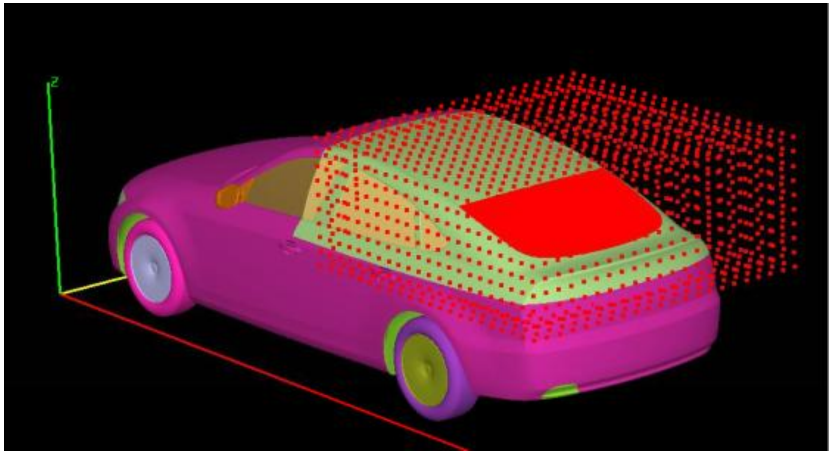
- Coefficients a_i^k are computed by solving an $N \times N$ system that emerges by retrieving the know displacement field at $\overrightarrow{b_i}$

RBF-based Grid Displacement

- ✓ Easy to set up
- ✓ Preserves mesh topology
- ✓ Easy to apply movement constraints by adding control points with zero displacement
- ✓ Allows high mesh deformations
- x High training cost when N>>. Requires a solution of an $N \times N$ (possibly dense) system
- x Requires considerable effort to reduce the training cost

The (rbf-morph)™ tool





- RBF-based morpher developed by University of Roma, UTV
- Two level approach to achieve high surface smoothness and good grid displacement characteristics
- The user operates on parameters that control a cluster of RBF control points
- Encapsulation boxes to limit movement to certain areas

Adjoint solver

- Continuous adjoint solver developed at NTUA
  - OpenFOAM-based, in-house adjoint solver
  - Differentiated turbulence models
    - ☐ Spalart-Allmaras: A. Zymaris et al, Computers & Fluids, 38(8), 2009
    - ☐ k-ε: E. Papoutsis-Kiachagias et al, Engineering Optimization, 47(3), 2015
    - ☐ k-ω SST: I. Kavvadias et al, Engineering Optimization, 47(11), 2015
  - Adjoint wall functions
    - ☐ A. Zymaris et al, Journal of Computational Physics, 229(13), 2010
    - ☐ E. Papoutsis Kiachagias, Archives of Computational Methods in Engineering, 23(2), 2016
  - A wide range of objective functions available
  - Automated optimization loops for shape, topology and flow control optimization

Sensitivities computation - Coupling with morpher

- Surface Integral (SI) based approach

Mesh sensitivities,
deformation velocities

$$\frac{\delta J}{\delta b_n} = -\int_S \left(\tau^a_{ij} n_j - q n_i\right)\frac{\partial v_i}{\partial x_k}\frac{\delta x_k}{\delta b_n}\, dS + \int_S \left(u_i R^u_i + q R^p\right)\frac{\delta x_k}{\delta b_n}\, dS$$

  - ✓ Fast computation
  - × Can be inaccurate, especially in highly stretched meshes for turbulent flows

- Field Integral (FI) based approach

$$\frac{\delta J}{\delta b_n} = \int_\Omega A_{jk}(\vec{U},\vec{\Psi})\frac{\partial}{\partial x_j}\left(\frac{\delta x_k}{\delta b_n}\right) d\Omega$$

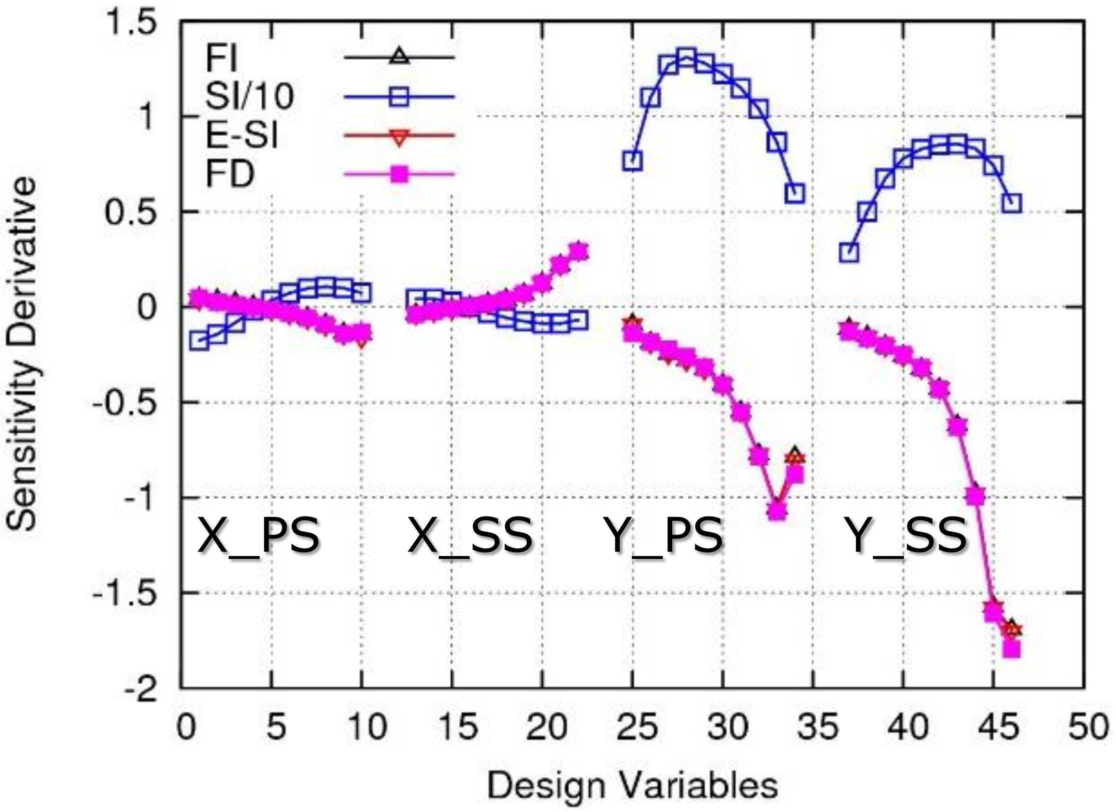
  - ✓ Much more accurate
  - × Slower, computation time scales with N

- Enhanced Surface Integral (E-SI) based approach

$$\frac{\delta J}{\delta b_n} = -\int_S \left(\tau^a_{ij} n_j - q n_i\right)\frac{\partial v_i}{\partial x_k}\frac{\delta x_k}{\delta b_n}\, dS + \int_S \frac{\partial m^a_i}{\partial x_k} n_k \frac{\delta x_i}{\delta b_n}\, dS$$

  - ✓ As accurate as FI
  - ✓ As fast as SI

A convincing example



- NACA0012 airfoil
- $Re = 1 \times 10^6$
- $y^+ = 0.2$
- $a = 2^o$
- Lift sensitivities
- Bezier-Berstein polynomials
- Differentiated Spalart-Allmaras turbulence model

SI sensitivities

- an order of magnitude off
- Practically all signs are wrong!

I.S. Kavvadias, E.M. Papoutsis-Kiachagias, K.C. Giannakoglou: "On the proper treatment of grid sensitivities in continuous adjoint methods for shape optimization", Journal of Computational Physics, 301, 2015

Optimization of an Ultra-light Aircraft

- Flow Conditions: $M_\infty = 0.08$, $a_\infty = 10^o$ and $Re = 10^6$

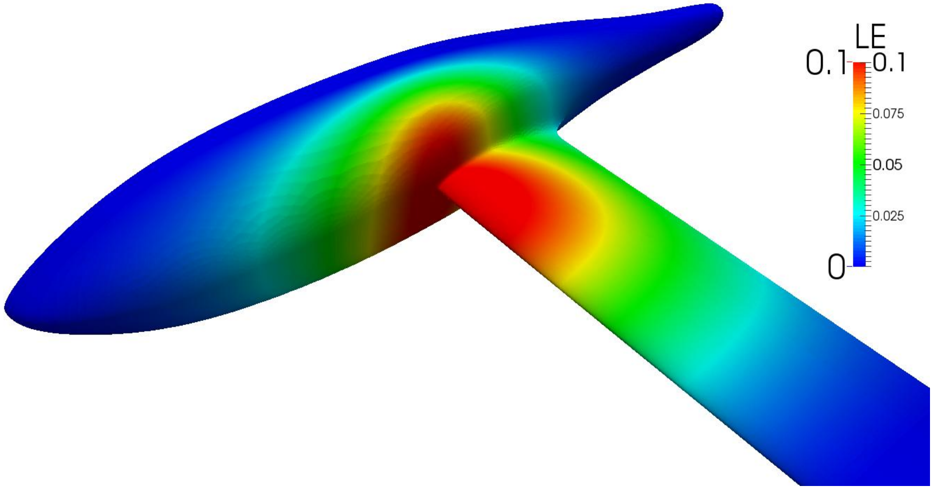
- Incompressible Navier-Stokes solver / Spalart – Allmaras turbulence model (simpleFoam)

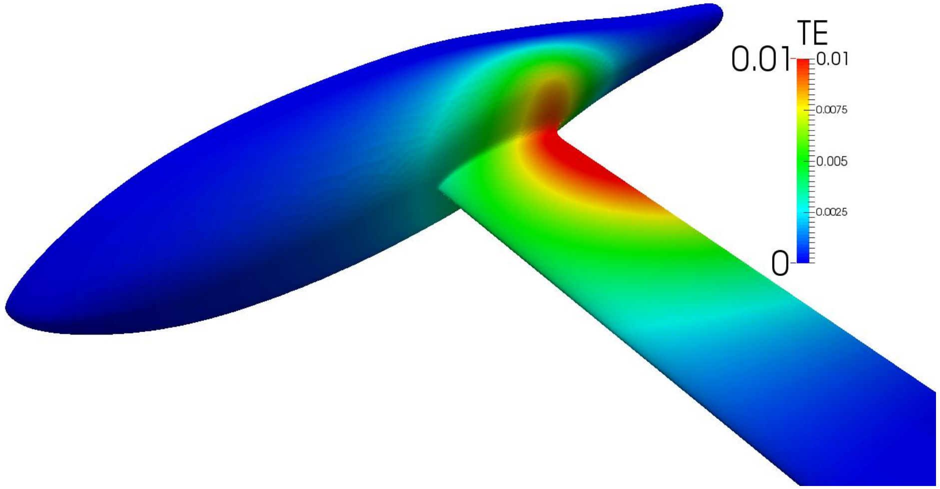
- SnappyHexMesh ~4.7 million cells

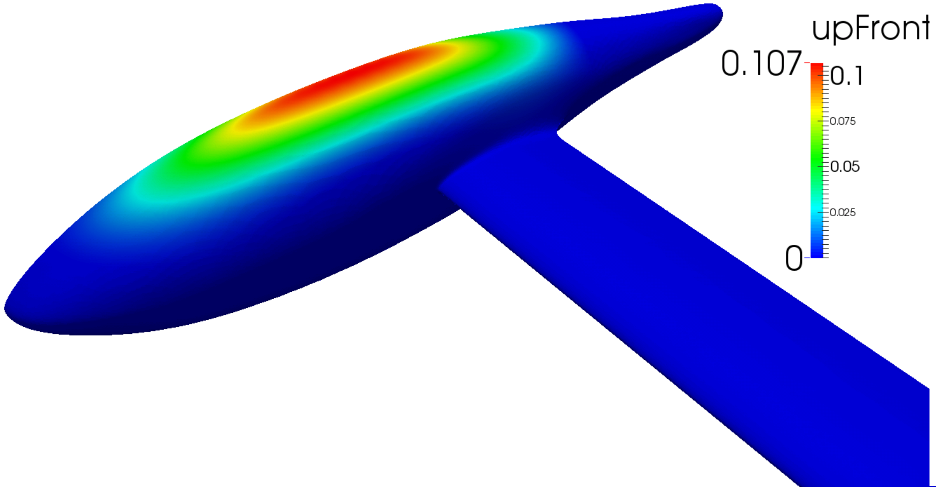
- Lift/Drag maximization

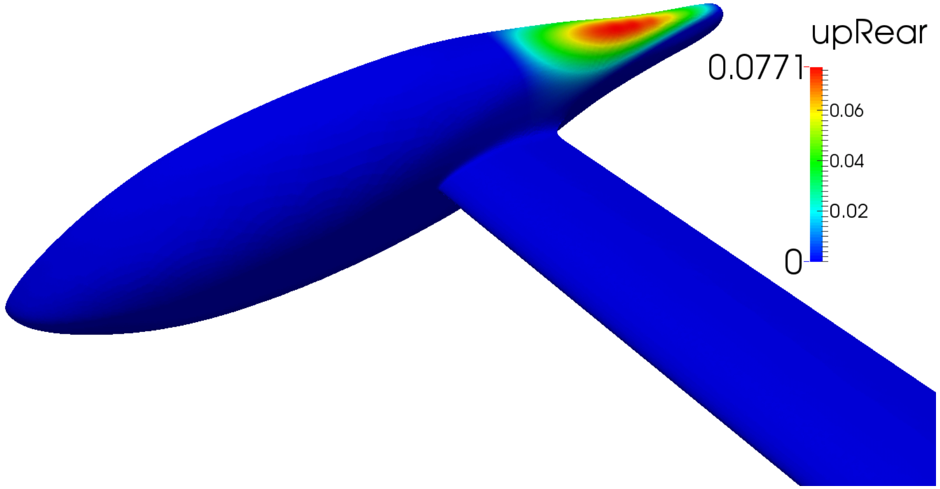
PIPISTREL

Design Variables, $\frac{\delta x_k}{\delta b_n}$

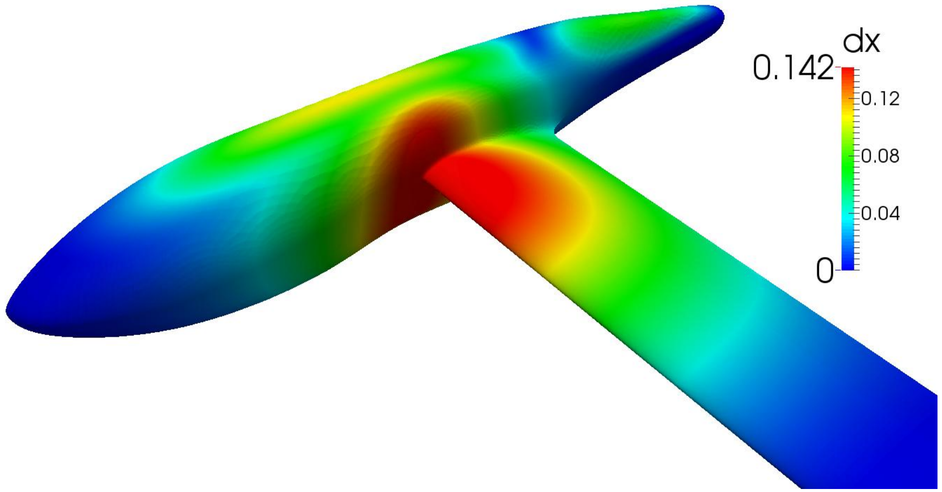


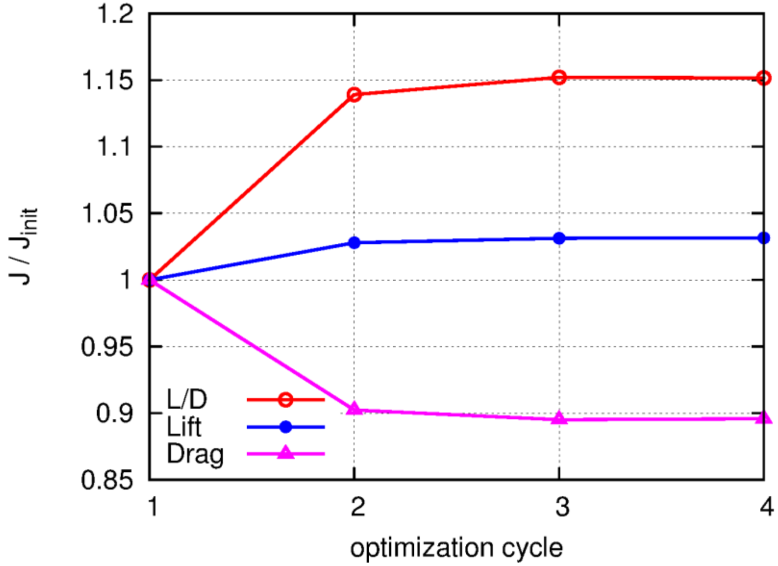


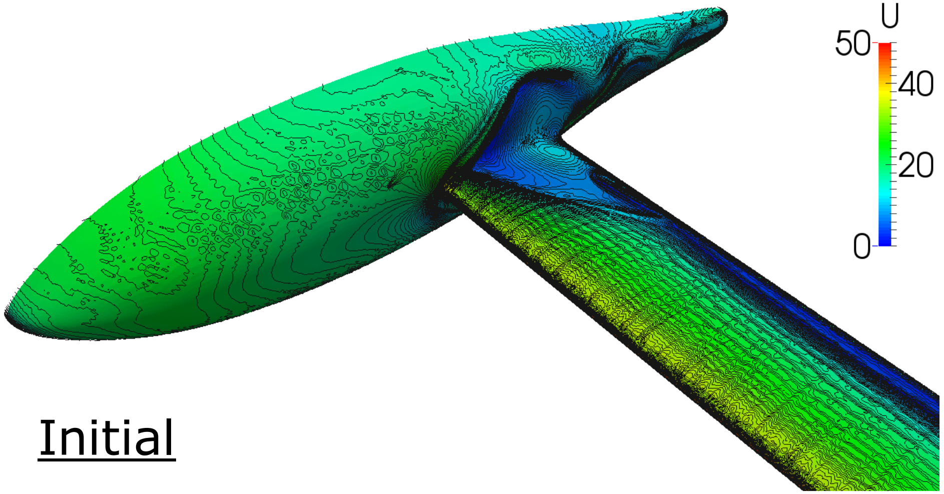




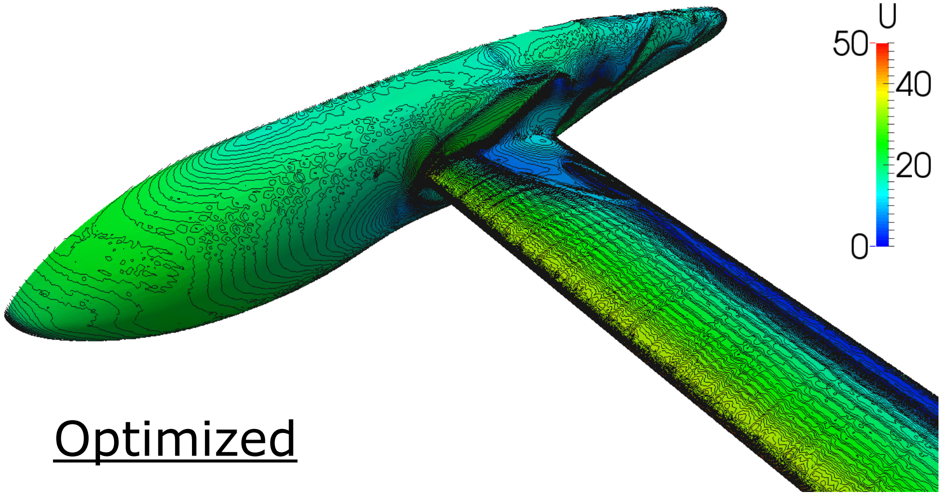
Optimization results







Initial



Optimized

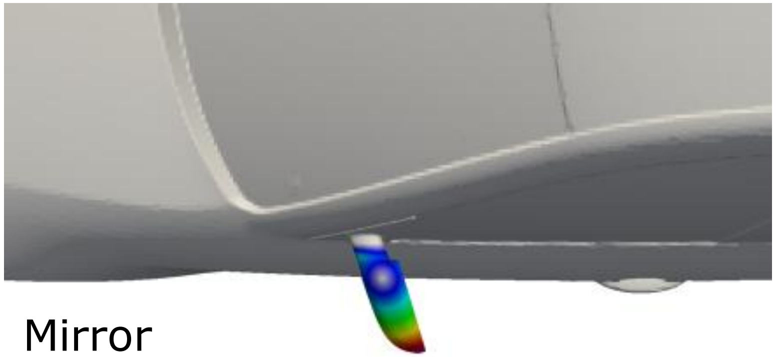
Application – The DrivAer car model

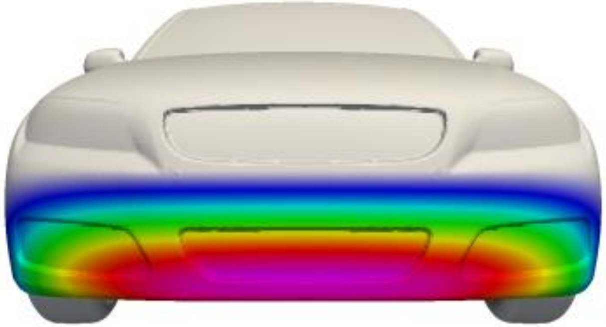
Shape optimization of the DrivAer car model

- Model developed by TUM, Institute of Aerodynamics and Fluid Mechanics
- Fast-back, smooth underbody, with mirrors and wheels (F-S-wm-ww)
- SnappyHexMesh ~5 Million cells
- Steady-State simulation, Spalart-Allmaras turbulence model
- Drag minimization
- Adjoint to turbulence model and adjoint wall-functions included

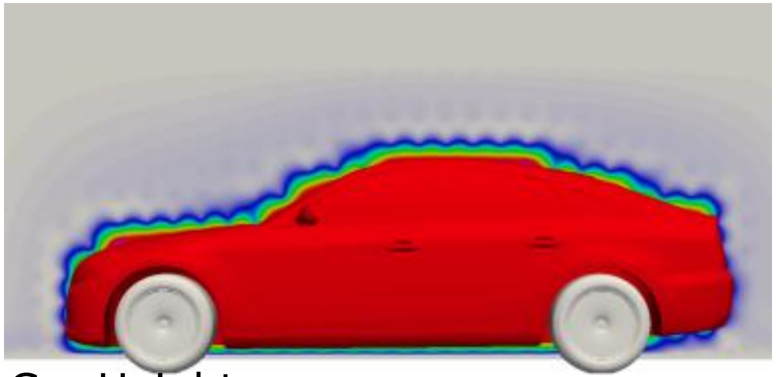
Design Variables, $\frac{\delta x_k}{\delta b}$


Rear Windshield


Mirror

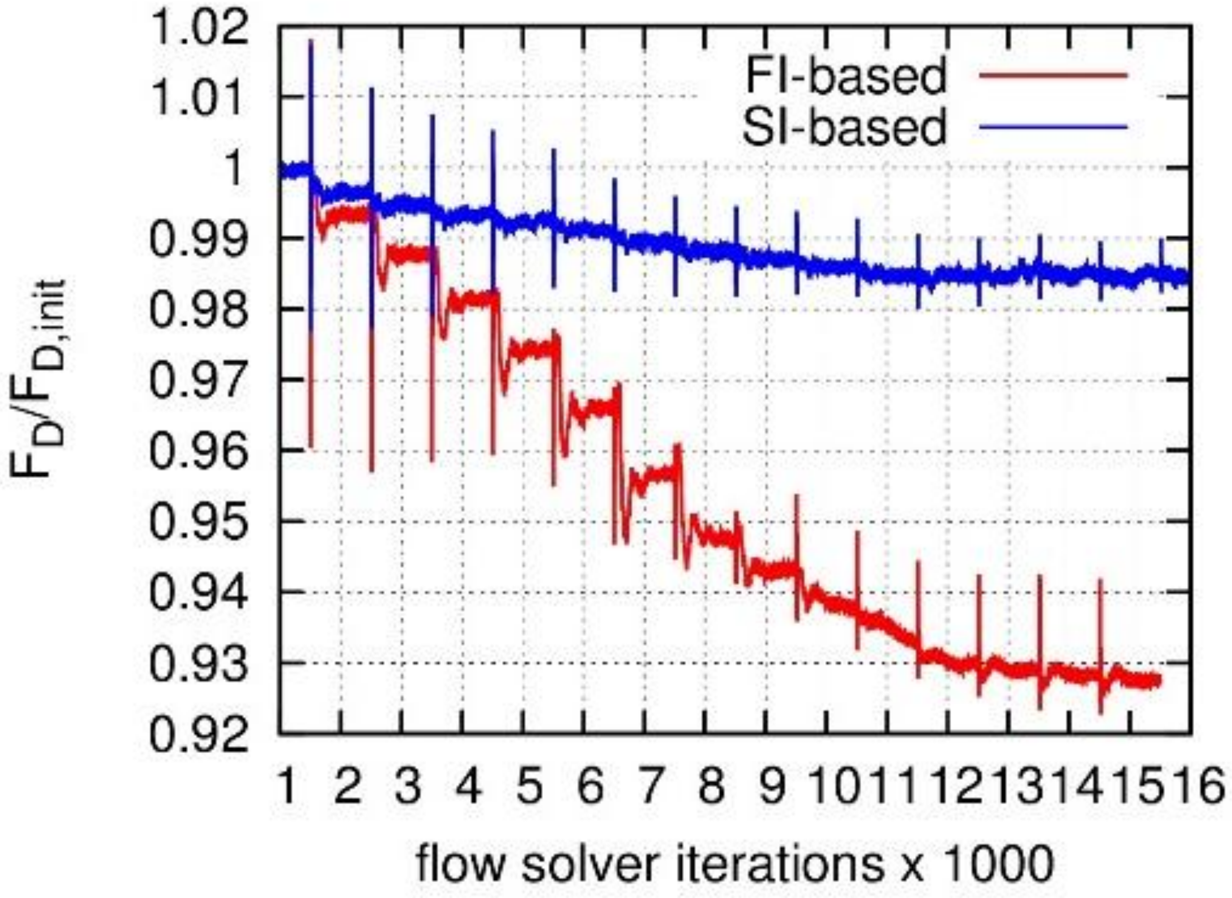

Front Underbody


Back Underbody


Car Height


Boat Tail

Convergence

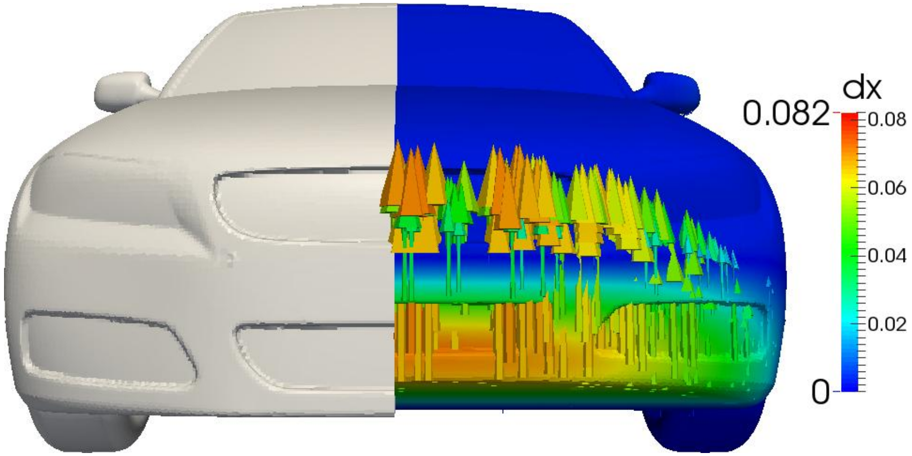


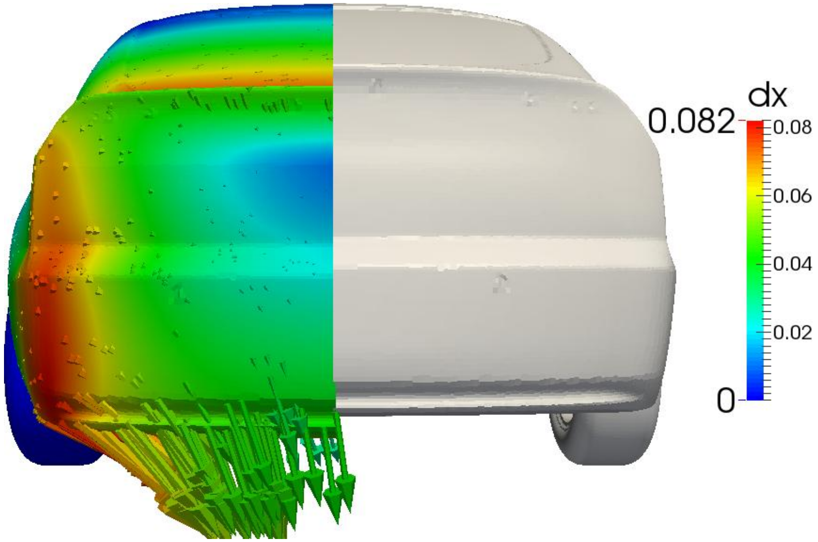
1000 flow solver iteration/optimization cycle

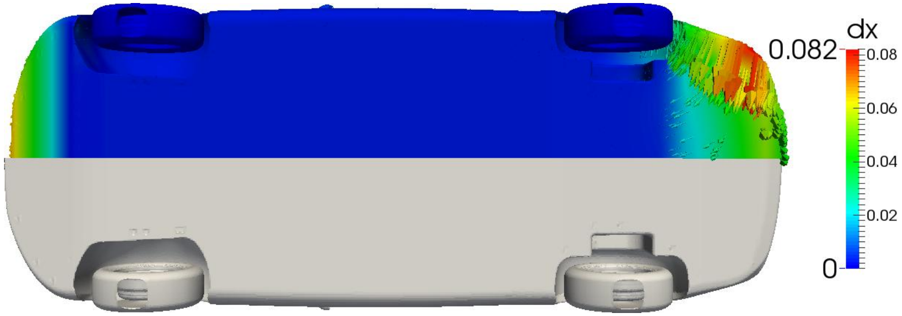
More than **7% drag reduction** in 15 optimization cycles (~ 30 EFS)

16 hours on 64 CPus

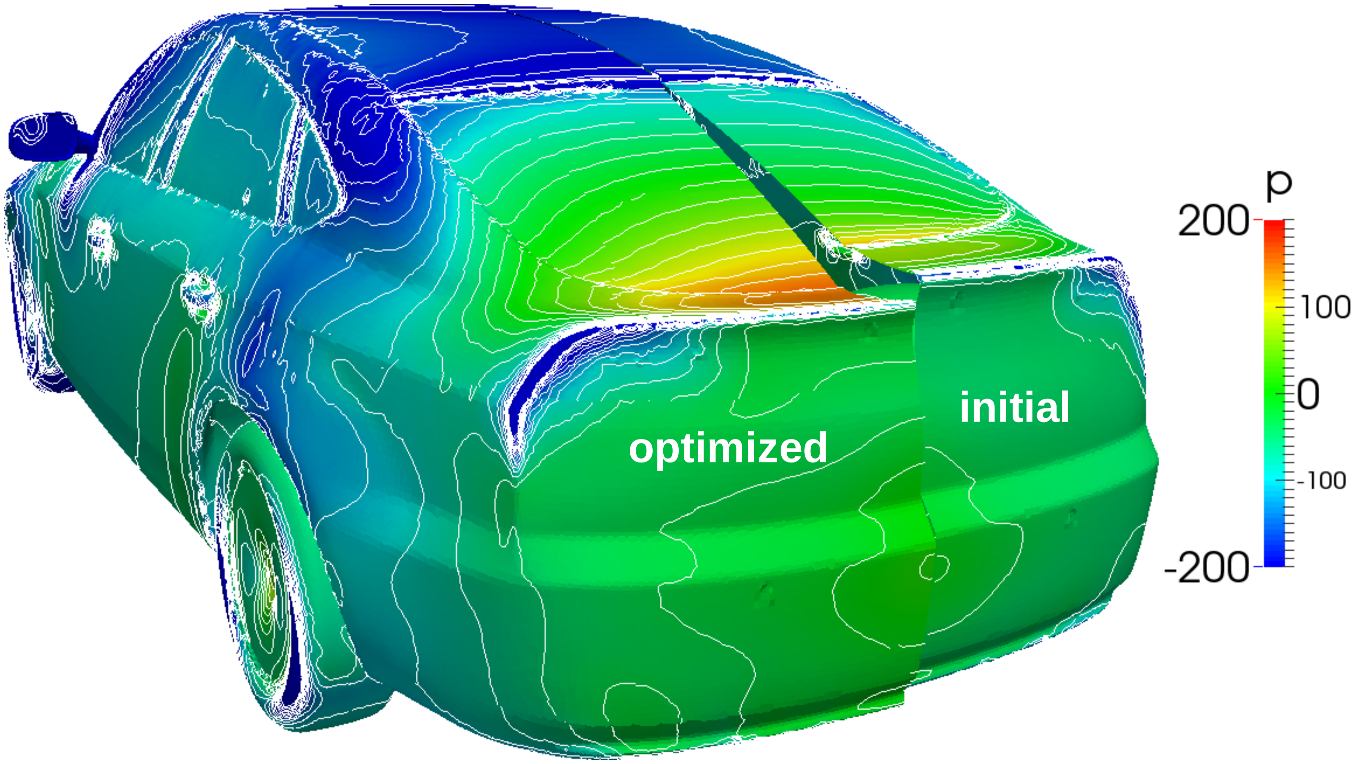
Shape Deformation







Spoiler creation – boat tailing



Two main drag reduction mechanisms

- Boat-tailing increases pressure on the back side
- Spoiler creates a “stagnation point” with an effect that pushes the car forward

Summary

- Efficient Shape optimization in the two applications
- 15% Lift/Drag increase and 7% drag reduction with overnight computations
- RBF morphing provides a robust and versatile way to parameterize both the surface and the volume mesh
- Appropriate definition of design variables can lead to “eye-pleasing” optimized geometries
- The FI (E-SI) sensitivity formulations compute accurate and reliable sensitivities for shape optimization in turbulent, industrial flows