Reduced Order Modeling of Automotive Crash Events via Proper Orthogonal Decomposition and Parametric Shape Morphing

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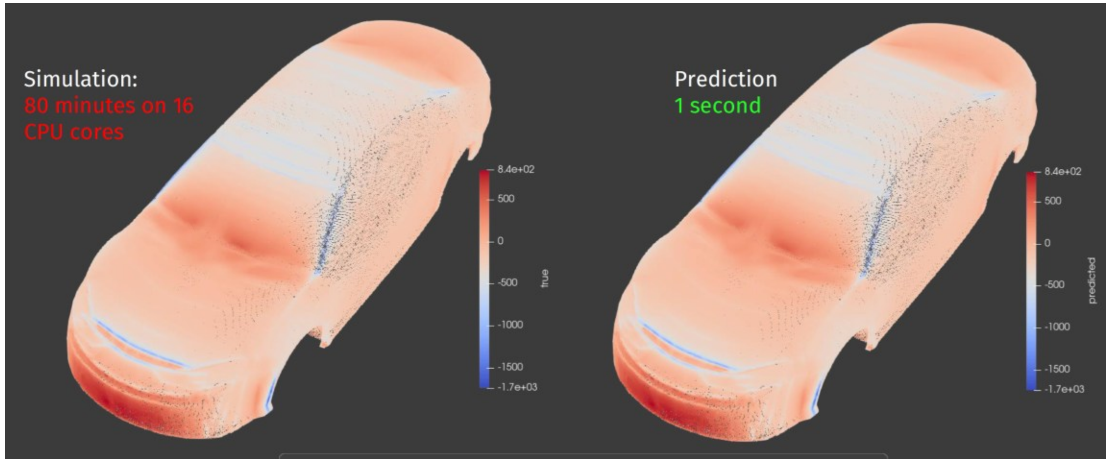
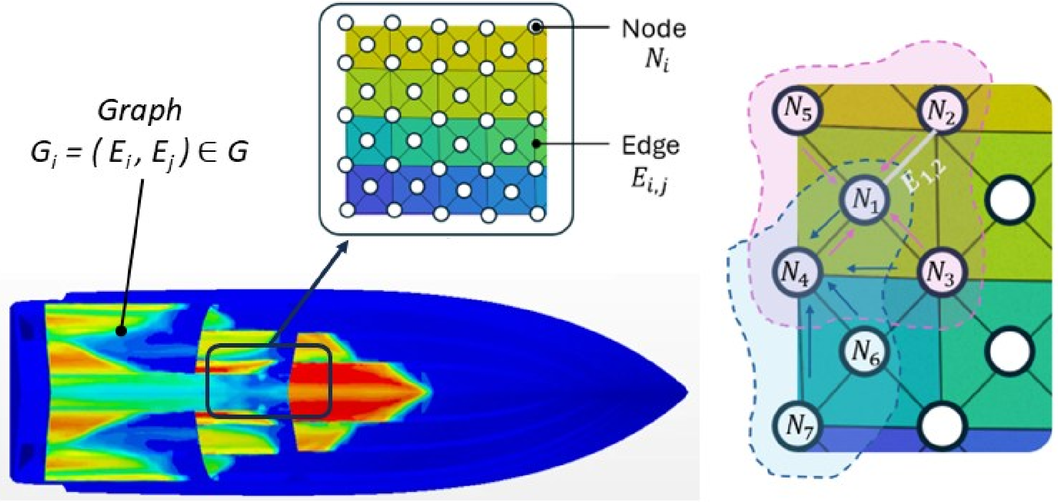
- Digital Engineering Applications
- RBF in a nutshell
- Interpolators in multi-dimensional spaces
- Fast RBF at works: interactive design.
- Research and Industrial Examples
  - Overview (CFD, FEA)
  - Reduced Order Model of an Explicit Analysis
- Conclusions
- RBF Morph?

Digital Engineering Applications

- **Digital Twin** – digital replica of asset useful at design and operation
- CAE adoption is evolving: single verification, design variations, automated optimization, **parametric space exploration** (snapshots)
- **Machine learning** is the reference for «AI» based approach
- High/medium fidelity simulations allow to generate the training data: **synthetic datasets**





RBF in a nutshell

source points

radial basis

$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \cdot \varphi\left(\left\|\mathbf{x}-\mathbf{x}_{\mathbf{k_i}}\right\|\right) + h(\mathbf{x})$$

polynomial

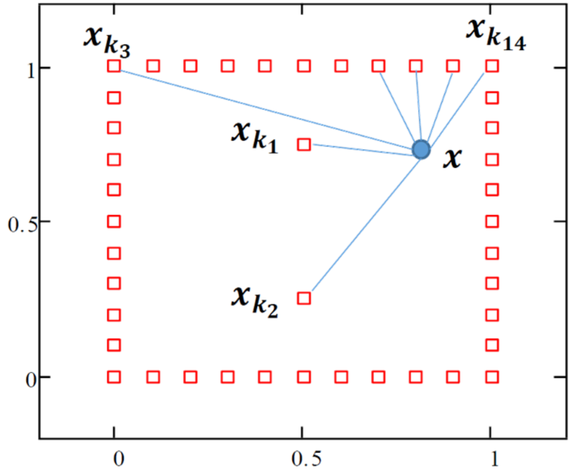
e.g. $h(\boldsymbol{x}) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z$

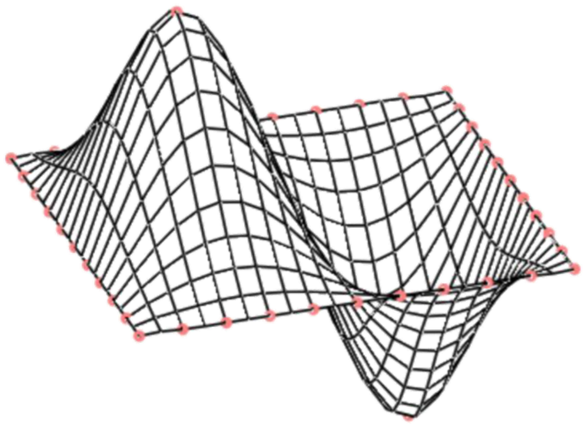
weight

shift of the target point to the i-th data site

RBF	φ(r)
Spline type (Rn)	r^n, *n odd*
Thin plate spline	$r^n\log(r)$ *n even*
Multiquadratic (MQ)	$\sqrt{1+r^2}$

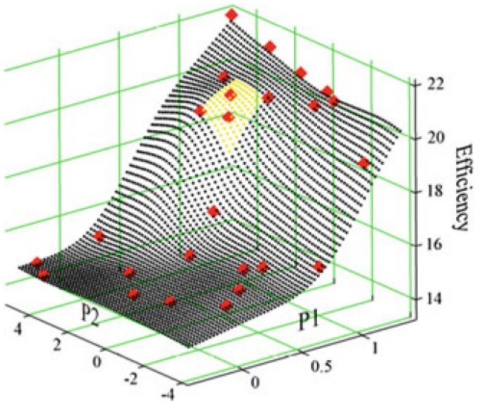
RBF are a very powerful mathematical tool able to interpolate **everywhere** in the $\mathbb{R}^n$ space a function given at scattered **source points**

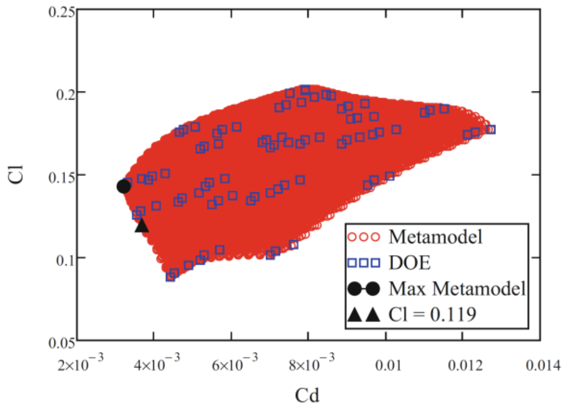




Interpolators in multi-dimensional spaces

- Data science problems
  - **Inference** $\mathbb{R}^n \Rightarrow \mathbb{R}^m$
  - Gaussian RBF is recognized as the “RBF neural network”
  - Useful for **surrogates** in **optimisation**
- 3D space manipulation (shape deformation, data mapping)
  - Field manipulation is a key enabler for **geometric intelligence**
  - Mapping is a key enabler for multi-physics and as a “morphing extender”





Fast RBF at works: interactive design.

CAE agnostic approach

Domain Identification
e.g., automotive, healthcare, aerospace

↓

Specific Need
e.g., aerodynamic efficiency, surgical treatment optimization

↓

End-User Identification
stylists/designers, clinicians, engineering teams

↓

High-Fidelity CAE Response
CFD/FEM/multiphysics; baseline geometry; KPI targets

↓

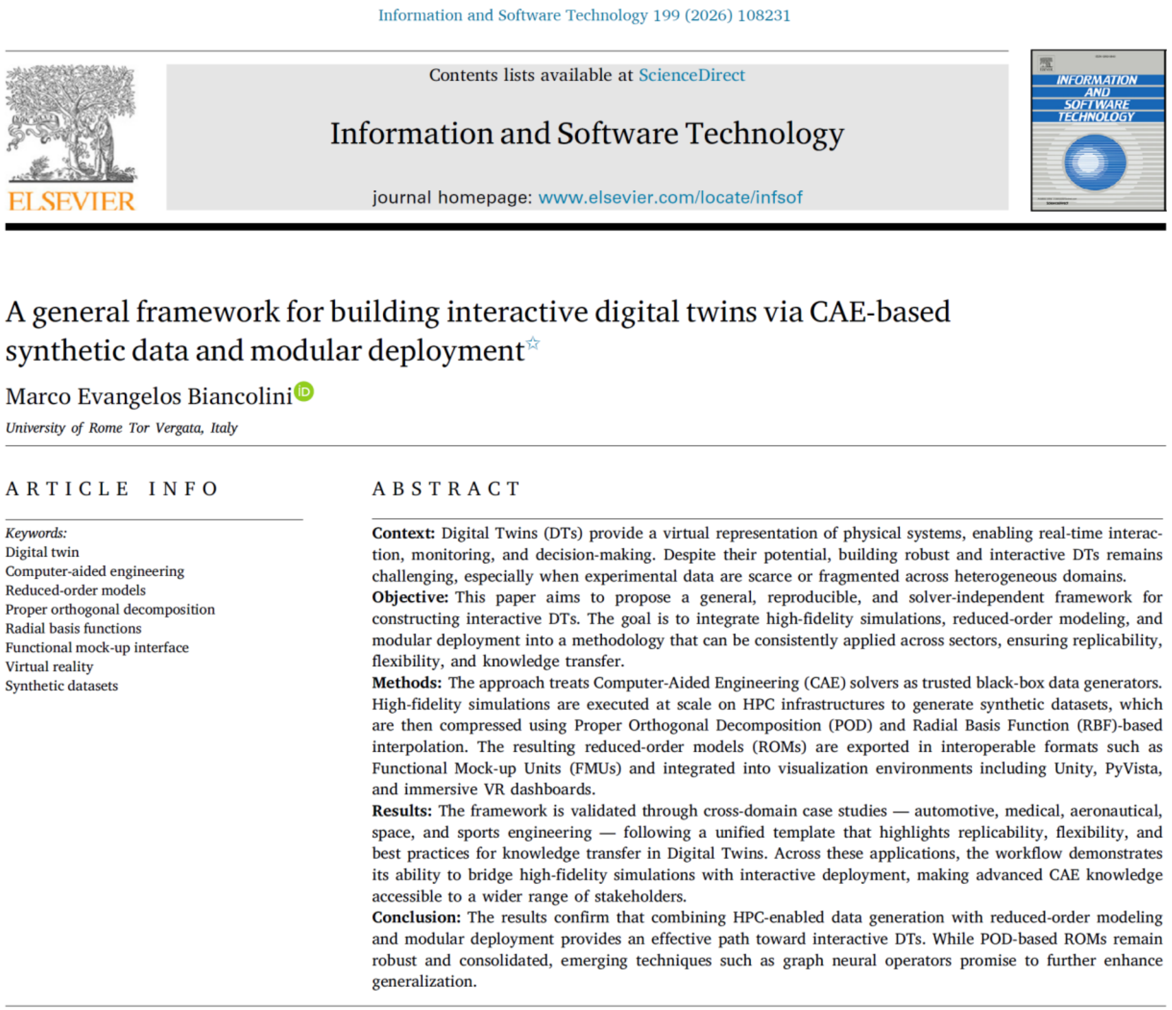
Parameter Selection
physical and geometric variables

↓

Workflow Execution
parameterization, HPC data, ROM compression, export (FMU/.npy/ONNX)

↓

Deployment
XR/VR, dashboard, software component



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A general framework for building interactive digital twins via CAE-based synthetic data and modular deployment

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Proper orthogonal decomposition
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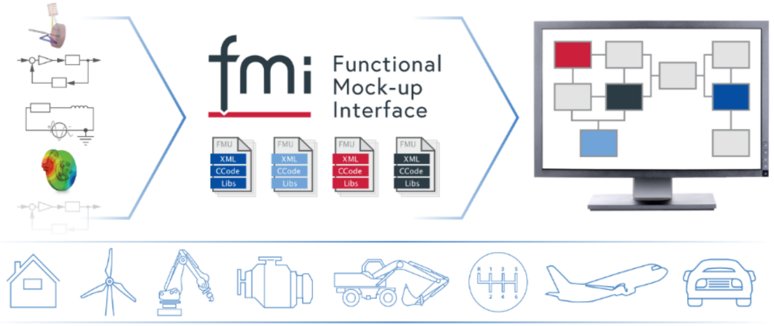
Functional mock-up interface
Virtual reality
Synthetic datasets

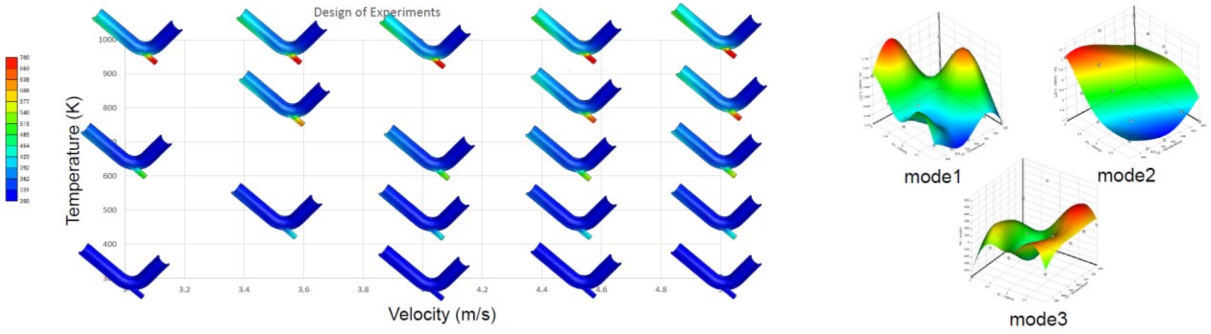
ABSTRACT

Context: Digital Twins (DTs) provide a virtual representation of physical systems, enabling real-time interaction, monitoring, and decision-making. Despite their potential, building robust and interactive DTs remains challenging, especially when experimental data are scarce or fragmented across heterogeneous domains.
Objective: This paper aims to propose a general, reproducible, and solver-independent framework for constructing interactive DTs. The goal is to integrate high-fidelity simulations, reduced-order modeling, and modular deployment into a methodology that can be consistently applied across sectors, ensuring replicability, flexibility, and knowledge transfer.
Methods: The approach treats Computer-Aided Engineering (CAE) solvers as trusted black-box data generators. High-fidelity simulations are executed at scale on HPC infrastructures to generate synthetic datasets, which are then compressed using Proper Orthogonal Decomposition (POD) and Radial Basis Function (RBF)-based interpolation. The resulting reduced-order models (ROMs) are exported in interoperable formats such as Functional Mock-up Units (FMUs) and integrated into visualization environments including Unity, PyVista, and immersive VR dashboards.
Results: The framework is validated through cross-domain case studies — automotive, medical, aeronautical, space, and sports engineering — following a unified template that highlights replicability, flexibility, and best practices for knowledge transfer in Digital Twins. Across these applications, the workflow demonstrates its ability to bridge high-fidelity simulations with interactive deployment, making advanced CAE knowledge accessible to a wider range of stakeholders.
Conclusion: The results confirm that combining HPC-enabled data generation with reduced-order modeling and modular deployment provides an effective path toward interactive DTs. While POD-based ROMs remain robust and consolidated, emerging techniques such as graph neural operators promise to further enhance generalization.

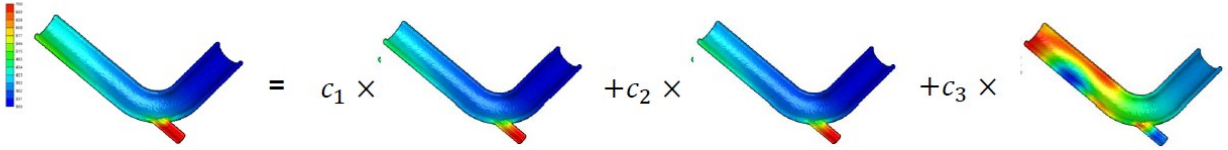
Interactive Digital Twins

- Reduced Order Models (ROM) are **compressed** (POD) ready to be **inferred** (RBF)
- Functional Mock-Up Units (FMU) make the models **portable**
- Unity **rendering**
- Meta Quest 3 AR/VR



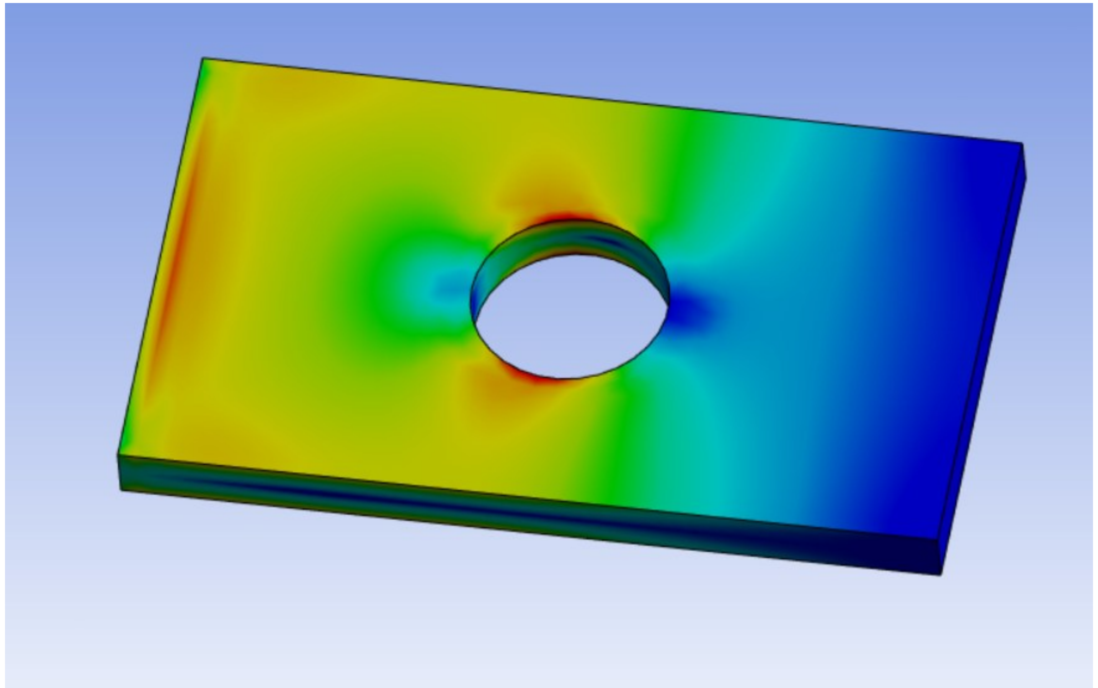


POD+RBF = ROM



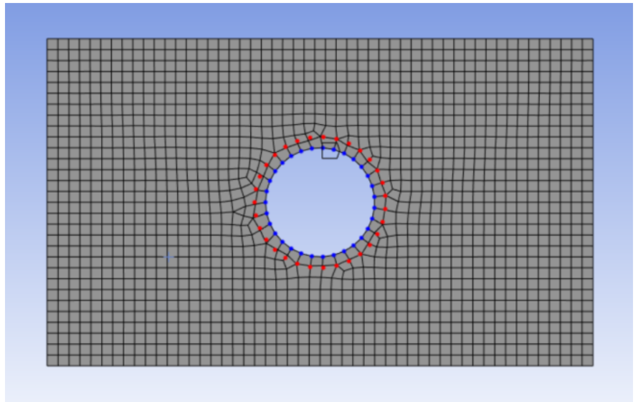
A simple FEA model – ROM - FMU

- Solid model created by **CAD**
- The notch effect is accurately captured by **FEA**
- RBF **mesh morphing** allows to create one **geometrical parameter** to change the diameter of the hole
- The applied load is the **physical parameter**
- Snapshots are exported and the **FMU** created by Twin Builder

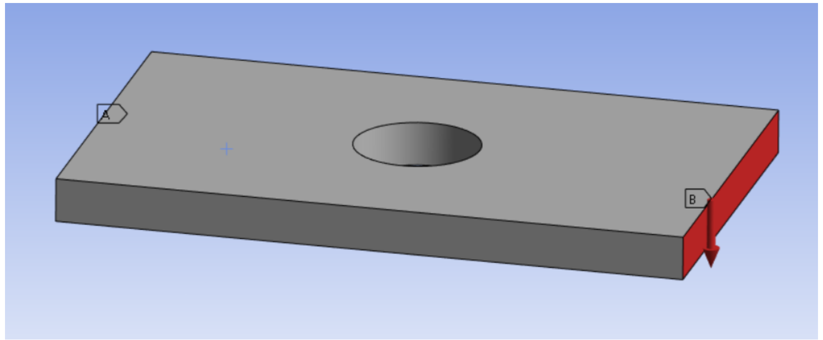


Workflow

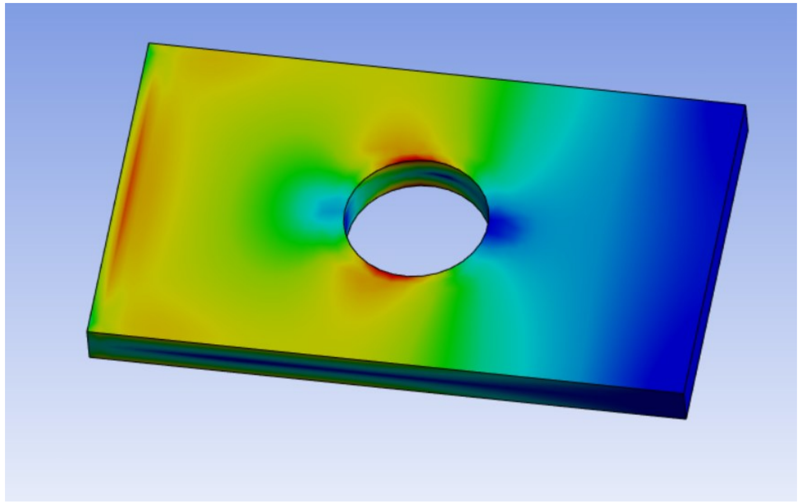
Step 1: Geometry and mesh → **Step 2: Setting** → **Step 3: Parameters** → **Step 4: DOE: 30 DPs** → **Step 5: ROM**



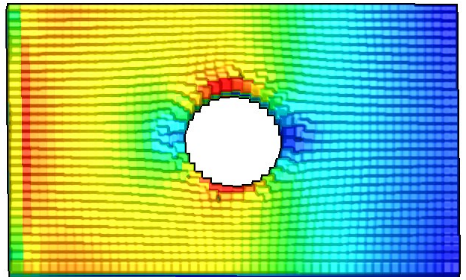
Shape parameter: radius offset

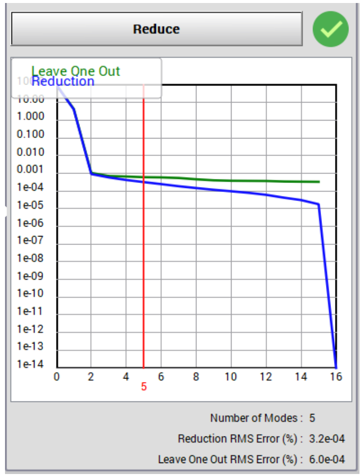


Physical parameter: Force



VM stresses

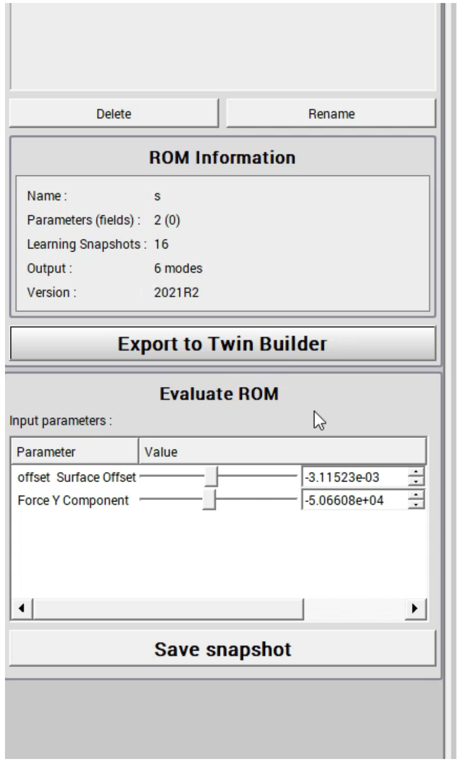


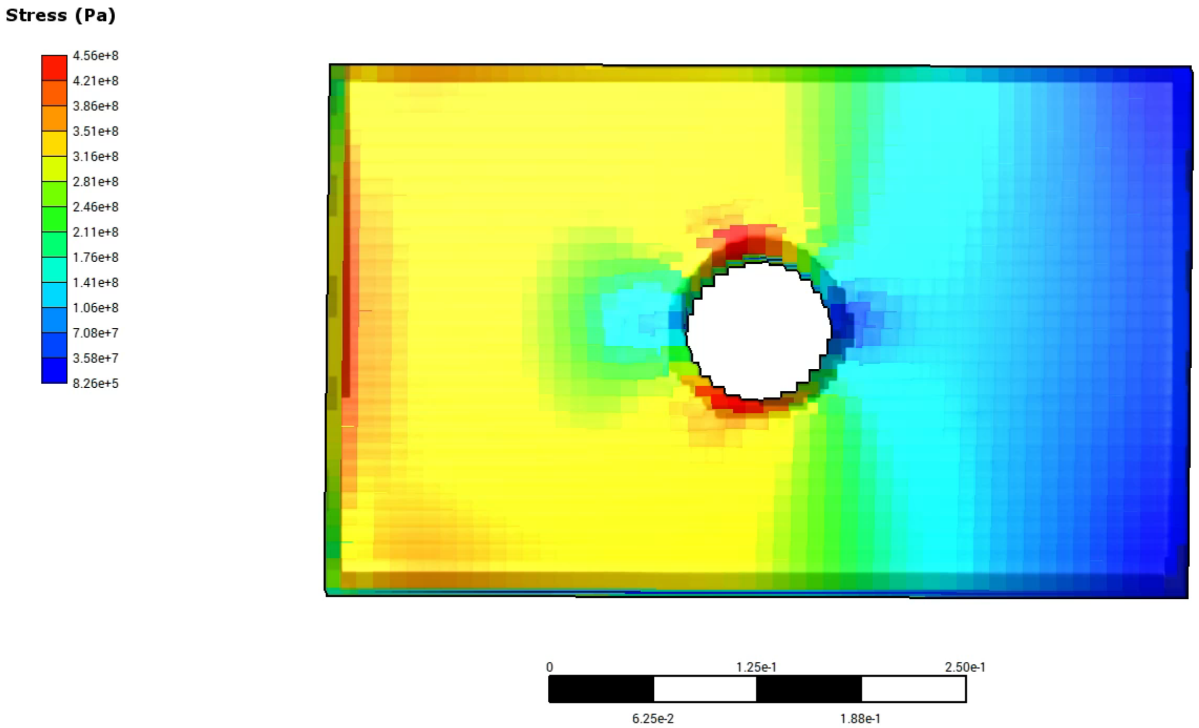


Ansys TB interface

Ansys Twin Builder

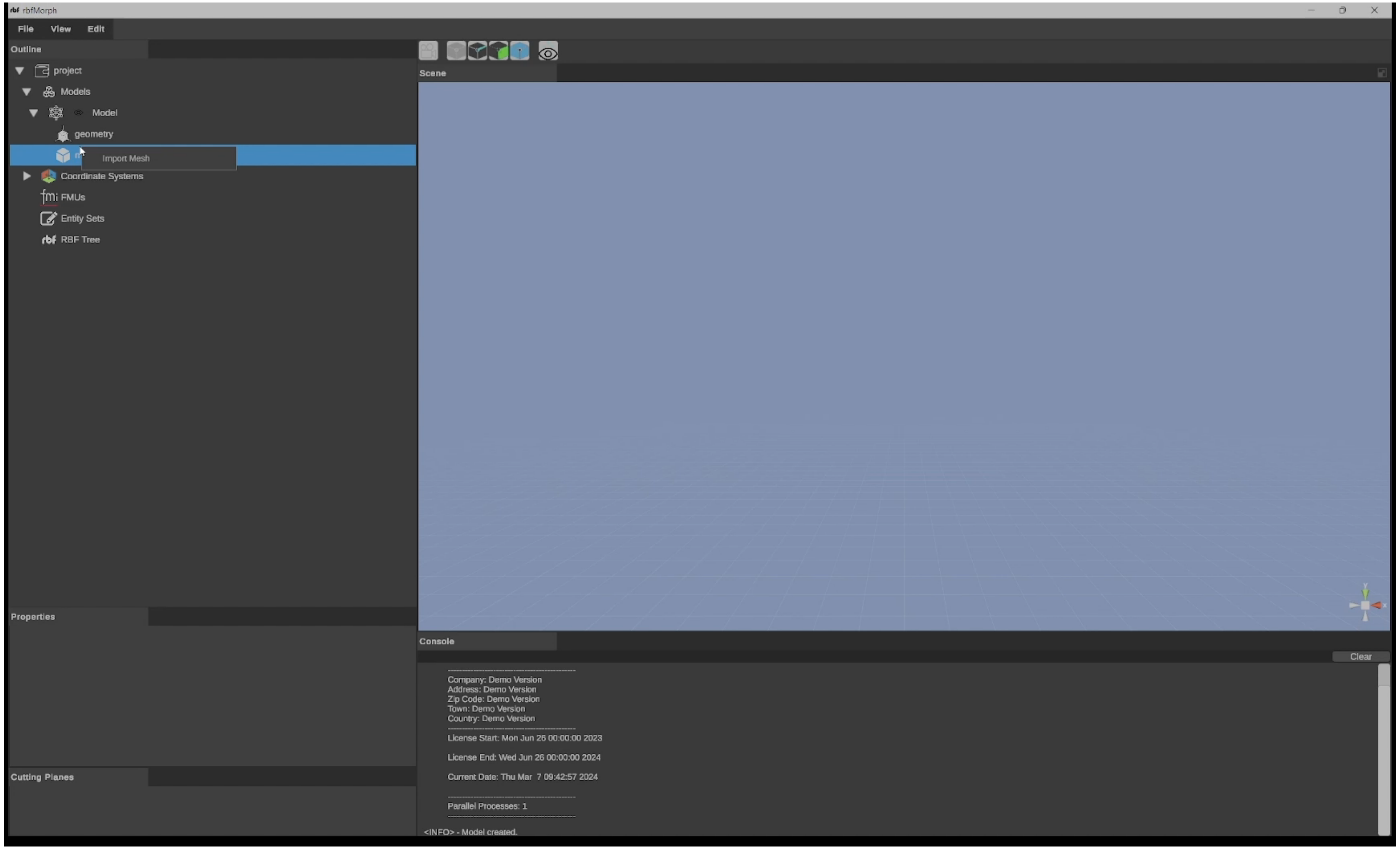
- ROM viewer
- Input parameters are controlled by the **sliders**
- Point-based **rendering**





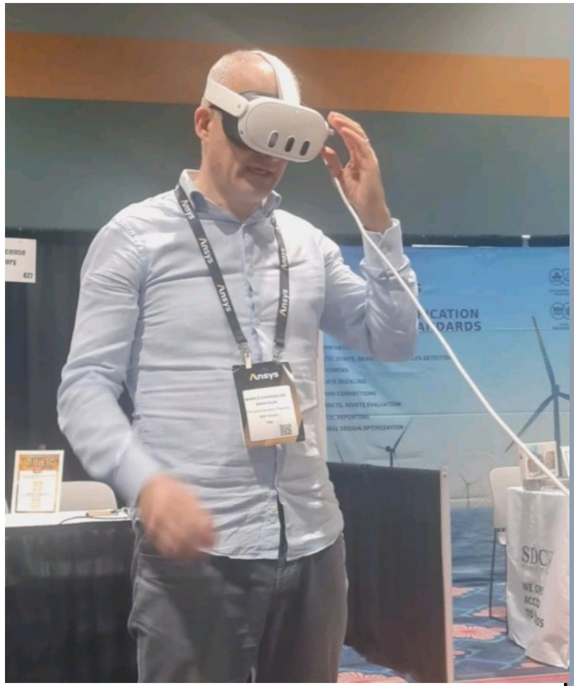
rbfCAE Unity UI

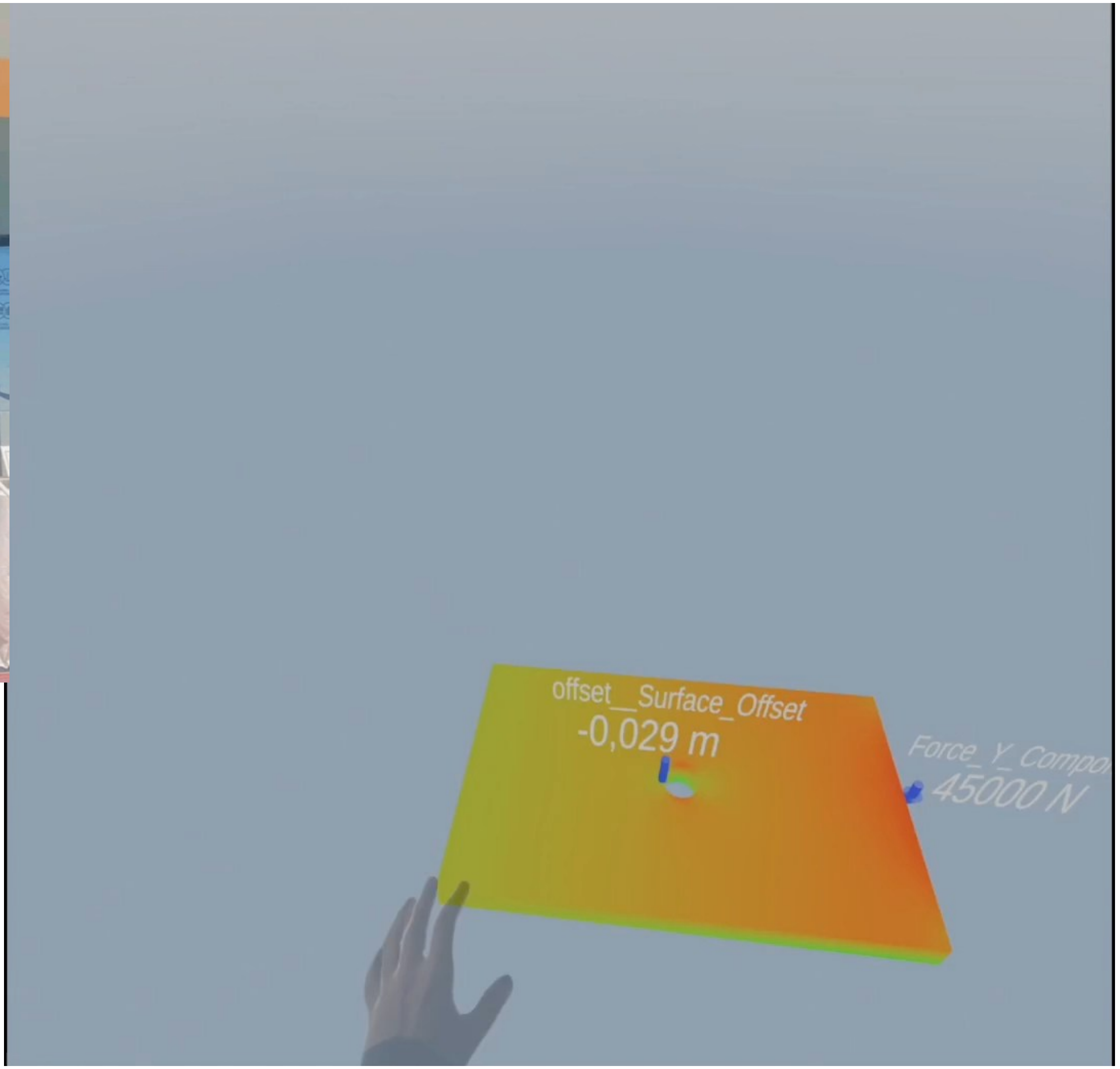
- Unity UI capable to read in **surface** and **FMU**
- Input parameters are controlled by **handles** (json descriptor)
- **Surface-based** rendering



rbfVR

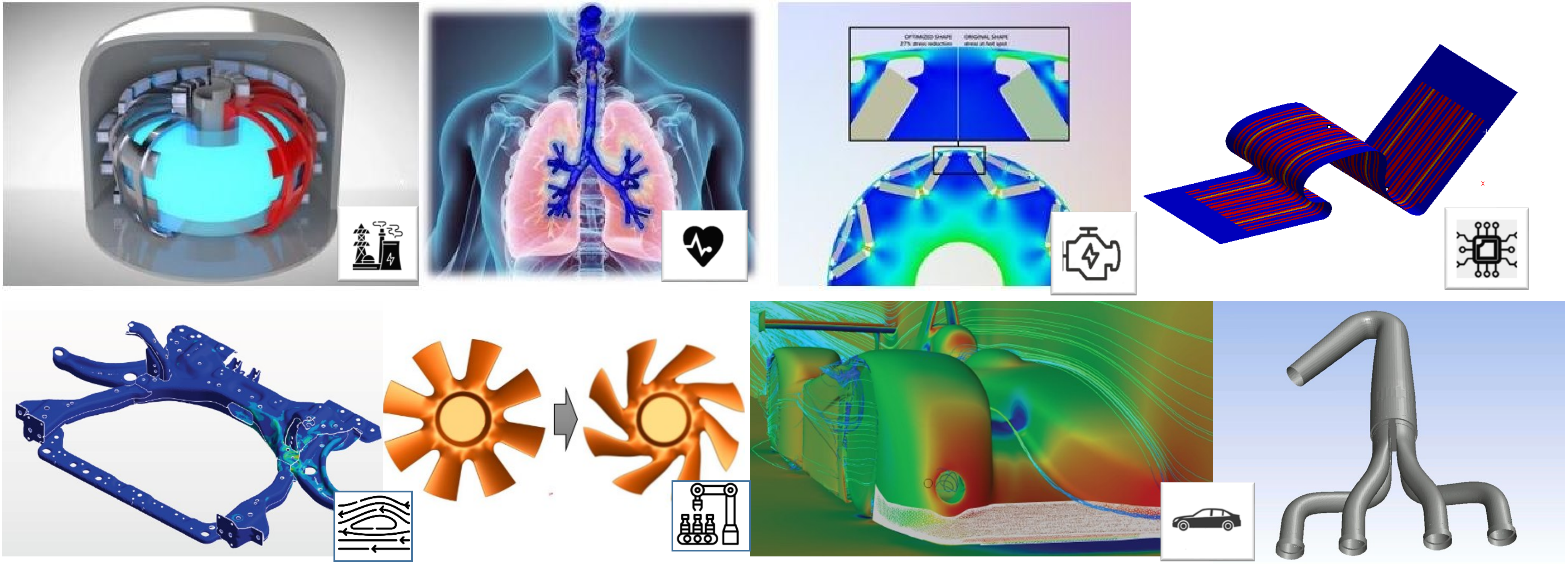
- FMU are translated to ARM
- Meta Quest 3
- Input parameters are controlled **by hands**
- We can add an **immersive scene**
- Wireless AR/VR





Research and Industrial Examples

Research and Industrial sectors



EU-funded research projects 2013-2025

aias

Funded by the European Union

RBF4AERO

FORTISSIMO

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CloudiFacturing

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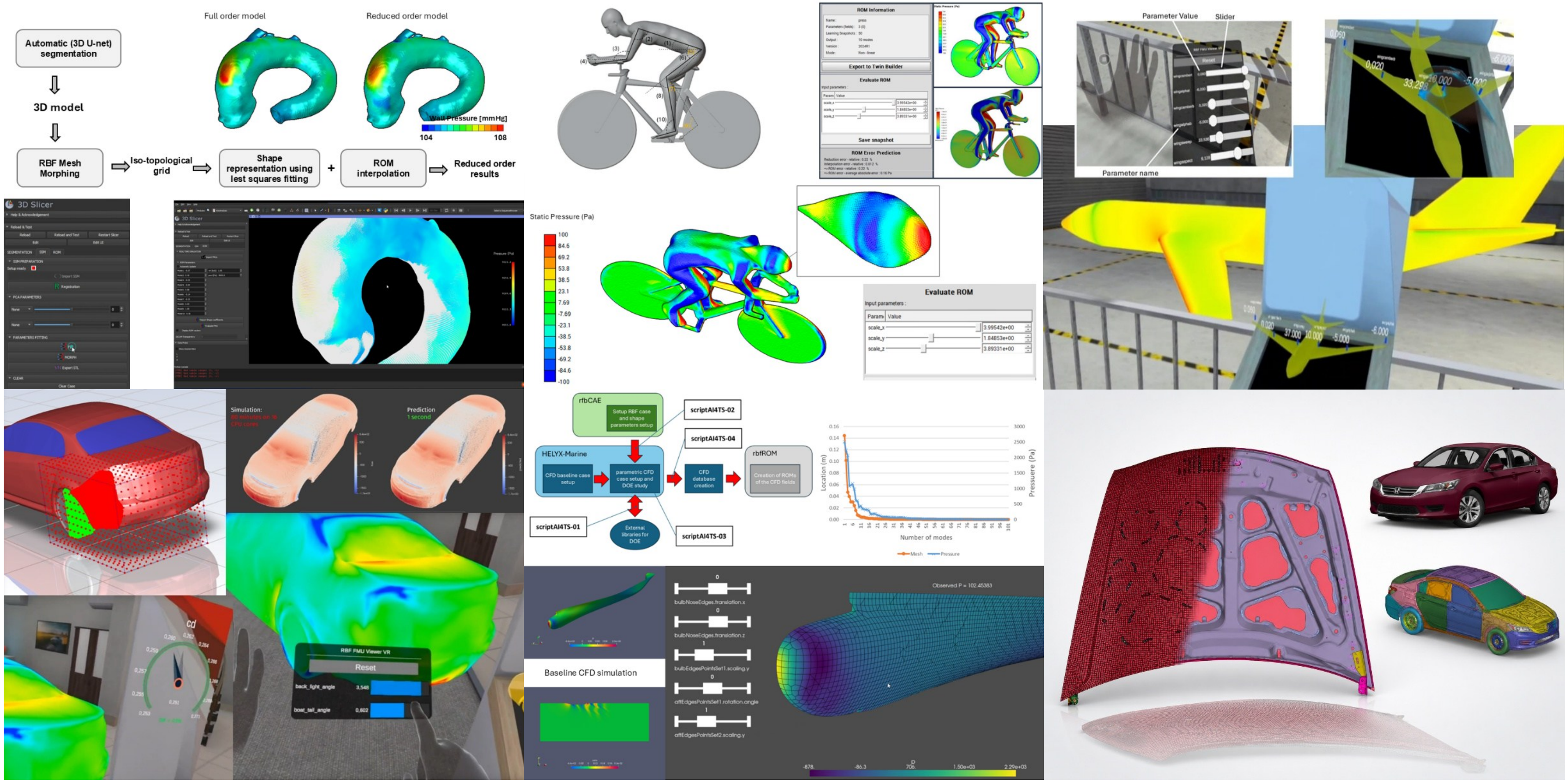
spinner
next generation spine experts

MEDITATE

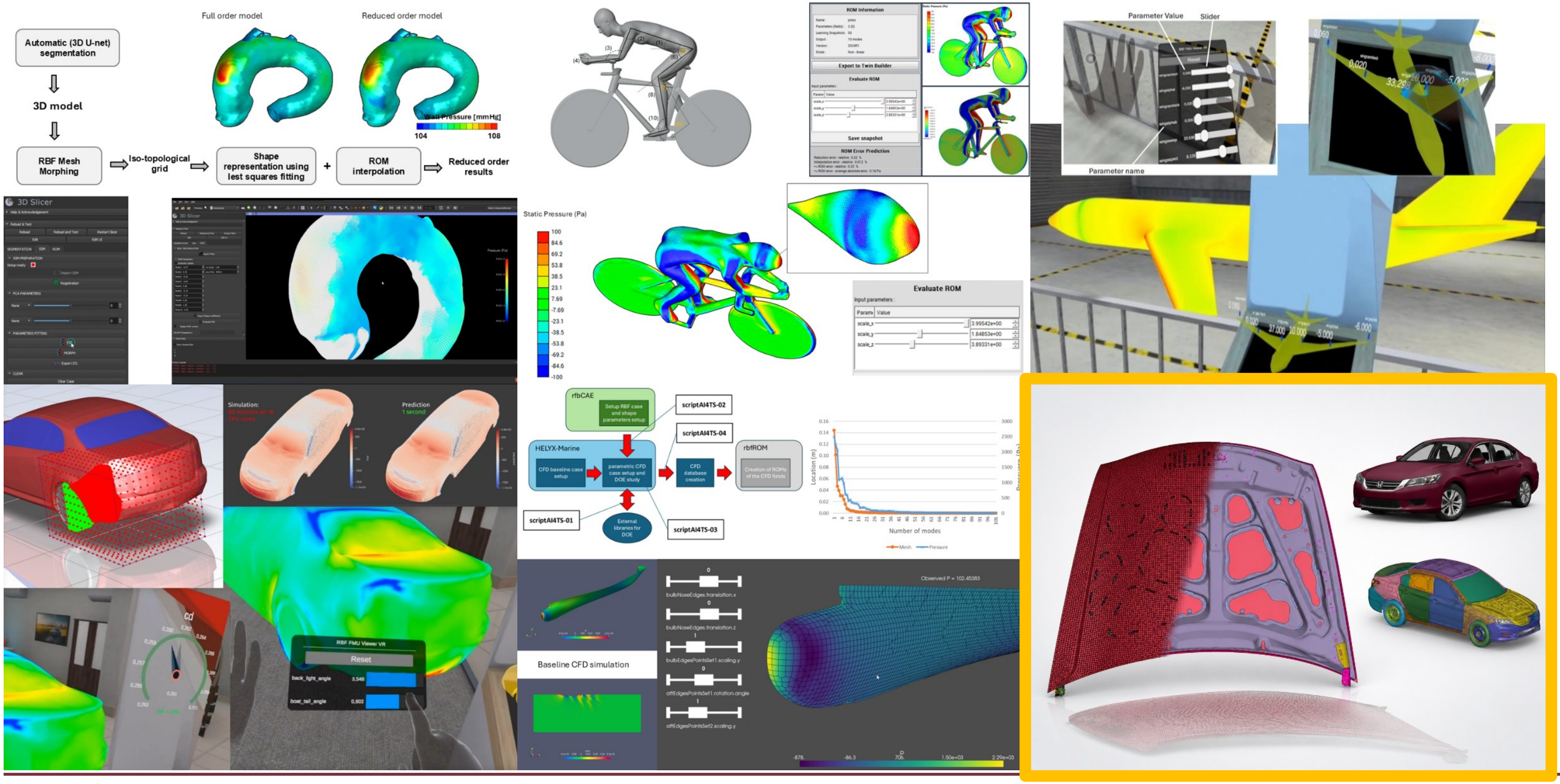
ff4EuroHPC

ff+

Overview


Automatic (3D U-net) segmentation
3D model
RBF Mesh Morphing
Iso-topological grid
Shape representation using lest squares fitting
ROM interpolation
Reduced order results
Full order model
Reduced order model
Wall Pressure [mmHg]
Static Pressure (Pa)
Evaluate ROM
Parameter Value
Slider
Parameter name
rbfCAE
HELYX-Marine
rbfROM
scriptAI4TS-01
scriptAI4TS-02
scriptAI4TS-03
scriptAI4TS-04
Number of modes
Baseline CFD simulation
RBF FMU Viewer VR
Reset

Overview



Automatic (3D U-net) segmentation
3D model
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Shape representation using lest squares fitting
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Full order model
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Wall Pressure [mmHg]
104
108
3D Slicer
Static Pressure (Pa)
Evaluate ROM
Input parameters
Parameter Value
Slider
Parameter name
Simulation:
Prediction
rbfCAE
Setup RBF case and shape parameters setup
HELYX-Marine
CFD baseline case setup
parametric CFD case setup and DOE study
CFD database creation
rbfROM
Creation of ROMs of the CFD fields
scriptAI4TS-02
scriptAI4TS-04
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External libraries for DOE
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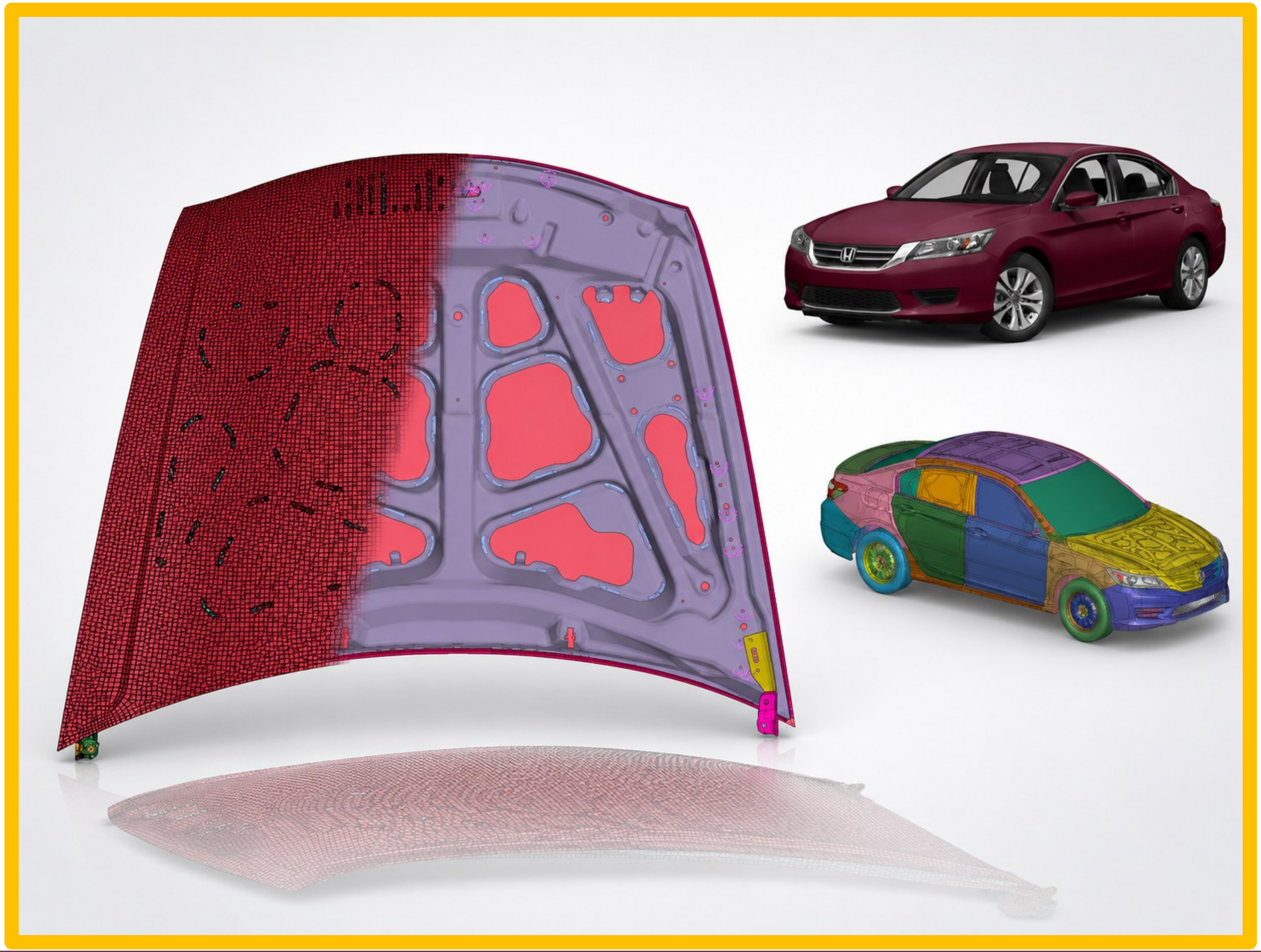
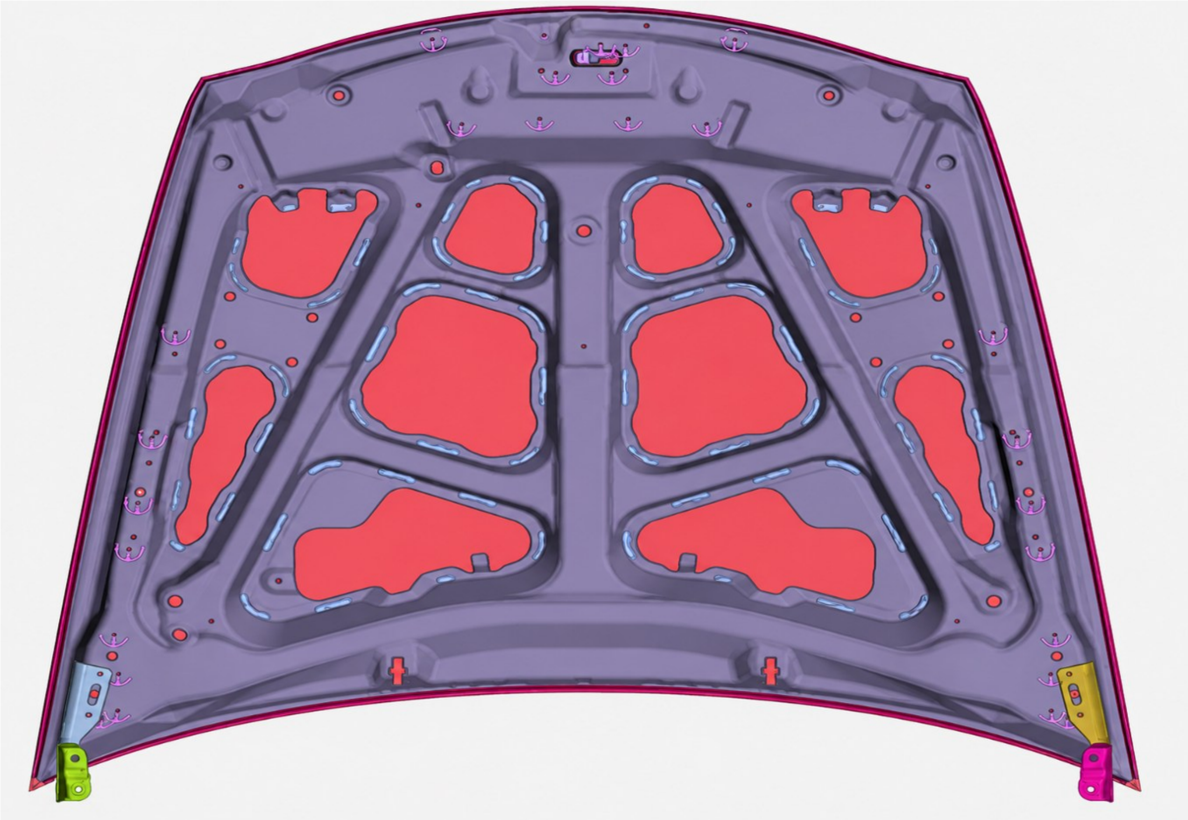
Case study: Bonnet Crash Design Exploration



Case study: Bonnet Crash Design Exploration

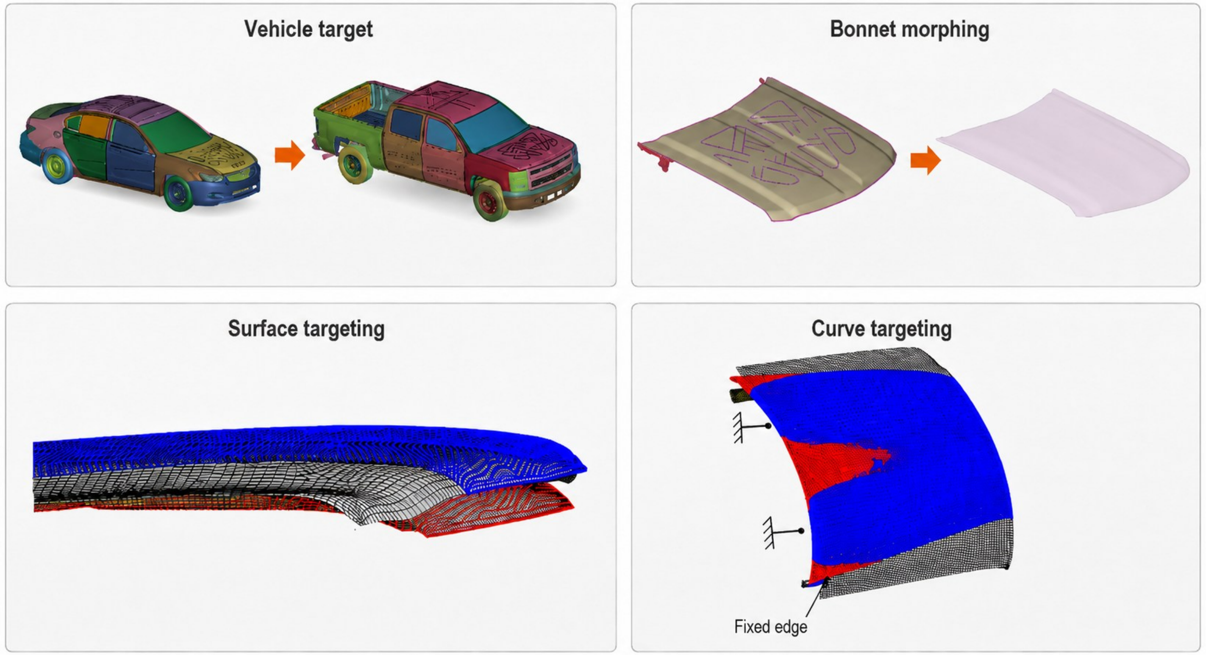
- The study builds upon a previous LS-DYNA crash analysis of a Honda Accord bonnet, where mesh morphing was used to match the Chevrolet Silverado geometry and crash performance.
- Here, the same baseline problem is revisited with a different approach: moving from a conventional optimization workflow to an interactive design exploration framework.
- The transient crash response is sampled at selected time instants and used to build a POD-based Reduced Order Model.
- The resulting ROM enables the bonnet design space to be explored interactively, providing an almost immediate reconstruction of the crash response for new configurations.



‘Integrating *RBF Morph* and *LS-DYNA* into *ANSYS Workbench* and *Mechanical* for car bonnet crash optimisation. Marco Evangelos Biancolini, Leonardo Geronzi’

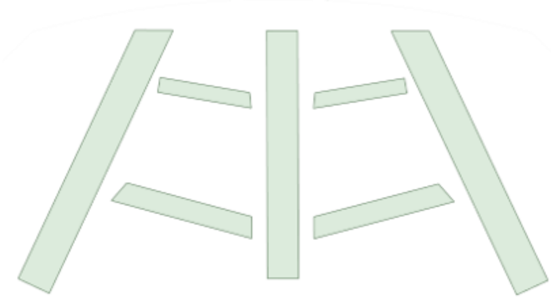
Case study: Bonnet Crash Design Exploration

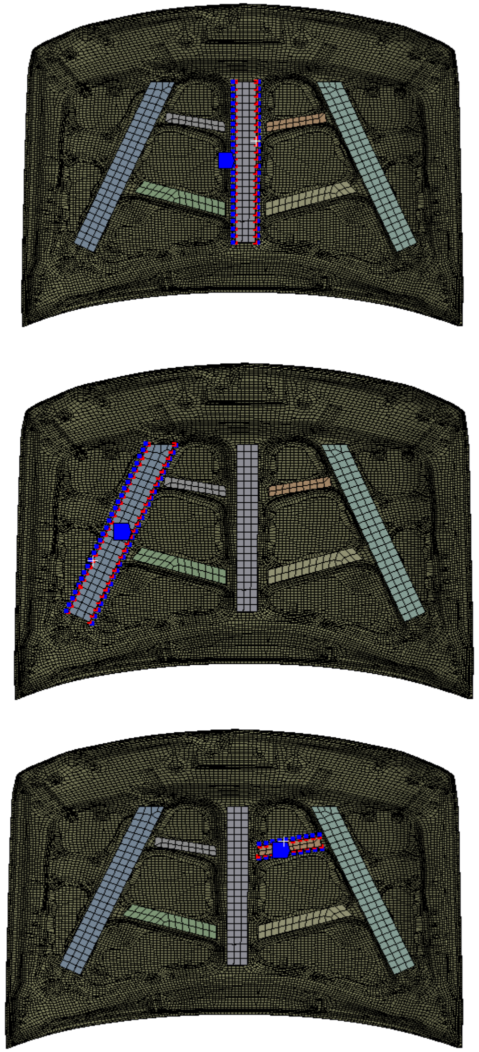
- Model transformation by **mesh morphing**
- The principle is to take the control on a set of point and to transfer the deformation to the whole mesh
- In this way the original model can be projected to the target one



Case study: Bonnet Crash Design Exploration

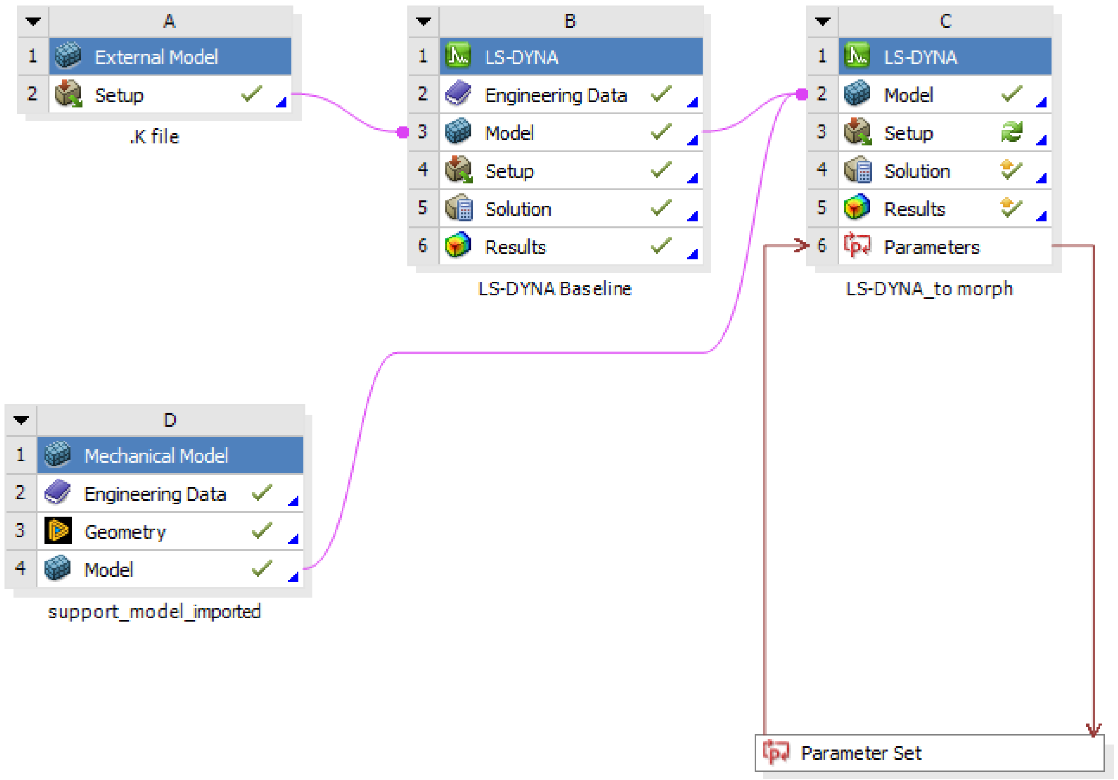
- As second step, parameterization by **mesh morphing** has been set up to search for the matching of kinematic response of the structure
- Using a supporting CAD model to drive the parameterization



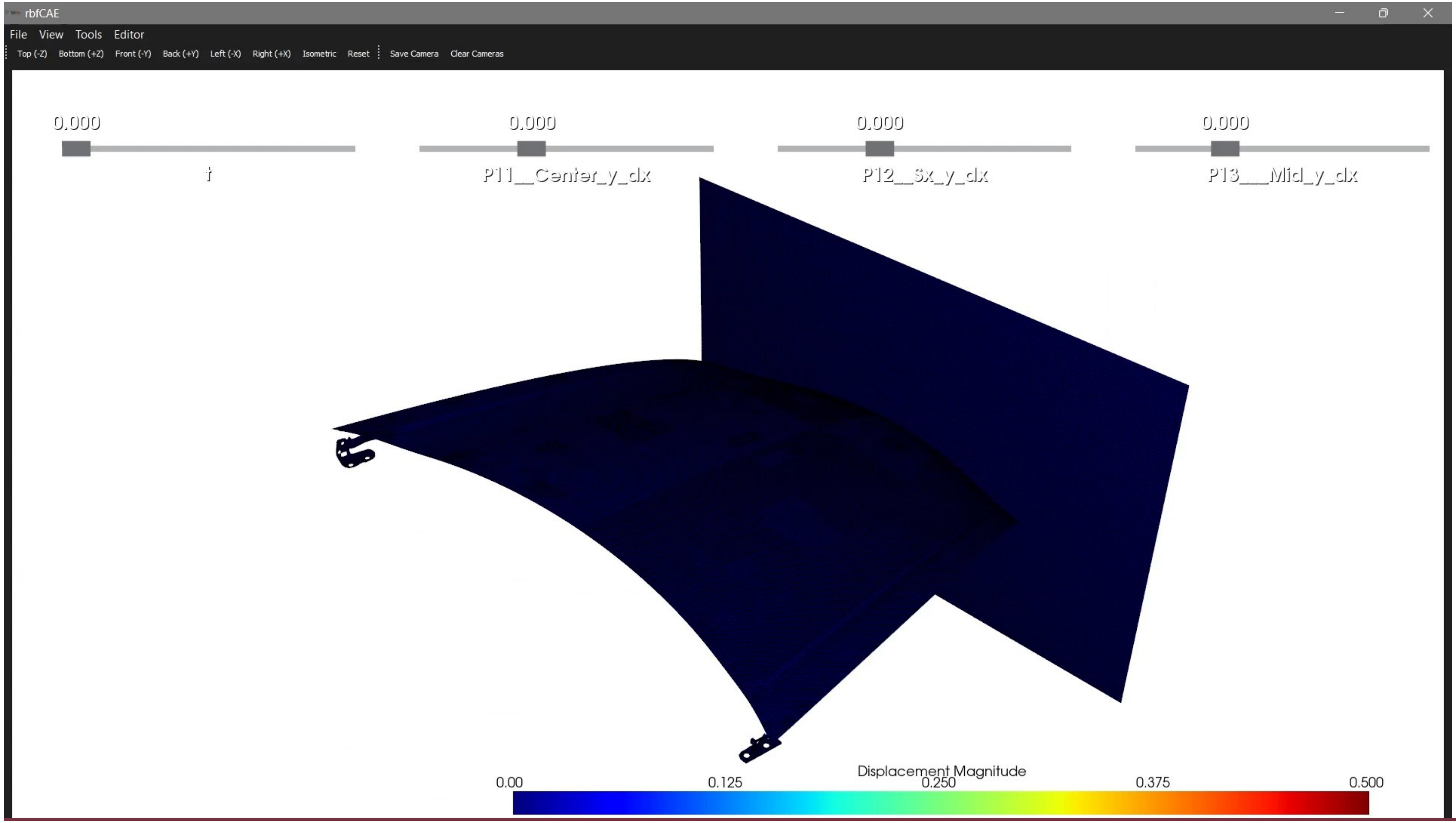


Case study: Bonnet Crash Design Exploration

- A Design of Experiments is performed over three geometric shape parameters, with one transient LS-DYNA crash simulation for each design point.
- The **transient response is sampled** at selected time instants, with each simulation state treated as an individual **snapshot for the POD**.
- Each snapshot is therefore associated with four input coordinates:
  - 3 geometric parameters
  - 1 time coordinate
- The resulting **ROM** describes the crash response as a continuous function of both shape and time, enabling the reconstruction of the transient behavior for different geometrical configurations.

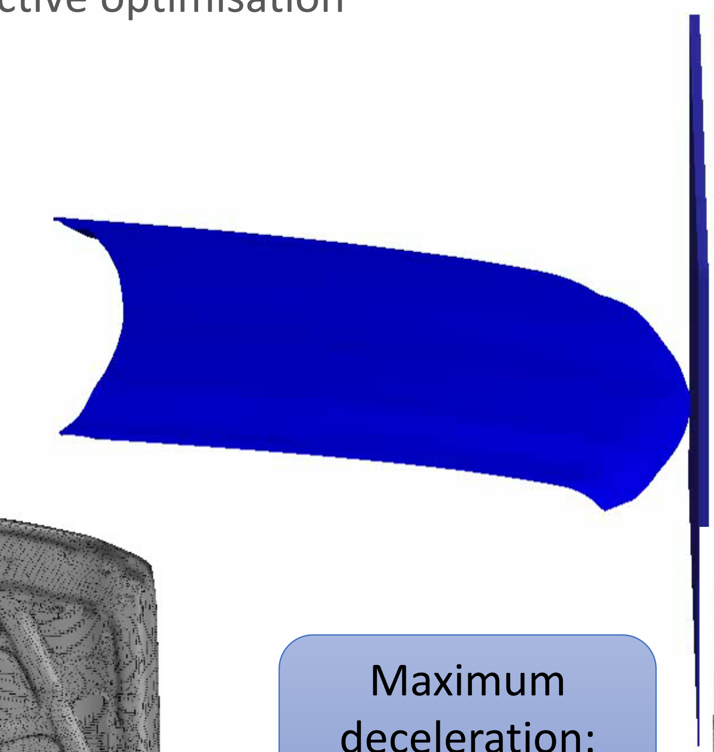


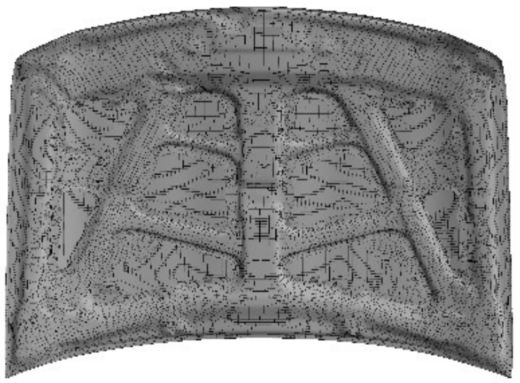
Case study: Bonnet Crash Design Exploration



Case study: ROM design choice

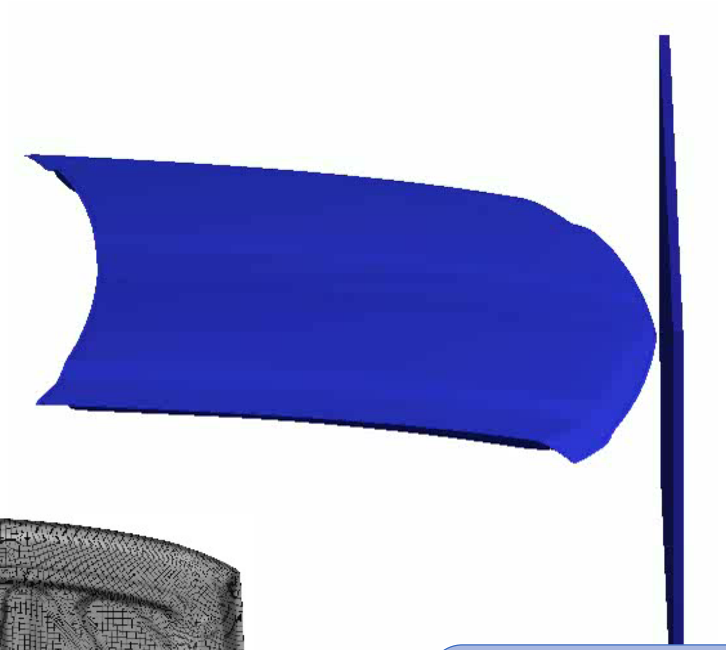
- Optimal solution resulting from the interactive optimisation

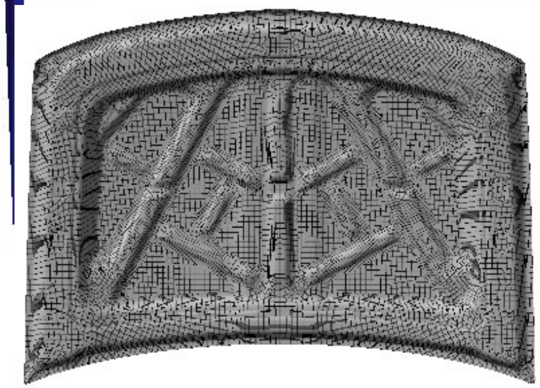




Maximum deceleration: 7.1 g

- Actual Silverado





Maximum deceleration: 6.9 g

Conclusions

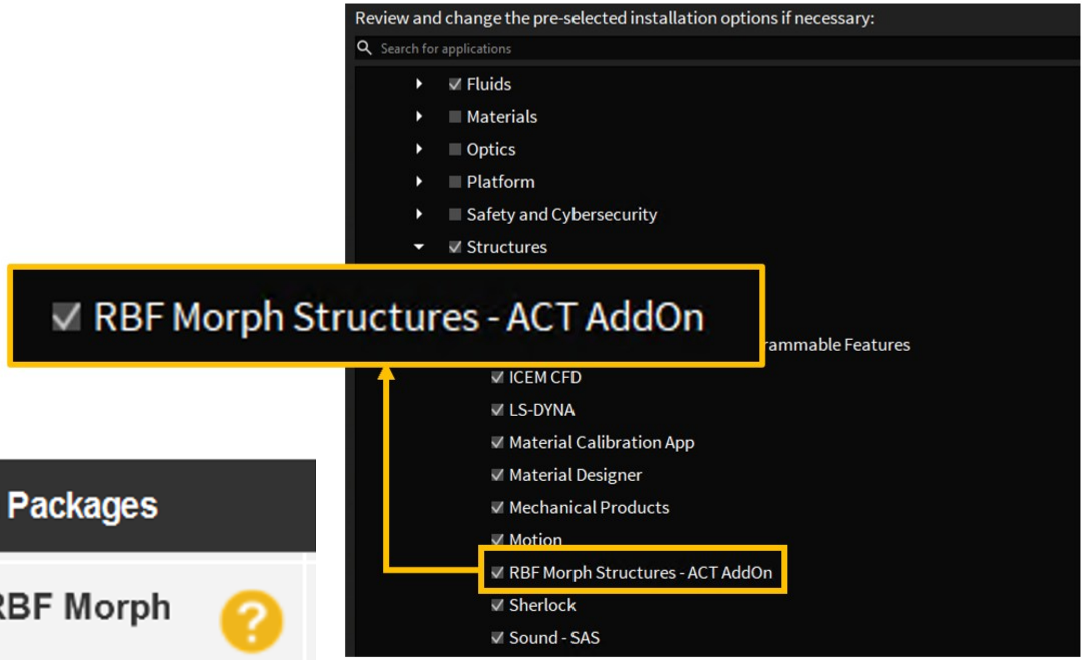
- **Fast RBF enable efficient geometry manipulation and parameterization**, providing a bridge between CAD models and high-fidelity CAE simulations.
- The proposed workflow combines **mesh morphing, LS-DYNA simulations and POD-based ROMs** to transform transient crash analyses into **interactive design exploration tools**.
- By embedding **shape parameters and time into the reduced space**, the ROM enables fast reconstruction of the structural response across the explored design space.
- This approach supports the transition from **simulation-based optimization** to **interactive and real-time CAE-driven decision making**.

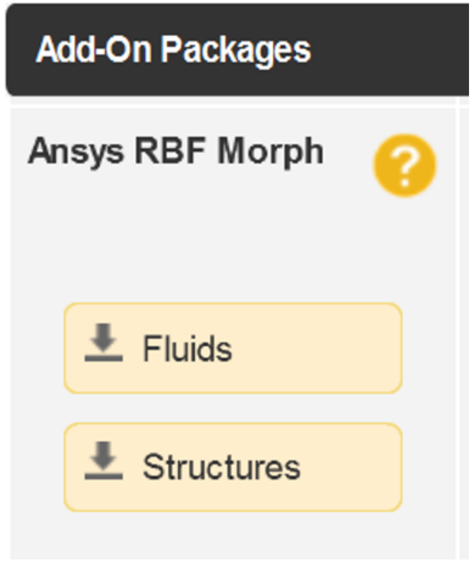
Open challenges

- Extension to **larger and more complex industrial models**.
- Improved **free-form interaction** for intuitive design exploration.
- Combination of **mapping, morphing and remeshing** to extend the applicability of synthetic datasets.

RBF Morph?

- An RBF mesh morphing solution fully embedded in Ansys
- **Ansys RBF Morph Structures** is an Add-On for Mechanical
- Full integration with **optiSLang, Twin Builder, SimAI**
- Support for **LS-DYNA** and **APDL**





THANK YOU!

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