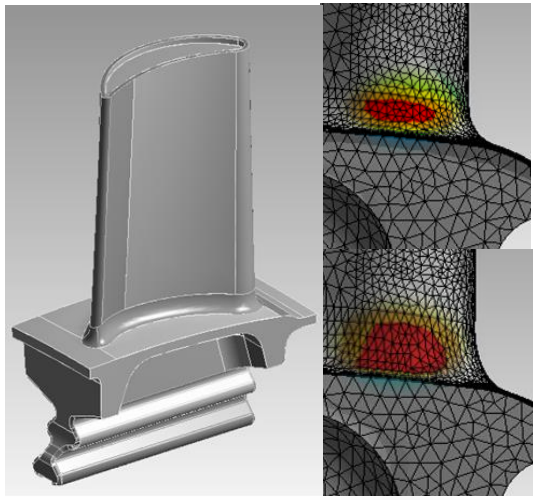
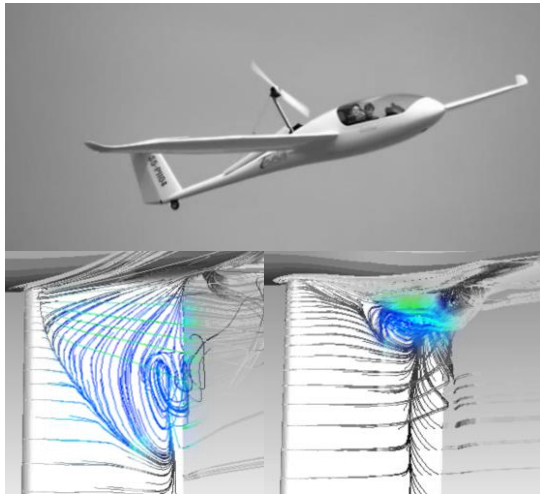




RBF Morph Introduction

Advanced mesh morphing for the definition of reduced order models and digital twins

Dr. Marco Evangelos Biancolini

CTO and company founder

RBF Morph srl

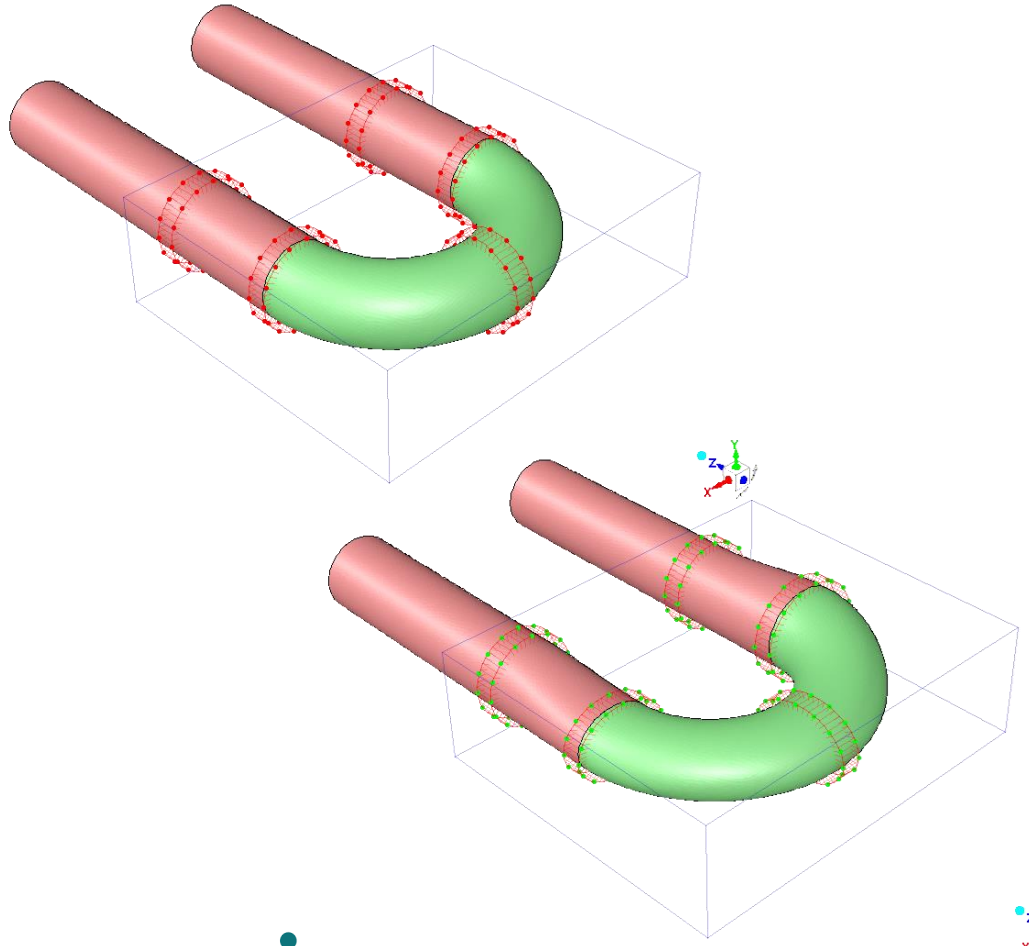
Outline

- A short introduction to RBF Morph and Radial Basis Functions (RBF) background
- Advanced mesh morphing software solutions
- An overview of applications
  - Fluids
  - Structures
  - Digital Twins - Healthcare
- Conclusions

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

Shape parameterization strategy

- Geometric parameterization by **mesh morphing**
- The principle is to take the control on a set of point and to transfer the deformation to the whole mesh
- A **new shape** of the CAE model **ready to run**
  - for structural analysis in the FEA solver
  - for flow analysis in the CFD solver



Radial Basis Functions mesh Morphing

- We offer **Radial Basis Functions** (RBF) to drive mesh morphing (smoothing) from a list of source points and their displacements.
  - Surface shape changes
  - Volume mesh smoothing.
- RBF are recognized to be one of the **best mathematical tool** for mesh morphing.

$$\begin{cases} s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi(\|\boldsymbol{x} - \boldsymbol{x_{s_i}}\|) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi(\|\boldsymbol{x} - \boldsymbol{x_{s_i}}\|) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi(\|\boldsymbol{x} - \boldsymbol{x_{s_i}}\|) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

Radial Basis Functions mesh Morphing

(rbf-morph)™

Welcome to the World of Fast Morphing!

www.rbf-morph.com

- Main advantages
  - No re-meshing
  - Can handle any kind of mesh
  - Can be integrated in the CAE solver (FEM/CFD/FSI)
  - Highly parallelizable
  - Robust process
  - The same mesh topology is preserved (adjoint/ROM)
  - CAD morphing (iso-brep)

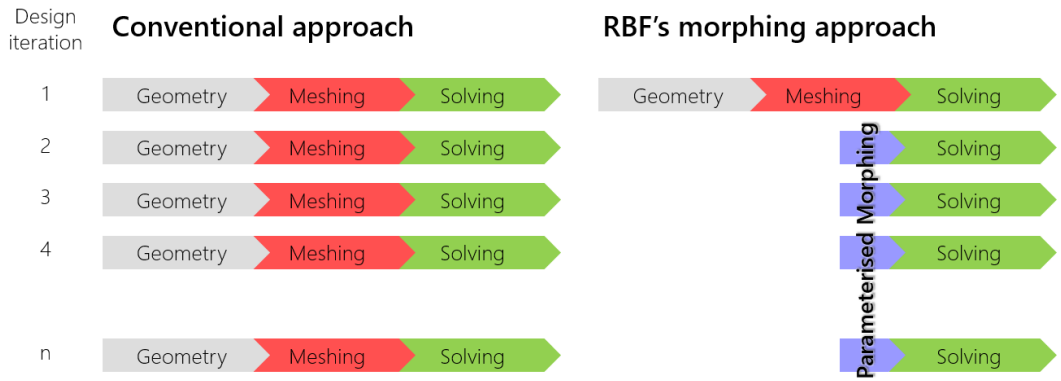
Parametric CAE models

CAE models supported includes flow analysis (CFD) and structural analysis (FEM)

RBF Morph makes the CAE model parametric with respect to the shape.

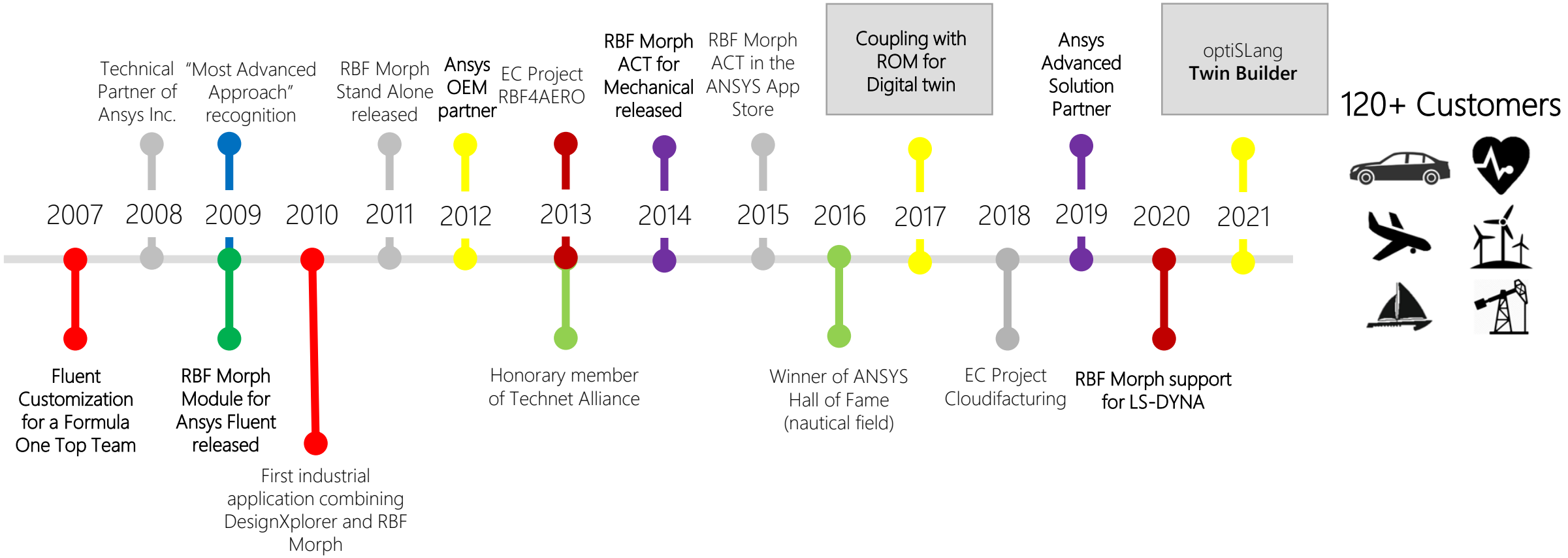
Works for any size of the mesh.

Shape parameters can be steered with the optimizer of choice.



- It's **easy and fast**: shape parameters are defined in the CAE GUI. No need to iterate the CAD.
- The turnaround time of the optimization is usually **reduced by a factor five** (weeks becomes days)

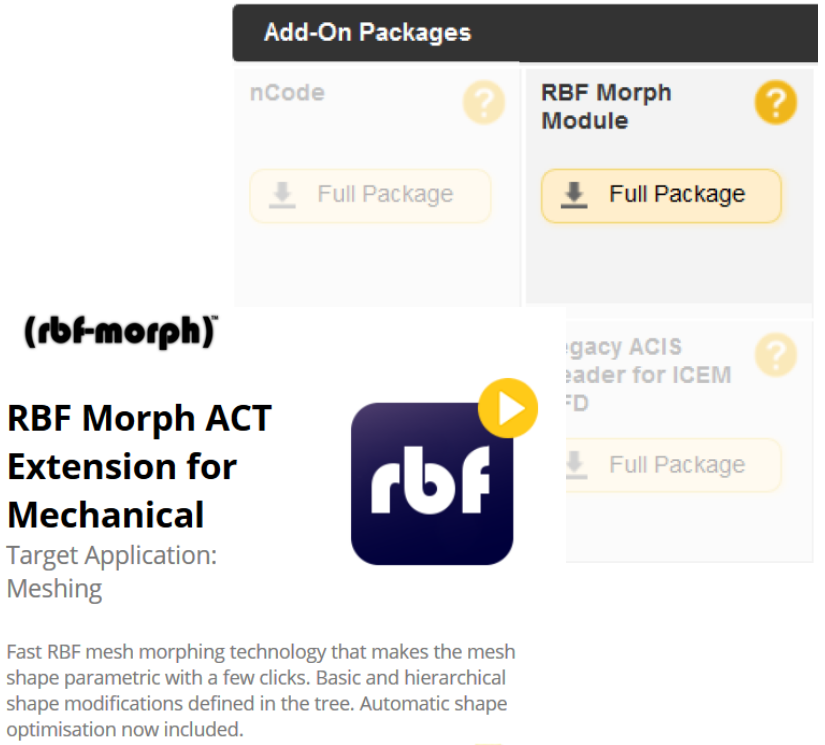
A solution based on 10+ years of experience



We offer Ansys integrated solutions…

ACT Extension (FEM)

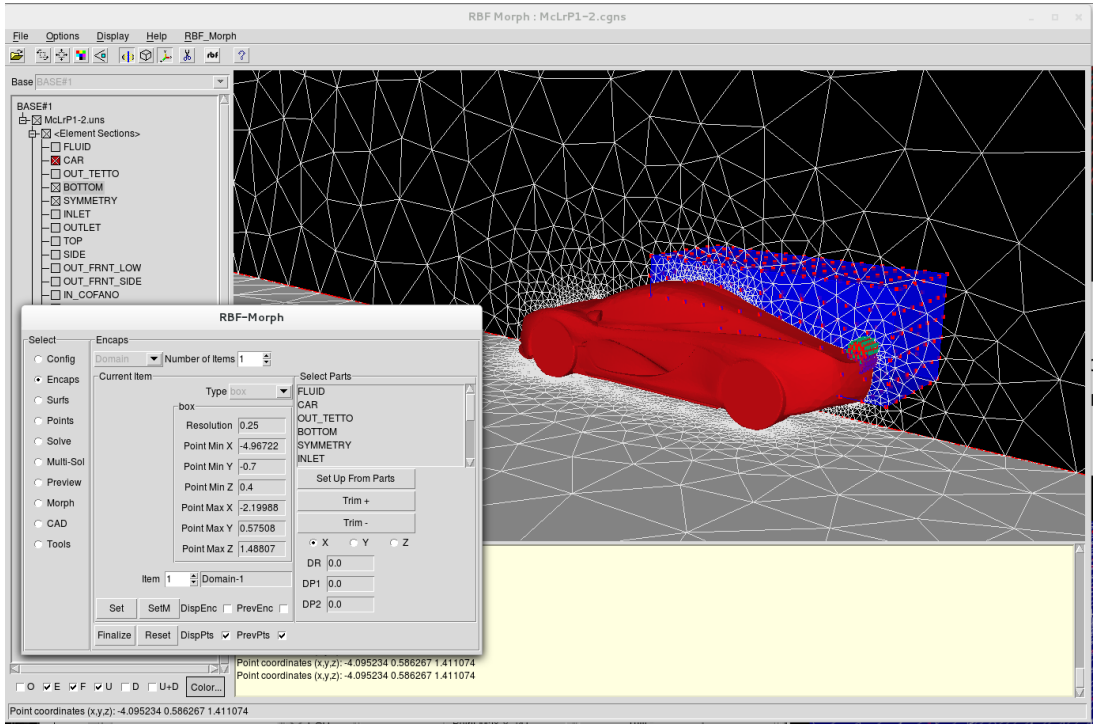
- Released in **2014**
- Fully embedded in ANSYS **Mechanical** (parametric)
- Benefits of **underlying geometry** (or aux geo with dead meshes)
- …**WB** Meshing



Fluent Module (CFD)

- Released in **2009**
- Fully integrated within Fluent (GUI, TUI & solving stage), Workbench and **Adjoint Solver**
- Multi physics features (**FSI**)

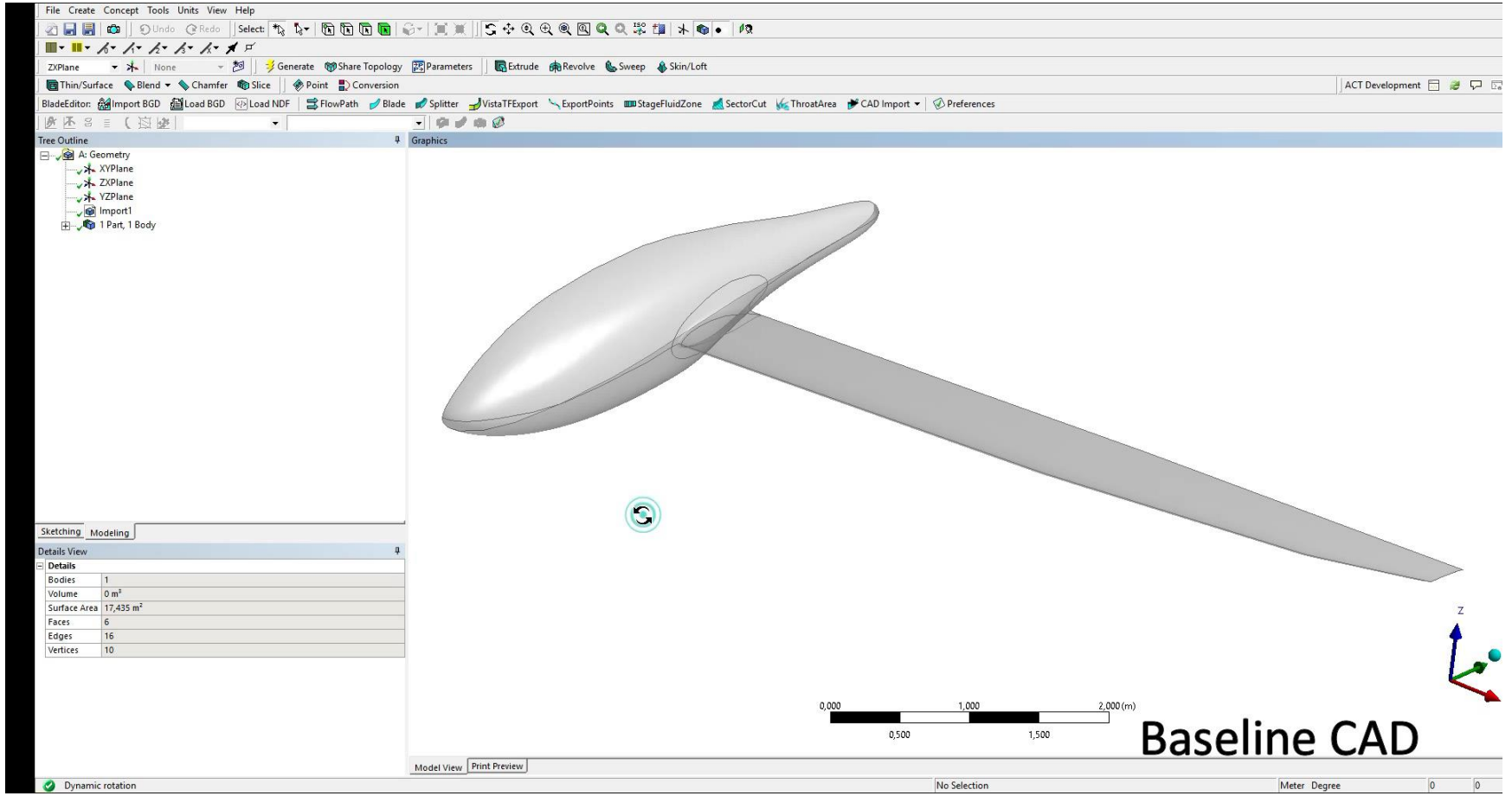
…and a Stand Alone software



- Released in 2011
- Read in **STL and CGNS file formats**.
- Solver independent process that supports **many mesh formats**
- **Scriptable** via tcl

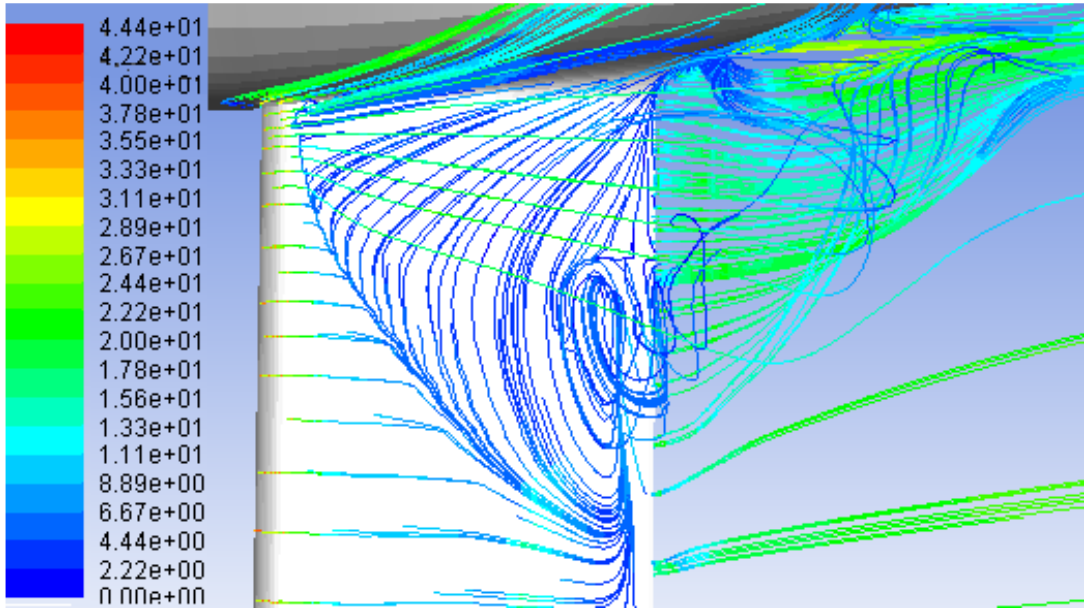
RBF Morph Fluent Module

https://youtu.be/EWsigyqByRg

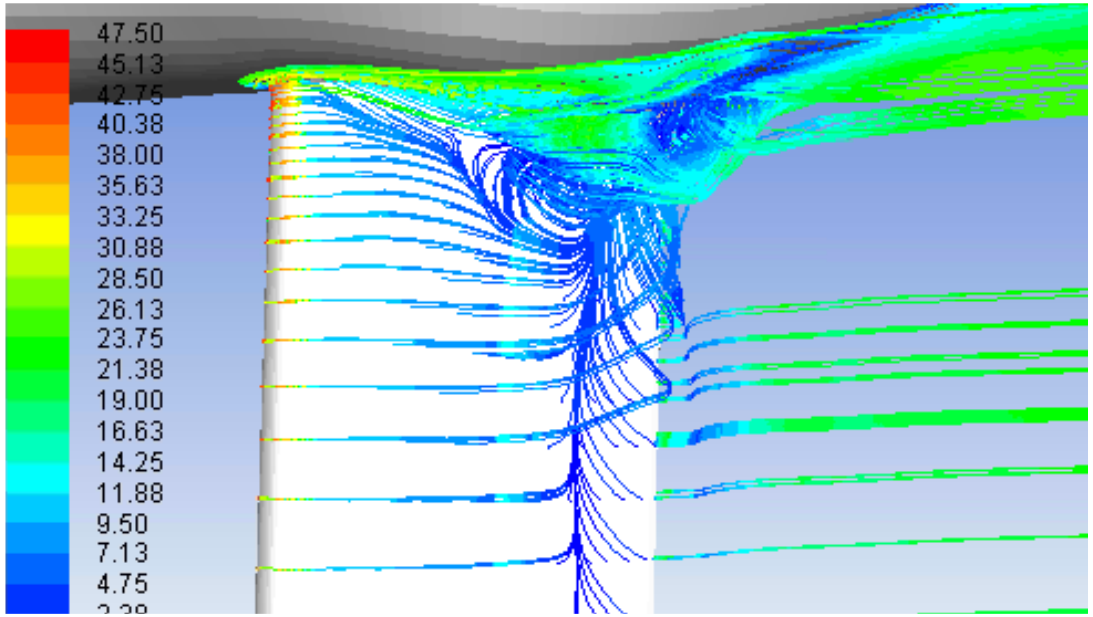


Glider optimization

Original design E=14.9

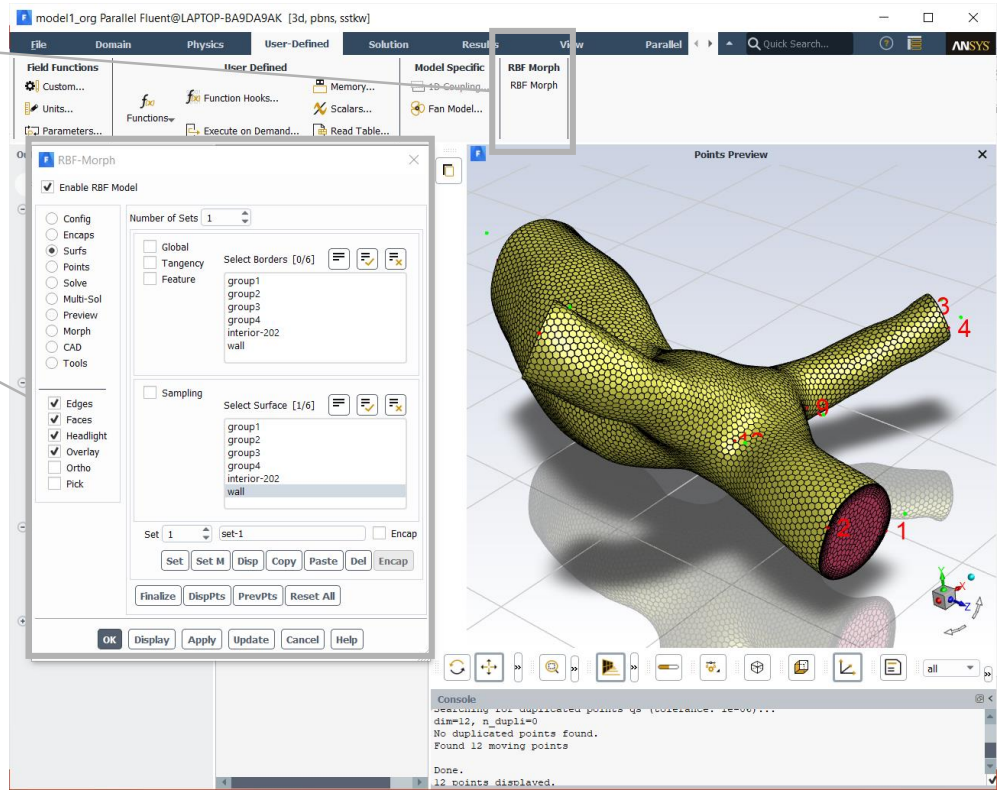


Optimal design E=20.1 (+35%)



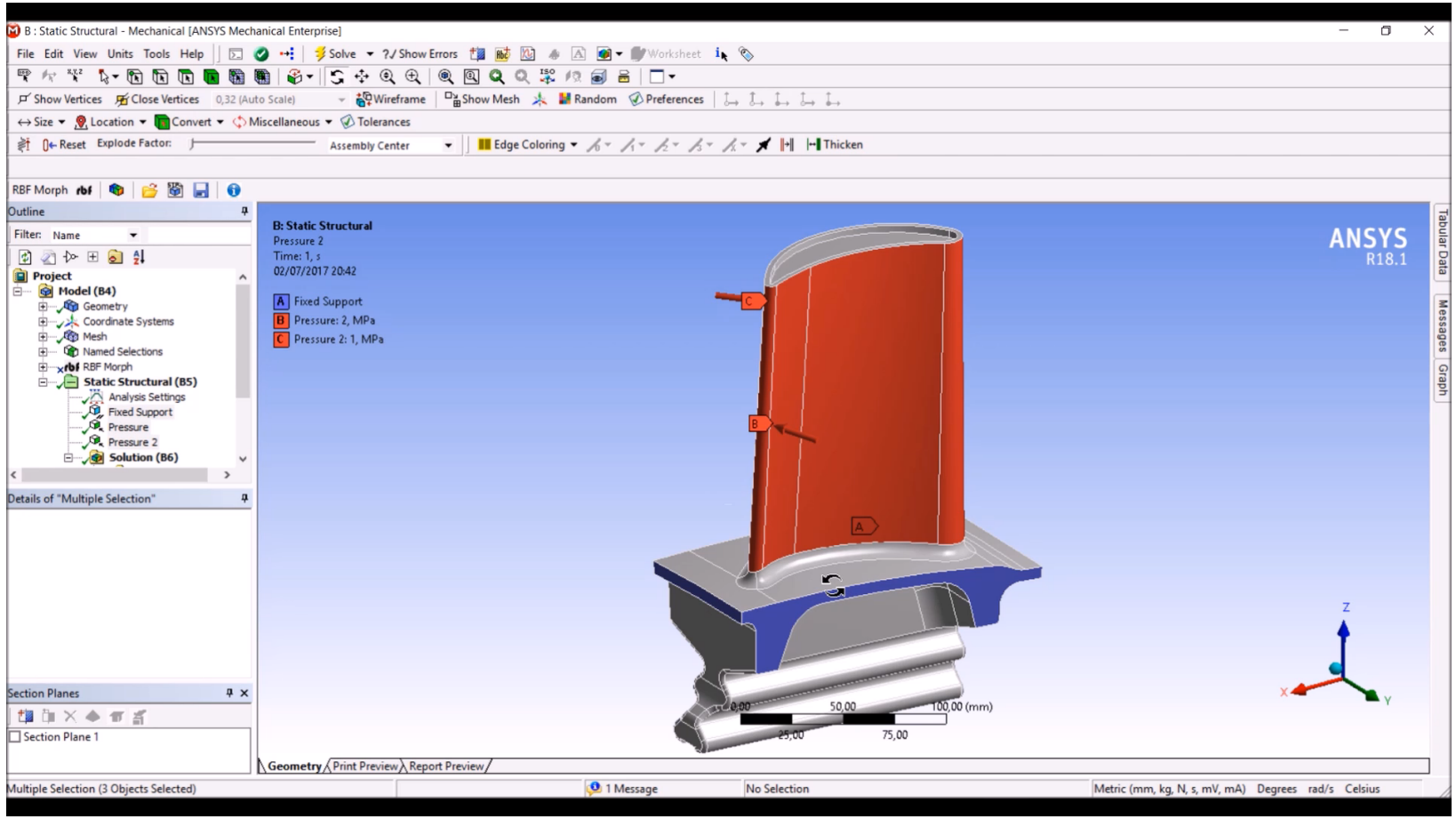
Fluent module

- Add on fully integrated within Fluent (GUI, TUI & solving stage), **Workbench** and **Adjoint Solver**
- Mesh-independent RBF fit used for **surface** mesh morphing and **volume** mesh smoothing
- **Parallel** calculation allows to morph large size models (many millions of cells) in a short time
- Management of **every kind of mesh** element type (tetrahedral, hexahedral, polyhedral, etc.)
- Support of the **CAD** re-design of the morphed surfaces
- Multi fit makes the Fluent case **truly parametric** (only 1 mesh is stored)
- Precision: exact nodal movement and exact feature preservation (**RBF are better than FFD**)

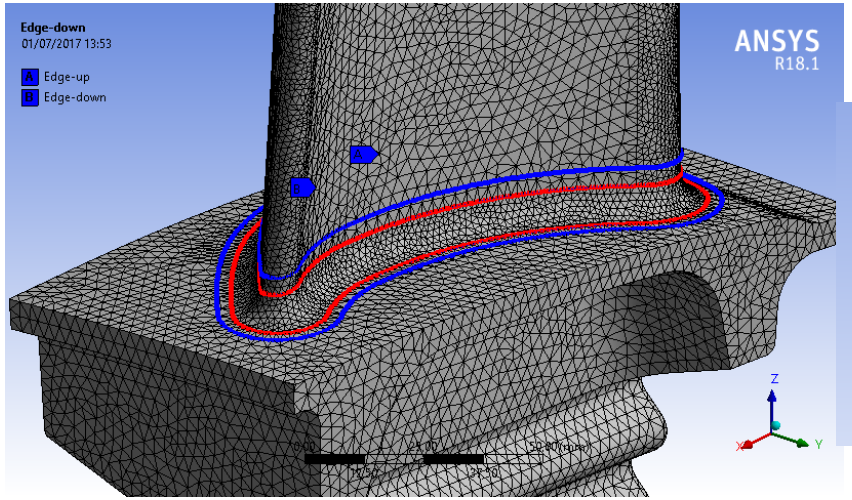


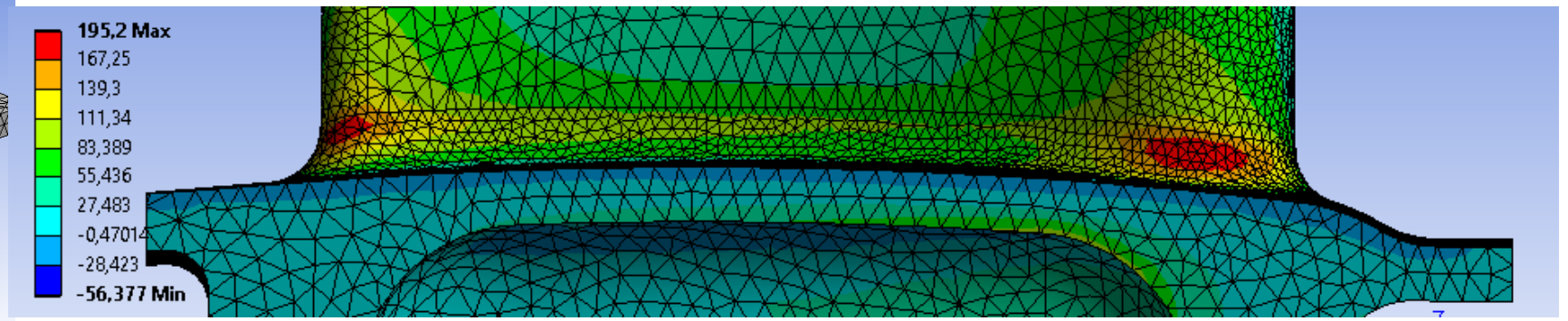
RBF Morph ACT Extension

https://youtu.be/TUOJGAG7Wtk

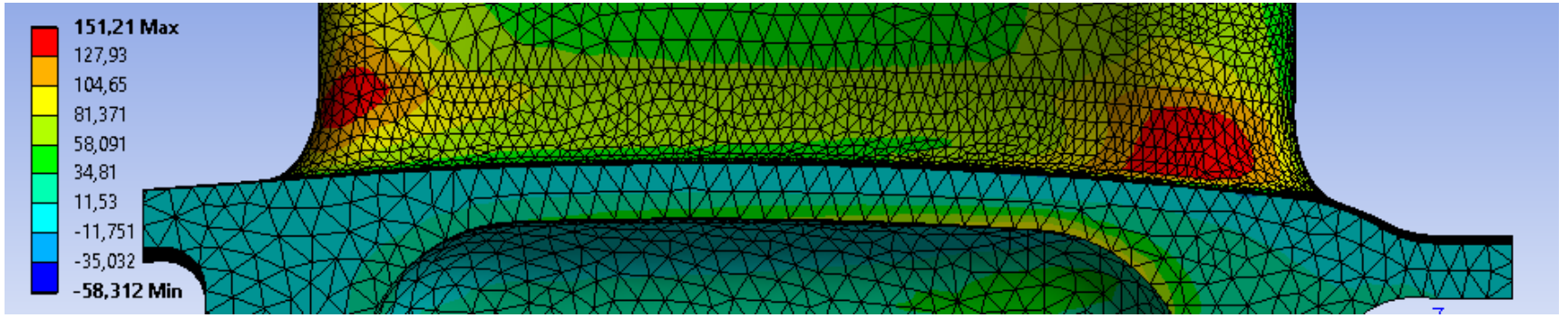


Blade fillet stress reduction



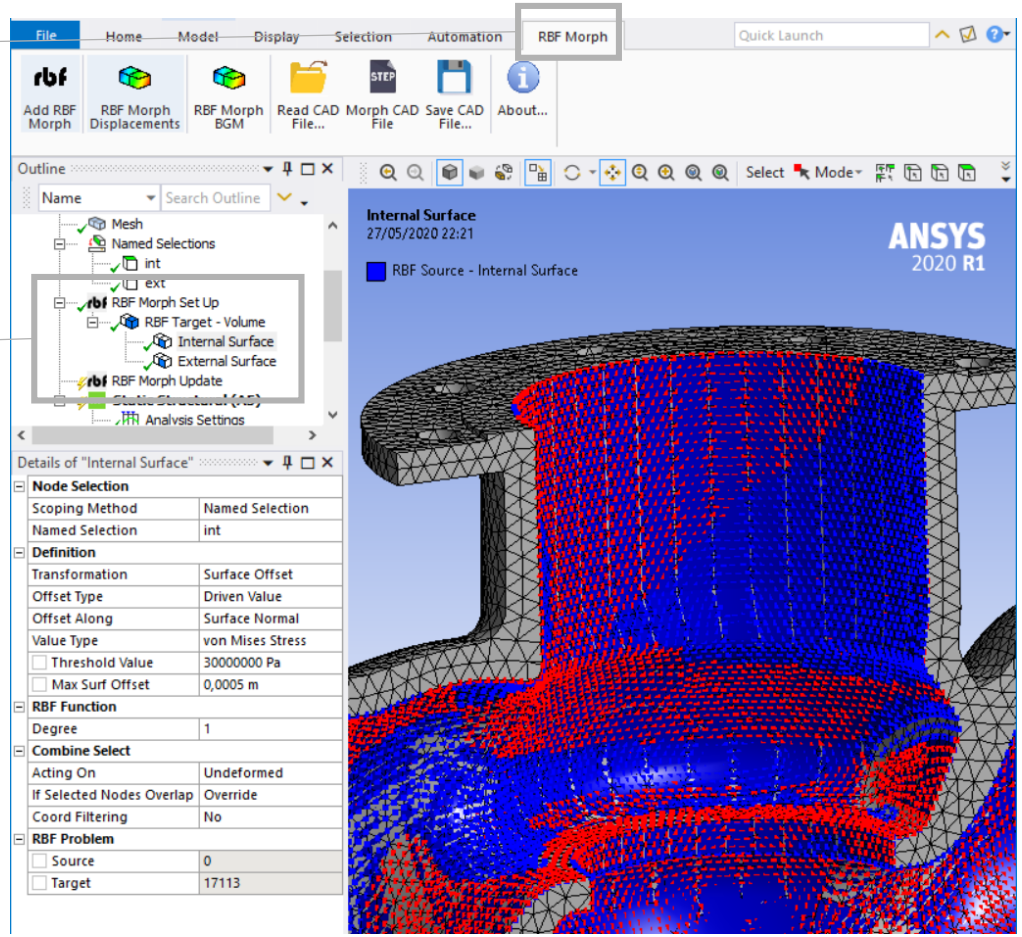


- Two parameters allow to get a 22.5% stress **reduction**



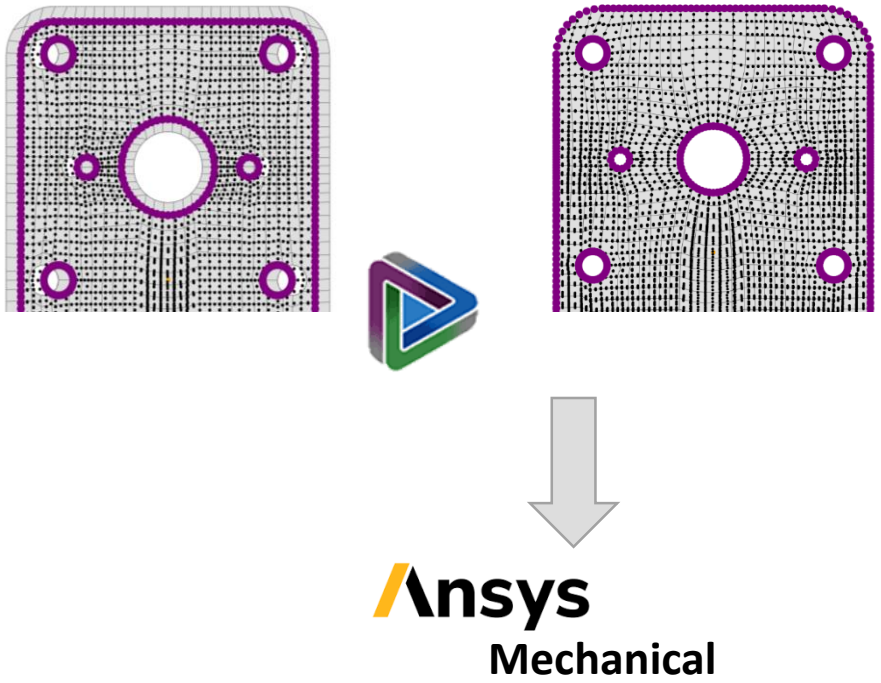
ACT Extension for Mechanical

- Deeply integrated in ANSYS Mechanical: same **look & feel**, same interaction logic, **same parameters!**
- Nested in the usual Mechanical **tree** as an added object, shares its scoping tools for geometrical and mesh elements selections
- Written in python and xml, uses external **RBF library** (OpenMP and CUDA powered)
- Child **hierarchical** logic for complex morphing (two steps, three steps, …, n steps setups)



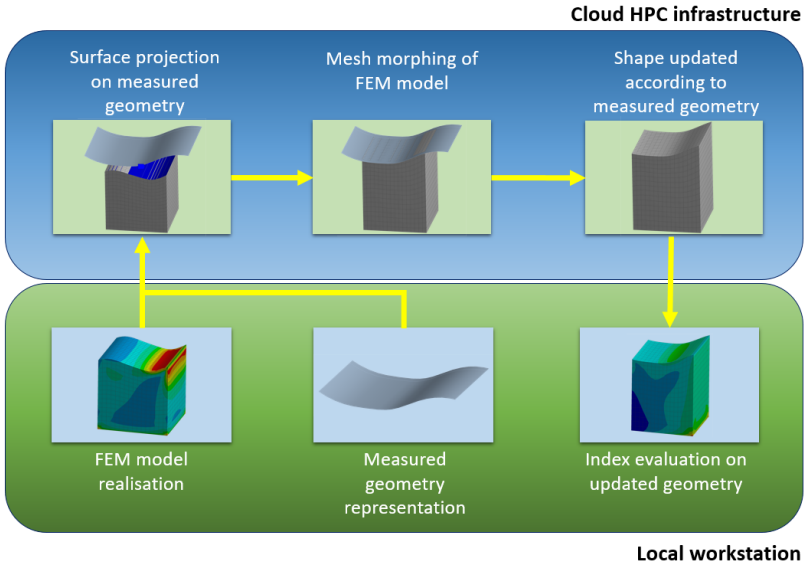
Prototype – Space Claim module

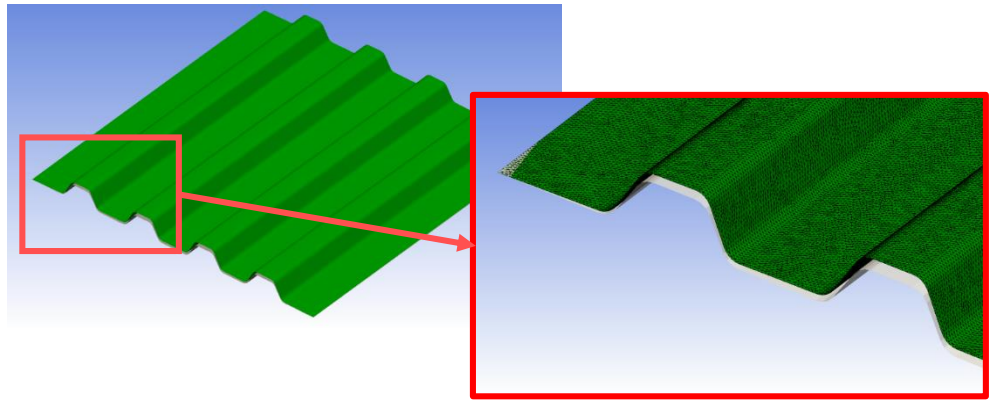
- Combines **direct modelling** within Space Claim (with persistent topology) and **mesh morphing**
- The RBF mesh morphing project is fully automated (no UI to set-up mesh morphing)
- The morphed mesh can be run in **Ansys Mechanical** (specific ACT can read in the shape)
- **Remeshed mesh** and **morphed mesh** are available for the same shape variation



RBF Morph Functions Library

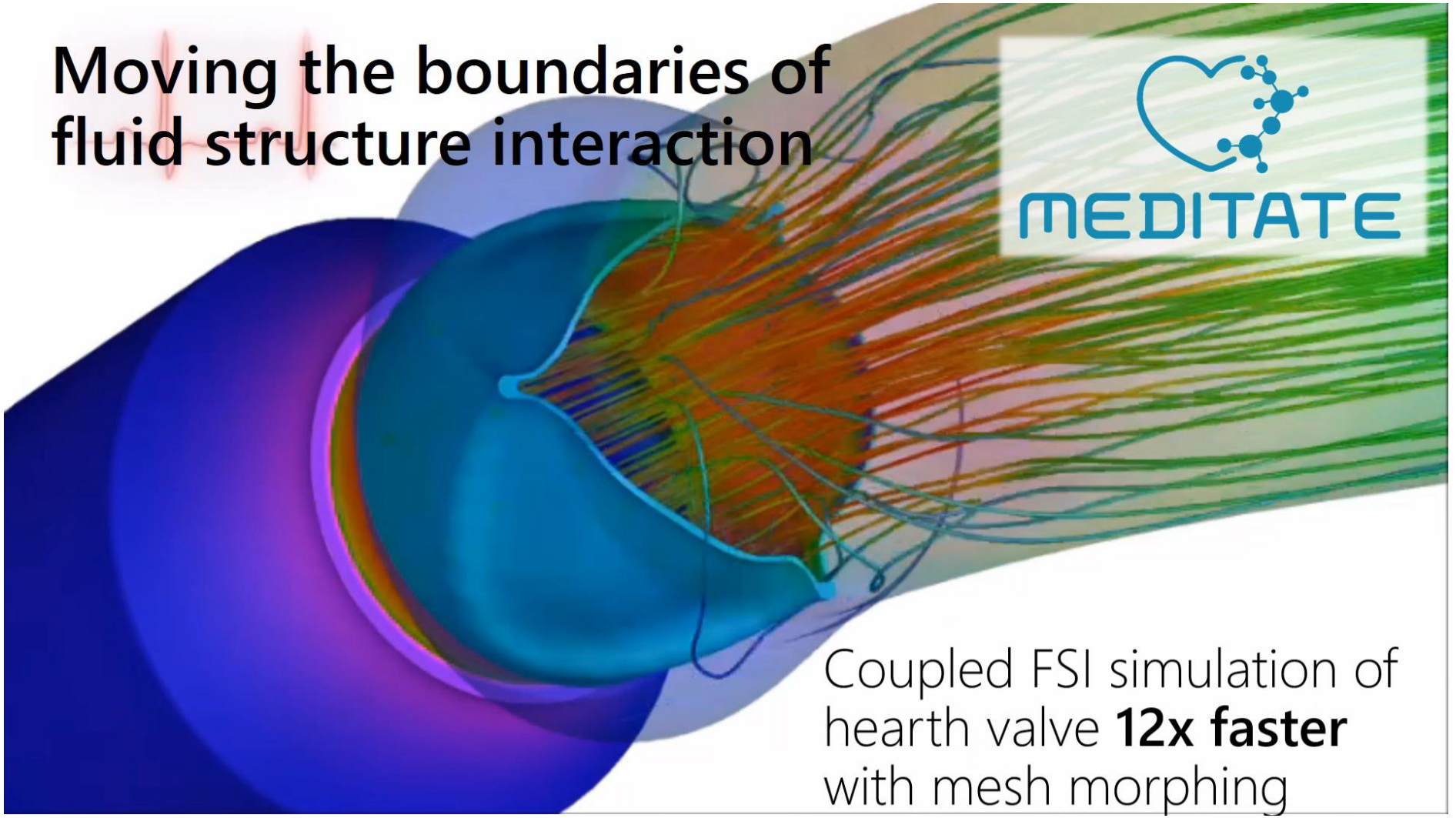
- **Fast implementation** of the RBF problem solver in C++
- **API** to directly access RBF solver, morpher, STL surface projection and strain-stress evaluation functions
- Successfully **integrated** with existing software line (in alpha and beta testing phase)
- Successfully used in the **CAE^{UP} Project**





What can we do for flow applications?

Advanced workflows powered by RBF Morph Fluent Module

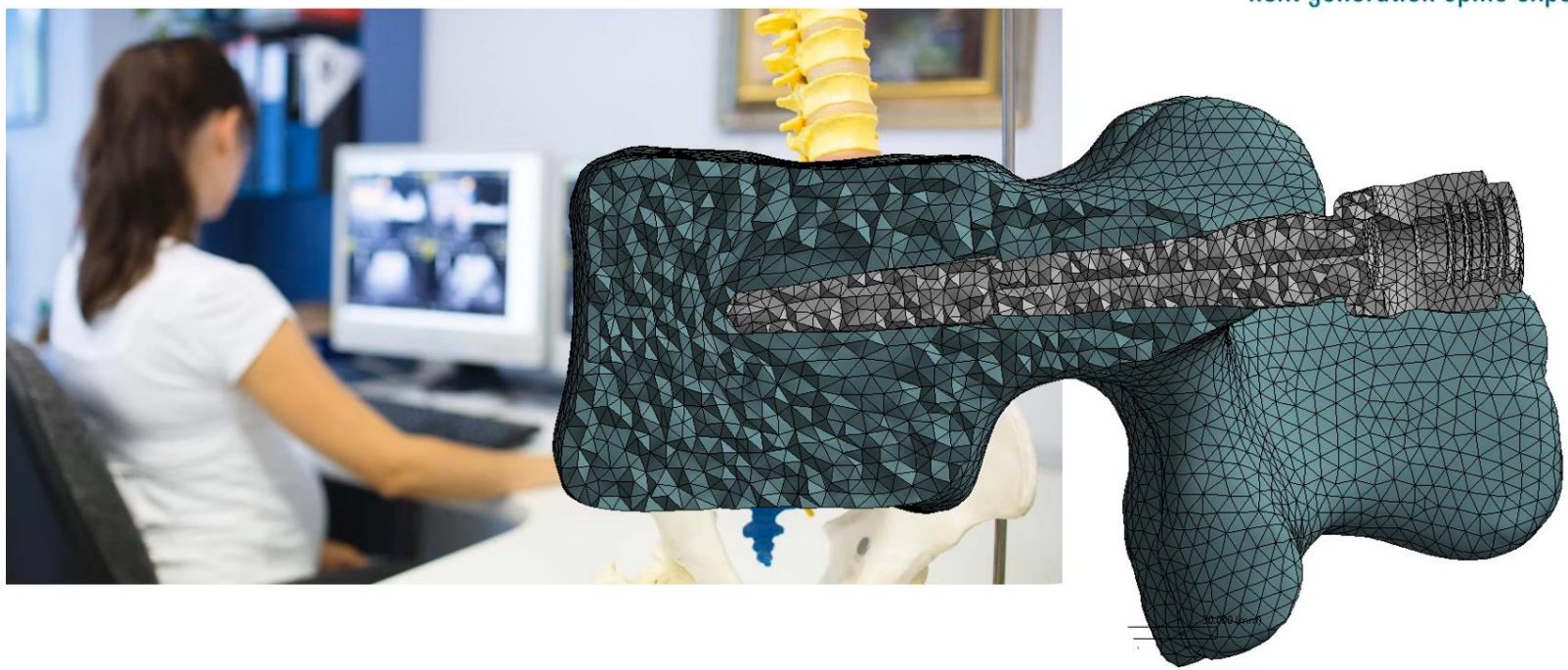


https://youtu.be/Txd6gvkhko0

What can we do for structural applications?

Advanced workflows powered by RBF Morph ACT Extension for Mechanical

Spine surgery Digital Twin



https://youtu.be/Txd6gvkhko0

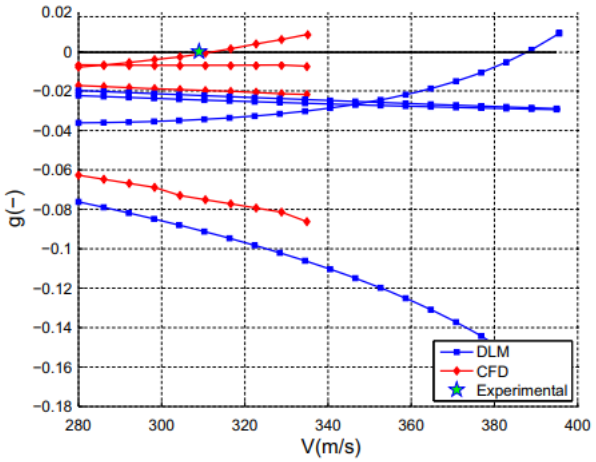
What can we do for digital twins?

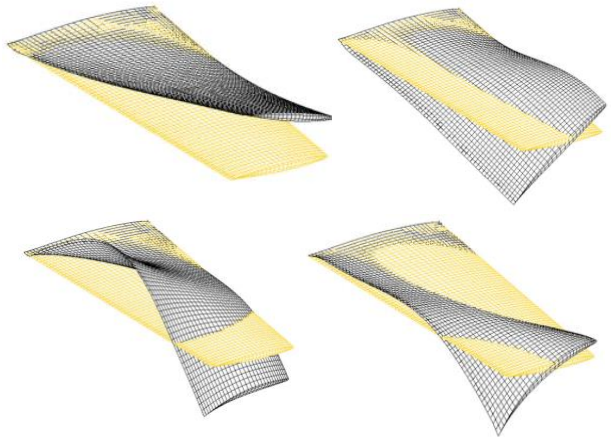
Mesh morphing allows to have shape parameters with a consistent mesh so enabling PCA, SVD and other compression techniques suitable for static and dynamic ROM generation.

rbf™

ROM & Digital Twin

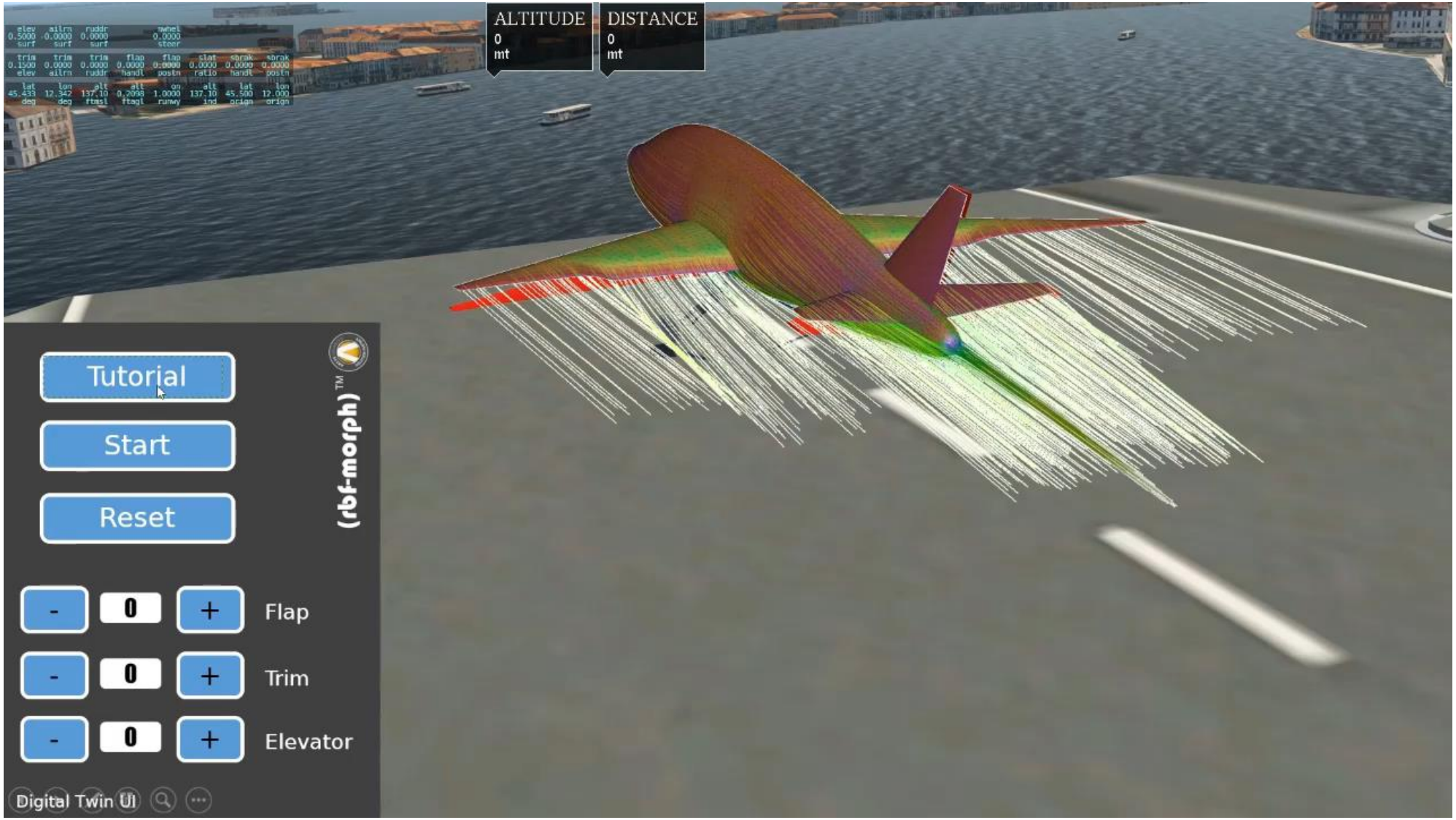
- Active on Reduced Order modeling (**ROM**) since 2016[1]. Mesh morphing is a key-enabler of the technology.
- ROM generated for the unsteady aerodynamics by means of a modal based approach: flutter identification
- Aircraft Digital Twin





[1] Castronovo, P., Mastroddi, F., Stella, F., & Biancolini, M. E. (2016). Assessment and development of a ROM for linearized aeroelastic analyses of aerospace vehicles. CEAS Aeronautical Journal, 8(2), 353–369. https://doi.org/10.1007/s13272-017-0243-6

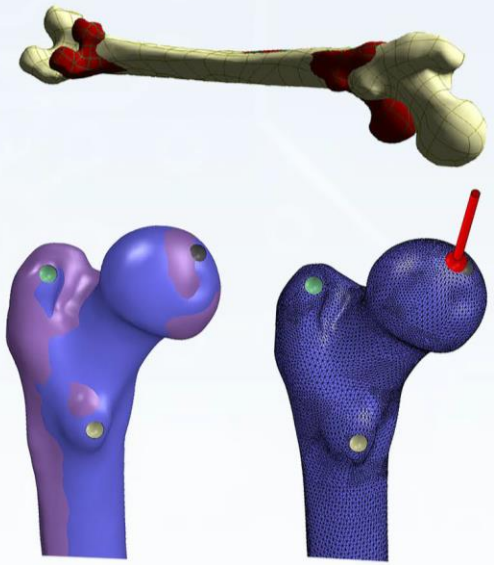
https://youtu.be/YDzGC6fhf4A



Medical Digital Twin

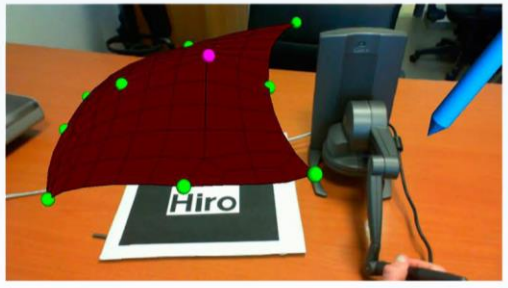
RBF MESH MORPHING

Radial Basis Functions (**RBF**) based Mesh Morphing allows to easily and rapidly adapt exhisting meshes to new shapes.



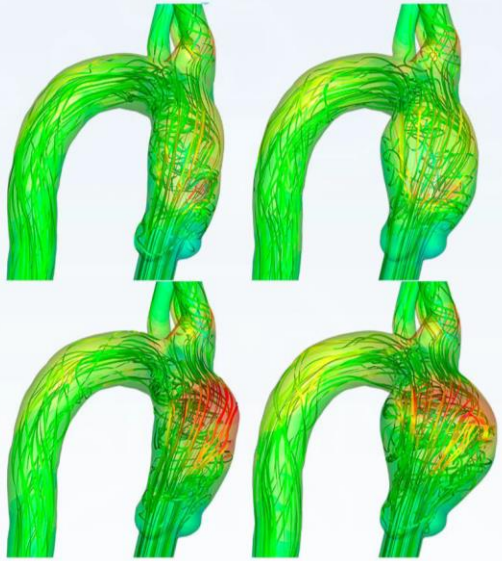
INTERACTIVE SCULPTING

Augmented Reality environment together with **Haptic Devices** allow to use fingers to interactively modify and sculpting model surfaces.



FAST RESULT ACCESS WITH ROM

Thanks to ANSYS® Reduced Order Model (**ROM**) technology, CFD and CSM results on morphed models can be inspected in real time.

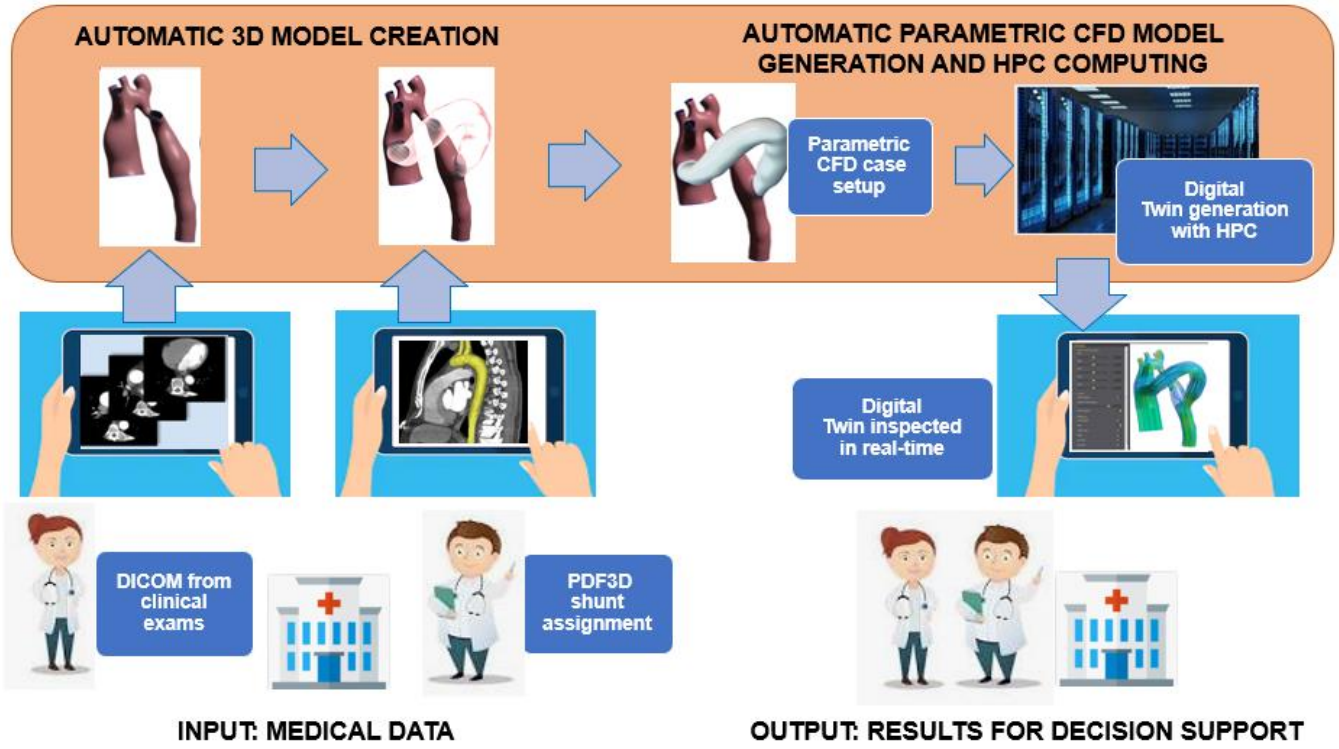


RBF4ARTIST

Digital Twin and mesh morphing application

Cloud-based HPC platform to support systemic-pulmonary shunting procedures.

- The surgeon will receive an MDT consisting of a structured set of numerical results of interest that will be real-time interactive ready to be explored.
- https://www.ff4eurohpc.eu/en/experiments/20210709105125 79/cloudbased_hpc_platform_to_support_systemicpulmonary_shunting_procedures



The Medical Digital Twin for Aneurysm Prevention and Treatment

MEDITATE

PATIENTS DATA

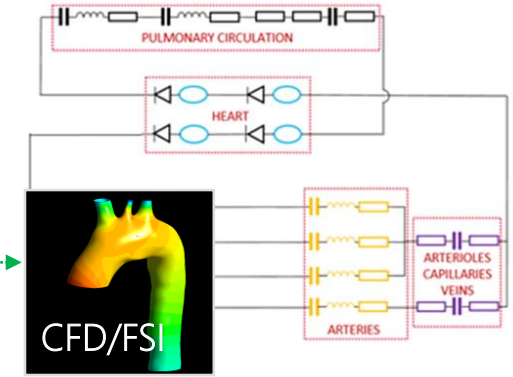
- **CT Scan**
- **MRI Flow**
- **Age, sex, size**
- **Pressure**
- **Hear rate**

Morph Mesh

0D Mod.

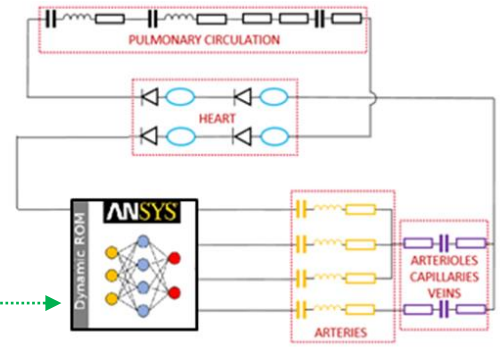
Shape Analysis

Co-Simulation



Hours

TwinBuilder Standalone

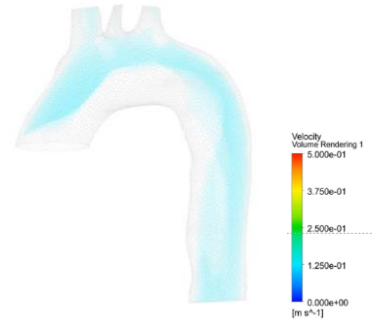


Real-Time

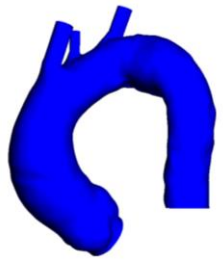
GUI Results for clinical use

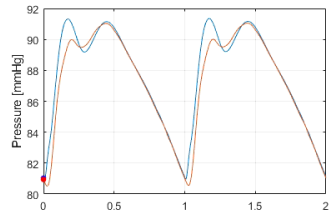
Wall Shear

Velocity



Strain/Stress





23/11/2021

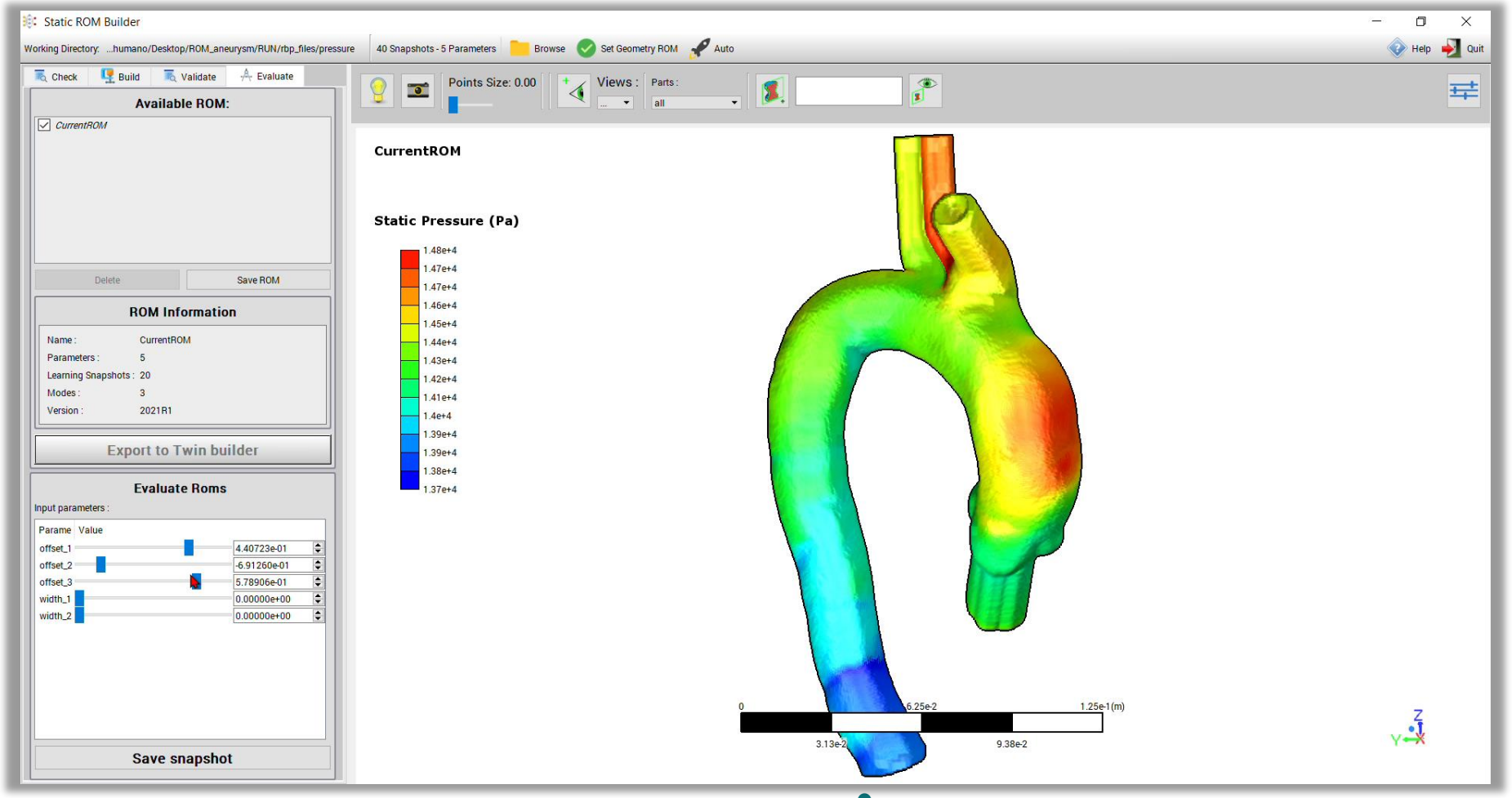
spinner next generation spine experts

Future Perspectives on Spine Surgery

The Medical Digital Twin for Aneurysm Prevention and Treatment

MEDITATE

ESR01/02 – The combined use of mesh morphing, force feedback device and static/dynamic reduced-order models for achieving real-time hemodynamic solution over geometric changes

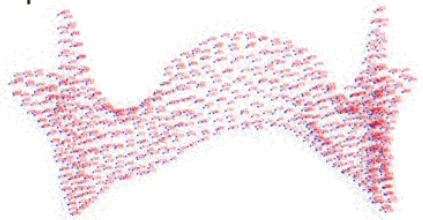


Mandible Morphing through PCA

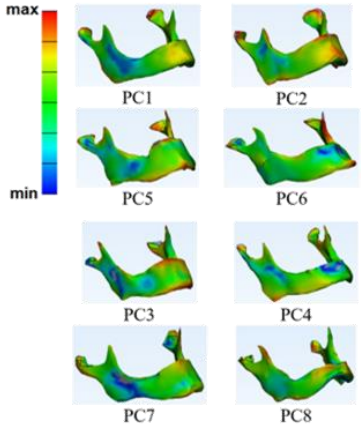
The morphing process has been repeated for the available set of 15 mandibles.

Nodes coordinates of iso-topological meshes have been used as **input** for the **Principal Component Analysis (PCA)**, which was performed through the open source tool MorphoJ[1].

First a Procrustes analysis was performed and the average shape is calculated, then the **Principal Components (PCs)** are evaluated.



Average mandible shape (blue nodes)



8 principal components have been selected, in order to account for **85%** variability of the original set of mandibles.

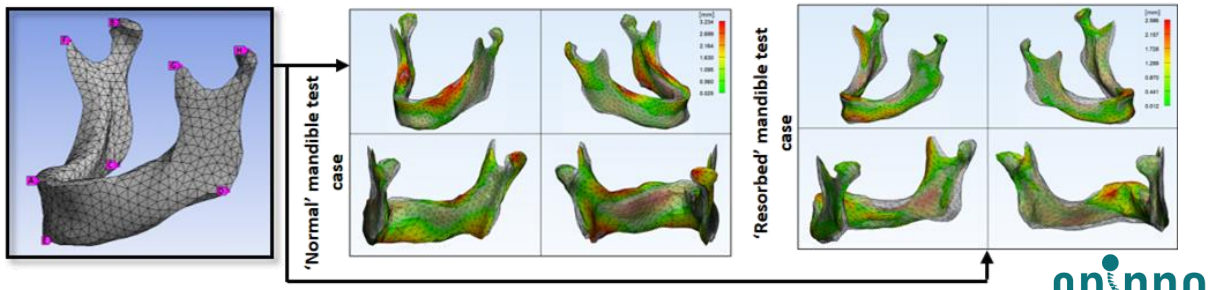
So **8 anatomical landmarks** have been identified for the statistical shape analysis.

PCs are used to describe whichever mandible as a **linear combination of principal modes of deformation of the 'average' mandible**, with proper weights:

$$\{y'\} = \{y\} + a_1 \cdot \{\Delta y_1\} + a_2 \cdot \{\Delta y_2\} + \cdots + a_n \cdot \{\Delta y_n\}$$

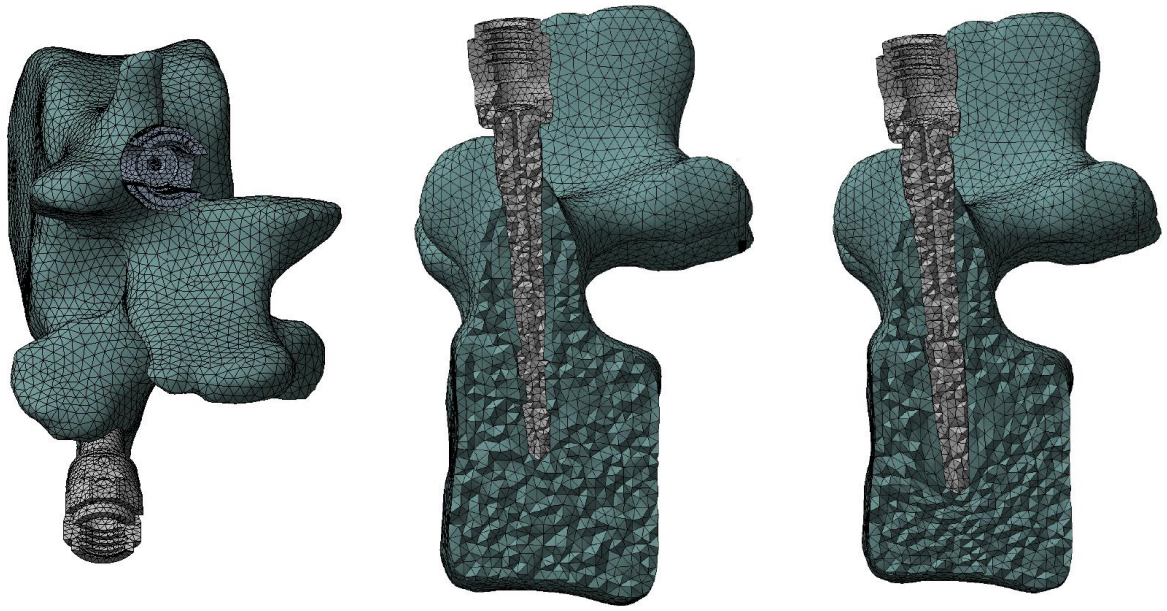
- $\{y'\}$: Vector of node coordinates for the current mandible
- $\{y\}$: Vector of node coordinates for the average mandible
- Δy_i: vector of node by node coordinates variations for '*i*' deformation modes
- a_i: weights to be given to deformation modes, these have been calculated thorough linear regression inside MATLAB

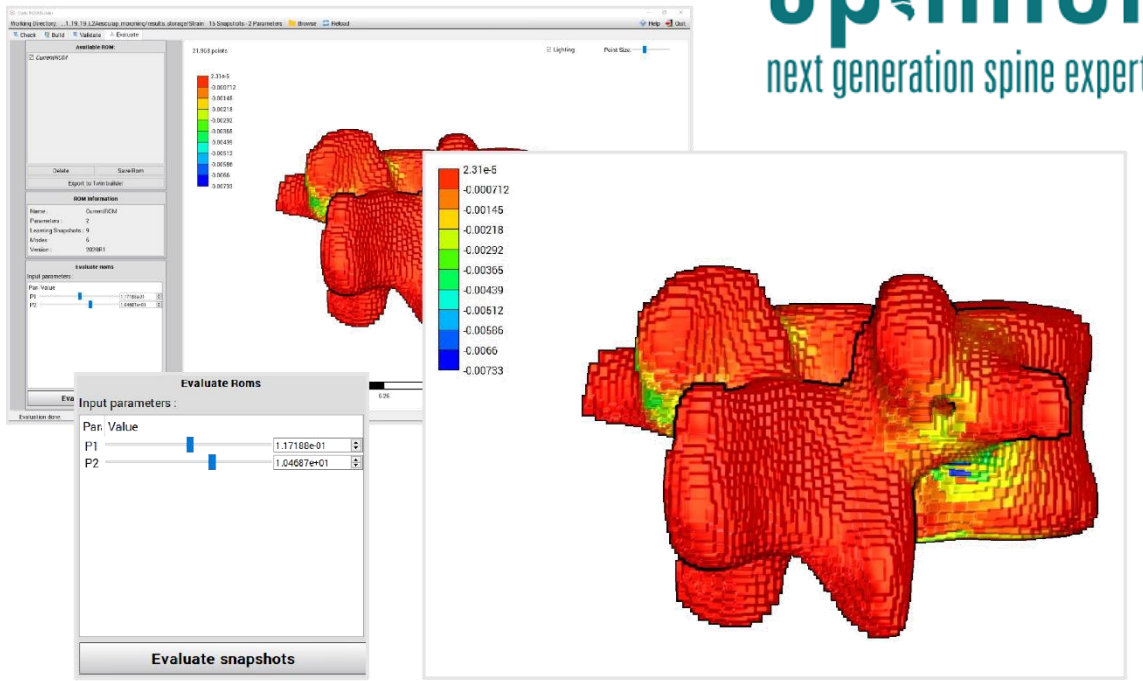
Knowing only **8 points'** coordinates of the actual bone a **full mandible geometry** can be generated with **a good level of approximation (mean error < 1 mm)**



https://link.springer.com/chapter/10.1007%2F978-3-030-31154-4_2

SPINe: Numerical and Experimental Repair strategies





https://www.designnews.com/design-hardware-software/mesh-morphing-explained

Conclusions

- RBF Morph is an advanced **mesh morphing** technology based on Radial Basis Functions
- A **shape parametric** mesh is obtained. Parameters can be steered using standard optimization tools
- Strong integration in **ANSYS products**: module for Fluent, ACT Extension for Mechanical and a prototype for SpaceClaim
- **Stand Alone** version and **Fast Library with API**
- Consistent parametric CAE meshes are a key enabler for **ROM generation**
- We are supporting **Healthcare Research** projects.

Many thanks for your kind attention!

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