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In Partnership with RDT
21 to 23 October
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Continuous Maneuver CFD in HELYX Using RBF-Based Reduced-Order Mesh Motion: A Formula 1 Braking Case

Dr. Ubaldo Cella

Senior CAE Engineer, RBF Morph

Dr. Marco Evangelos Biancolini

Founder & CTO, RBF Morph

Associate Professor, University of Rome Tor Vergata

Outline

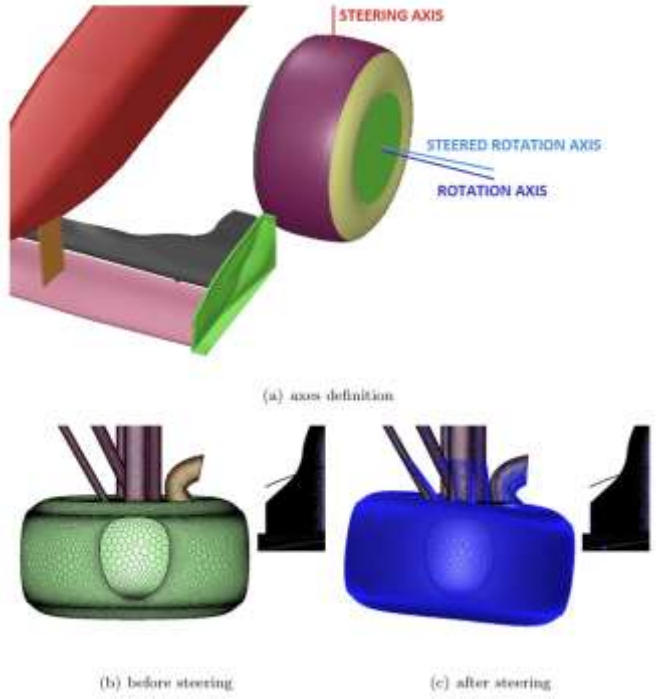
- The challenge: continuous transient maneuvering in CFD
- Theoretical background: Radial Basis Functions, Fast Radial Basis Functions and Reduced Order Models
- Proposed workflow and achieved results
- The rbfCAE platform
- Conclusions

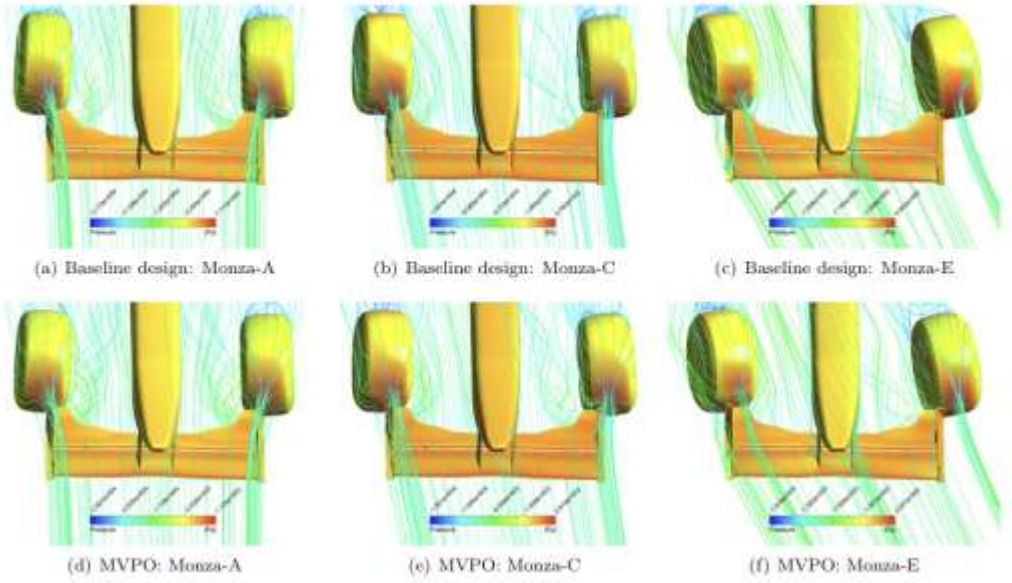
The challenge: continuous transient maneuvering in CFD

F1 aerodynamic optimization study back in 2014

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Petrone, Hill & Biancolini — 32nd AIAA Applied Aerodynamics Conference (2014)



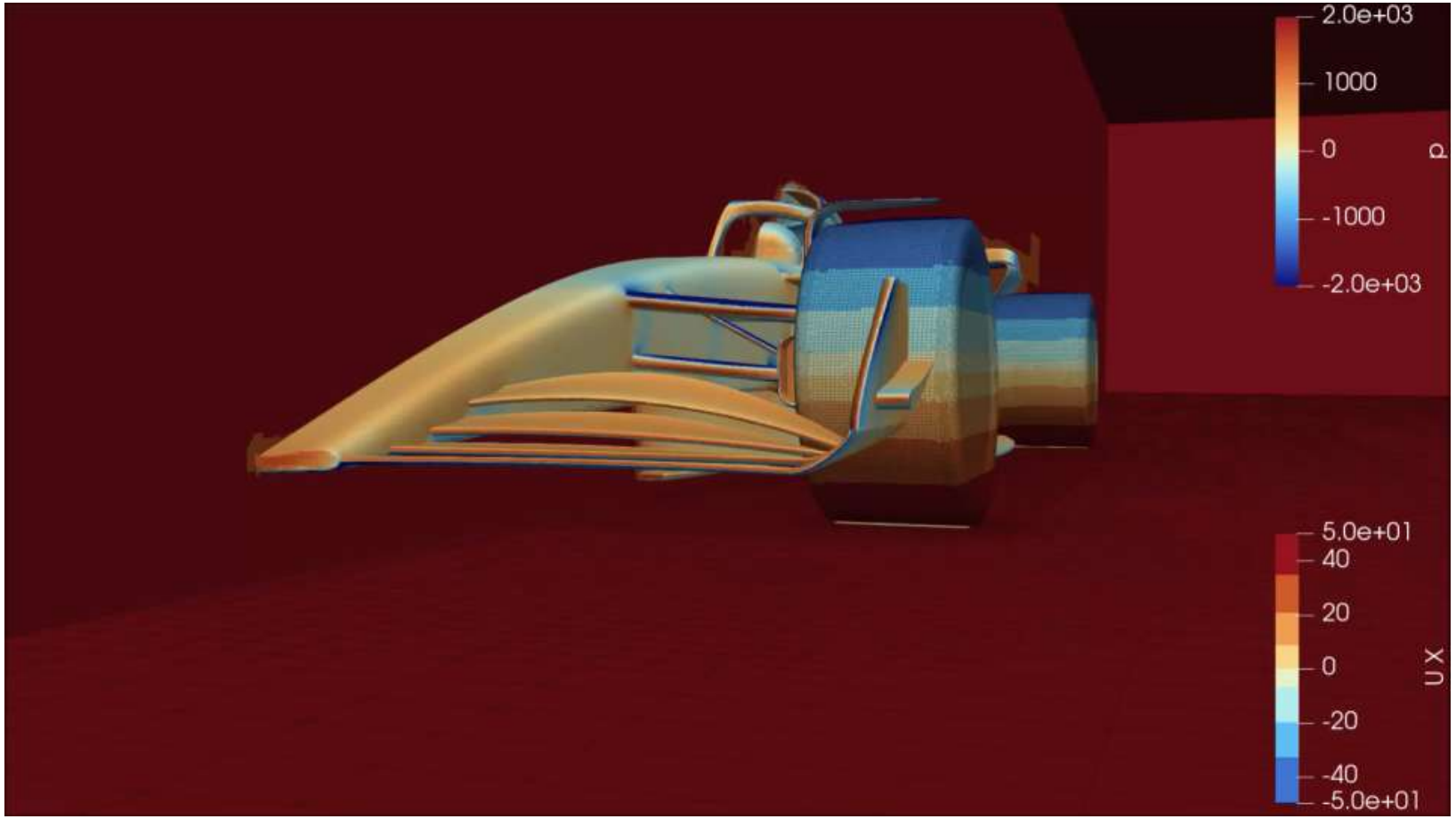


RBF geometry control, steering effects and track-by-track aerodynamic optimisation.

Continuous F1 braking maneuver

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Tyre–ground interaction, chassis dive and steering in a transient CFD simulation



- Continuous geometry evolution
- Tyre and contact patch deformation
- Avoid repeated mesh regeneration

Theoretical background

RBF, Fast RBF, SVD, POD, ROM

Radial Basis Functions (RBF) in a nutshell

source points

radial basis

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

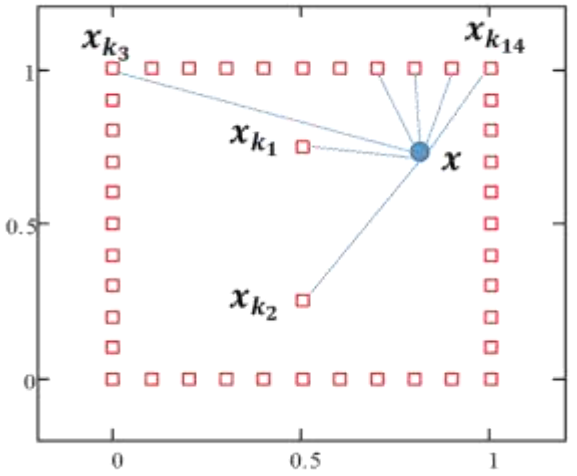
polynomial
e.g. $h(\boldsymbol{x}) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z$

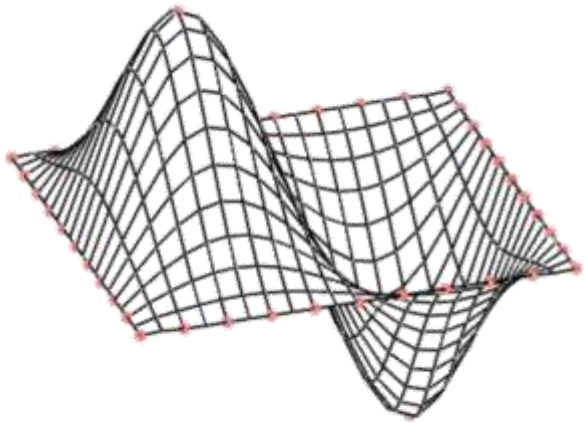
weight

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)	$\sqrt{1+r^2}$

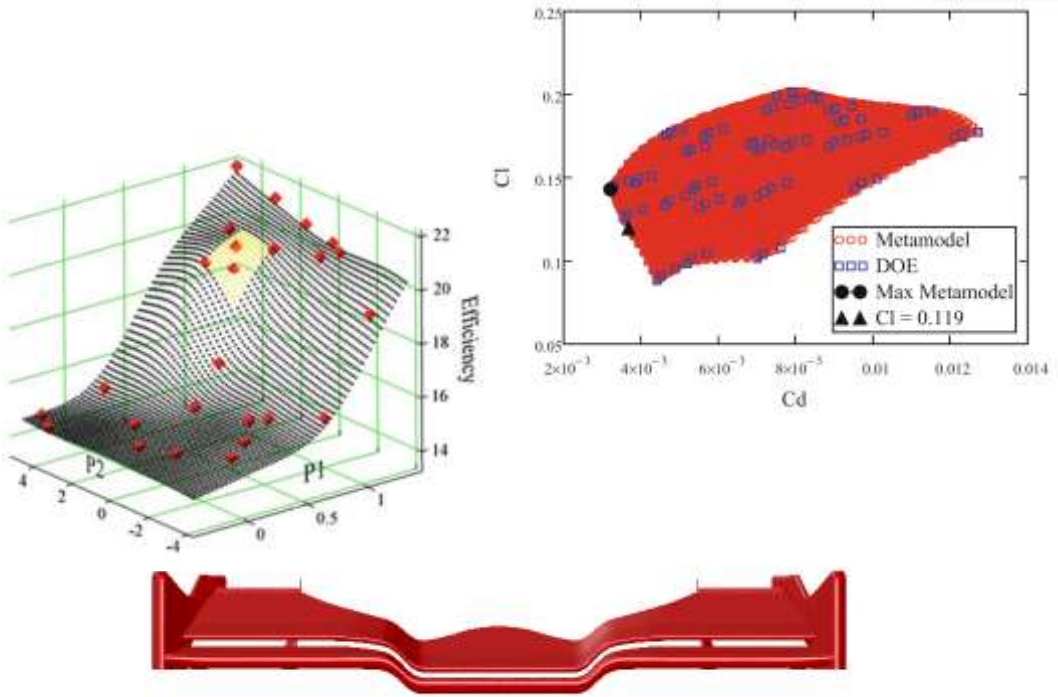
RBF are a very powerful mathematical tool able to interpolate **everywhere** in the $\mathbb{R}^n$ space a function given at scattered **source points**





Interpolators in multi-dimensional spaces

- **RBF** for 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**
- **Fast RBF** for 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"



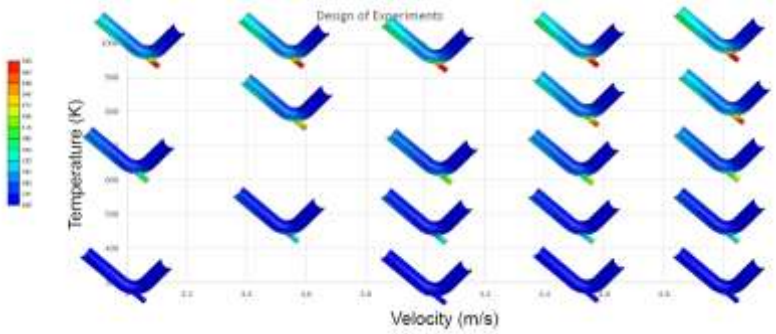
Portable Digital Models

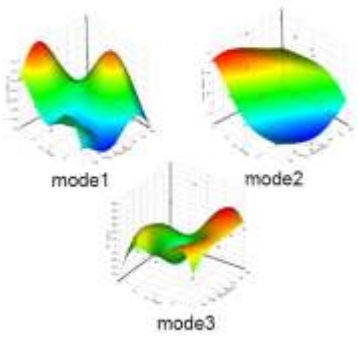
- **Singular Value Decomposition**

$$\mathbf{X} = \mathbf{U}\,\boldsymbol{\Sigma}\,\mathbf{V}^{\top}$$

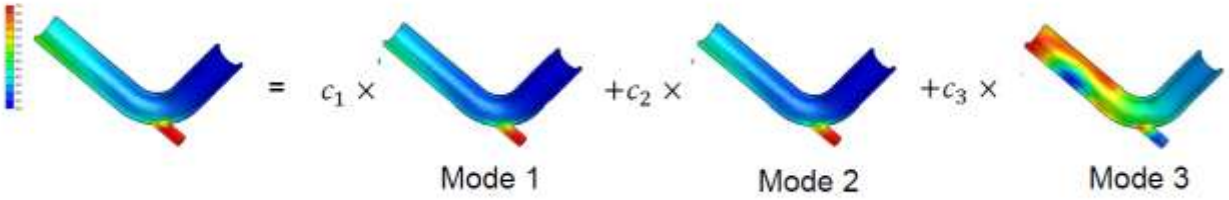
- **Reduced Order Models** (ROM) are compressed (POD) and ready to be inferred (RBF)
- Functional Mock-Up Units (**FMU**) make the models portable







POD+RBF = ROM



Proposed workflow and achieved results

ENGYS F1 car model

Two RBF interpolations, two different spaces

PARAMETER SPACE

RBF surrogate

$$\mathbb{R}^3 \rightarrow \mathbb{R}^6$$

CAD parameters → POD weights

PHYSICAL SPACE

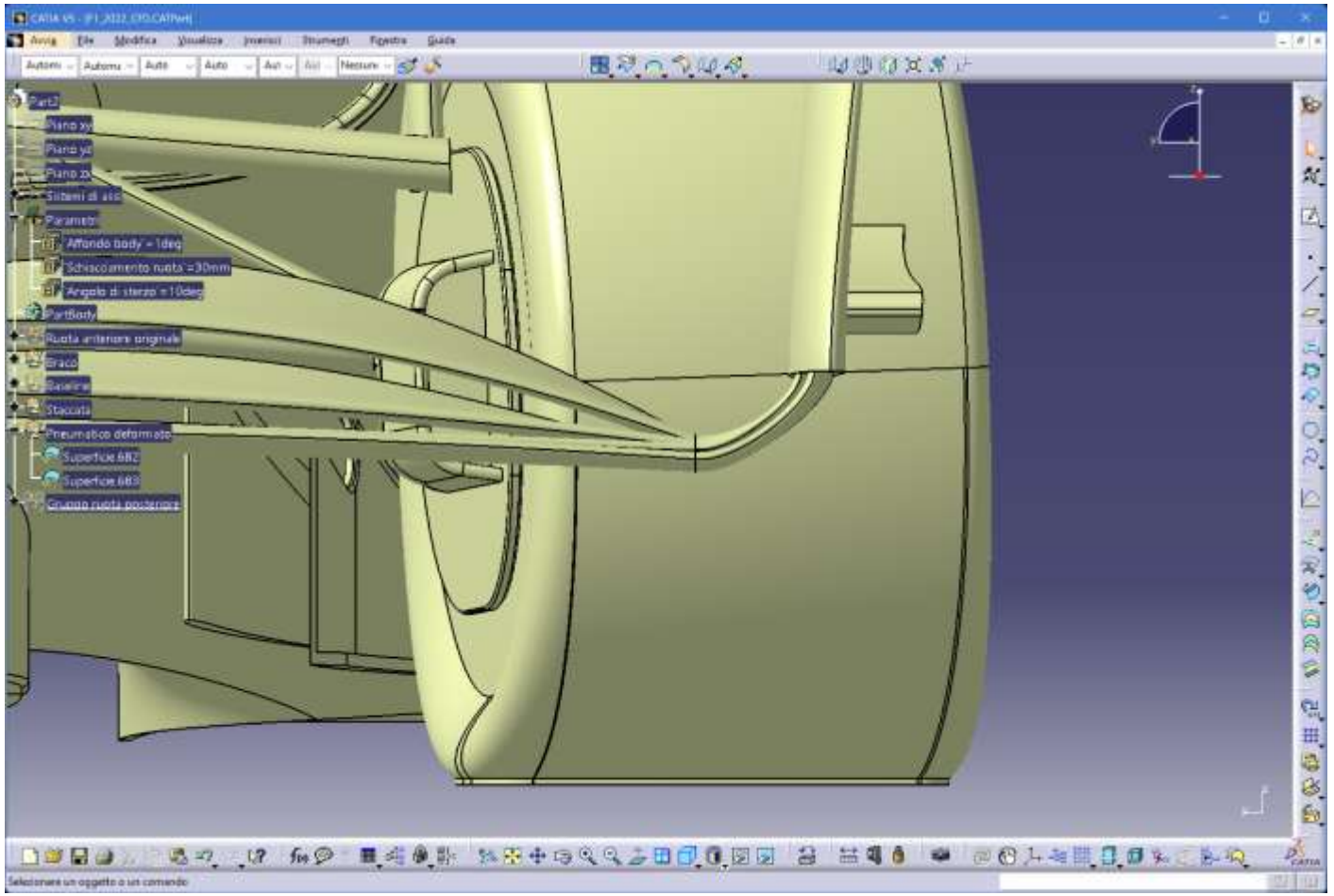
FastRBF morphing

$$\mathbb{R}^3 \rightarrow \mathbb{R}^3$$

Control modes → mesh displacement

Nonlinear interpolation in parameter space. Scalable deformation in physical space.

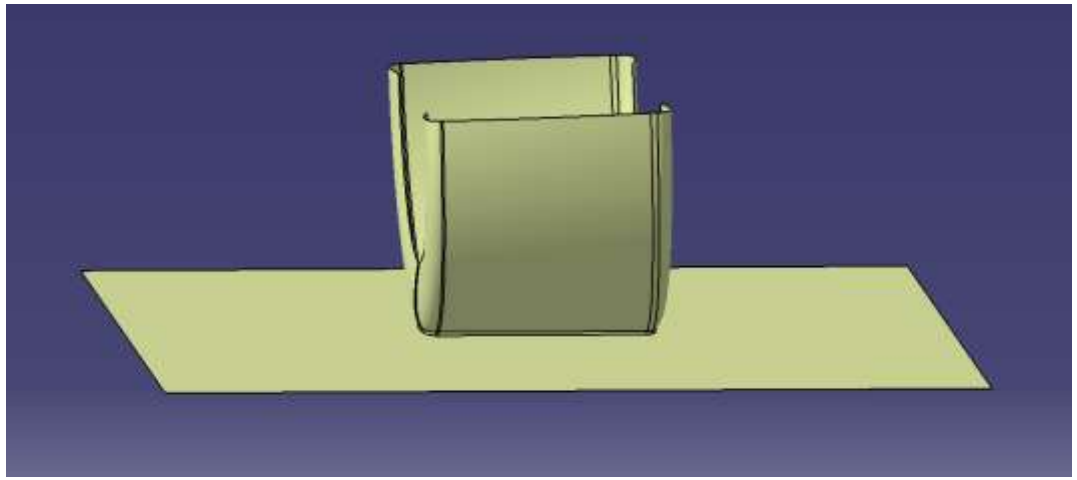
Three CAD parameters define the maneuver

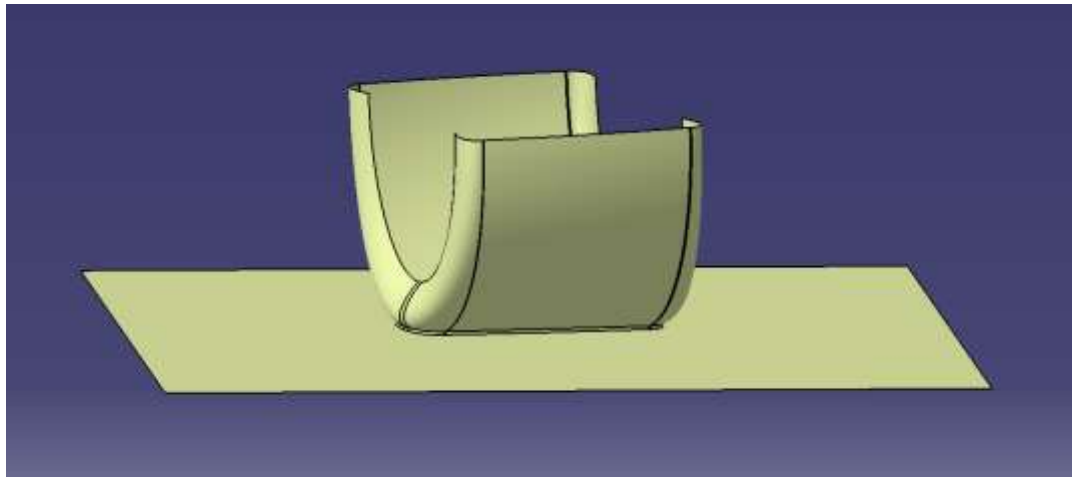


CATIA defines the geometric kinematics.

- Steering angle
- Chassis dive
- Tyre deformation

Geometry-aware control clouds



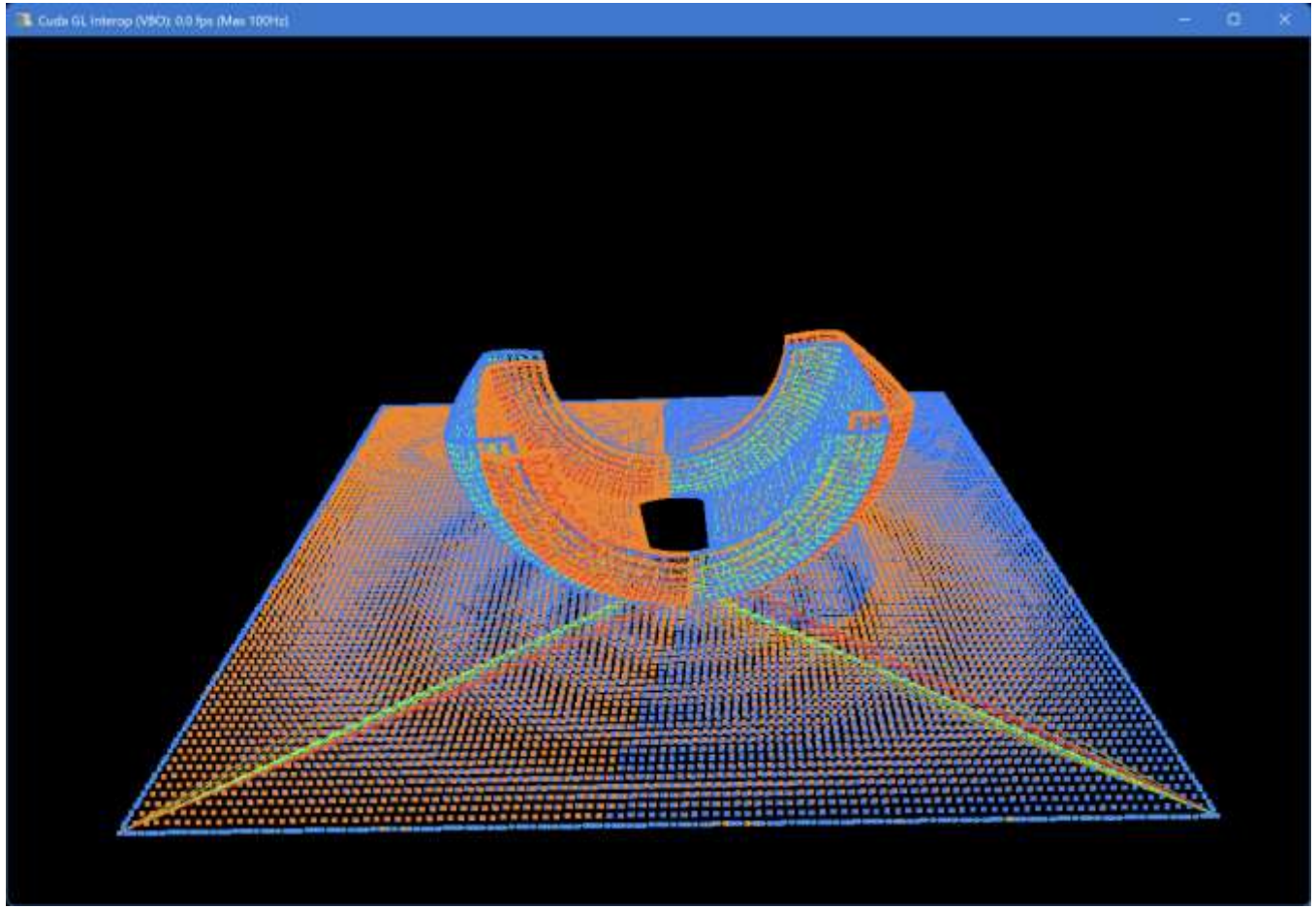


Baseline configuration

Deformed configuration

Iso-parametric STEP surfaces: half tyre, contact patch and ground tile.

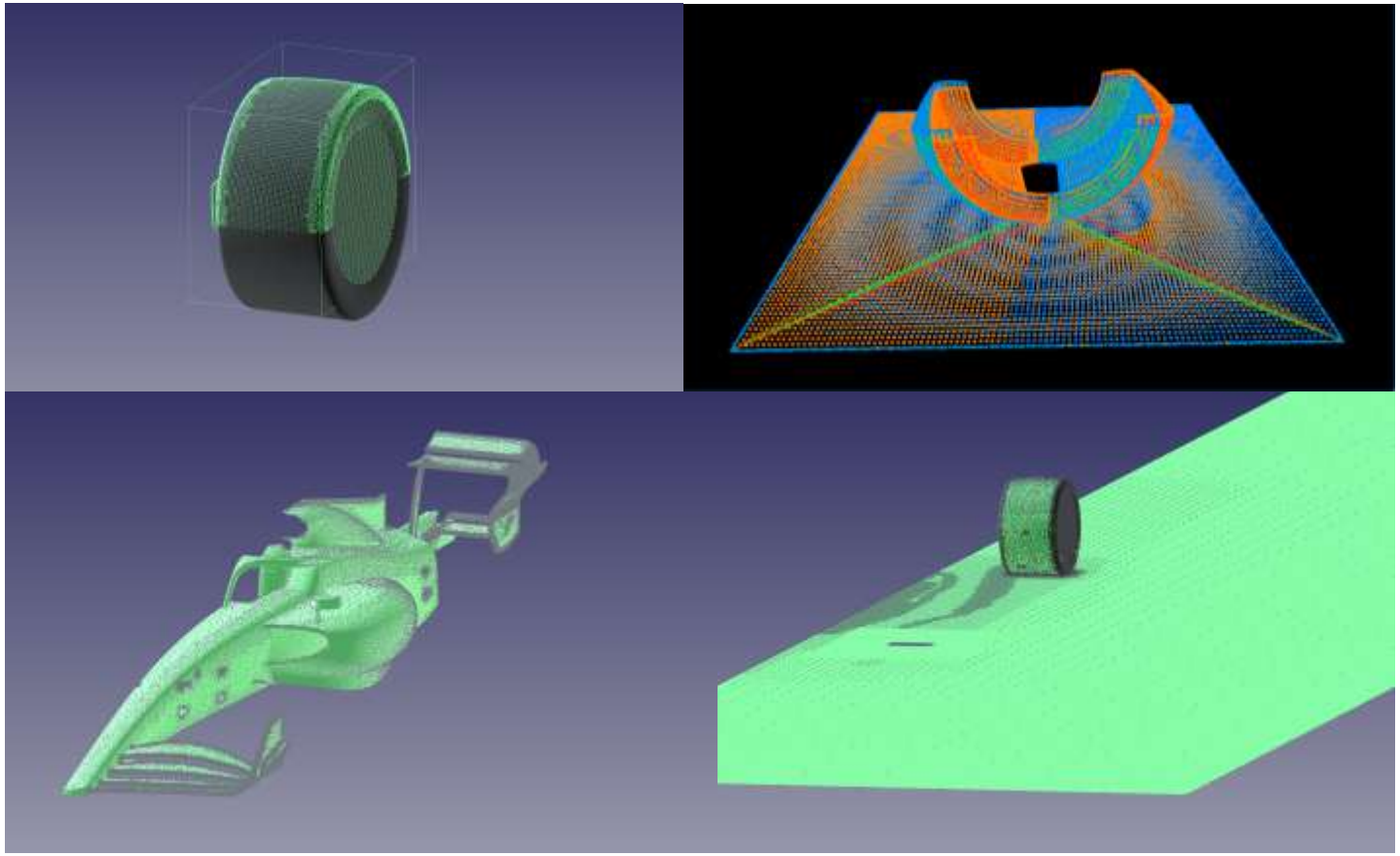
rbfROC: consistent CAD-driven point clouds



- STEP geometry correspondence
- Point-cloud tracking across CAD states
- Additional STL-derived control points

A complete control cloud for the full vehicle

- CAD-controlled points: tyre and contact region
- STL-controlled points: mesh-based components, processed and decimated in FreeCAD
- Ground control beyond the local contact tile
- Uniform point spacing promotes smooth surface and volume deformation



The control cloud is defined consistently for each sampled CAD parameter state.

DOE snapshots → POD → parametric RBF

3 CAD parameters

Steering · Dive · Tyre

DOE snapshots

Complete control-cloud displacements

POD compression

Six retained modes

RBF surrogate

3 parameters → 6 amplitudes

The nonlinear geometric response is distilled into six modal coefficients.

From control-point modes to volume fields

- For each POD mode, FastRBF constructs a spatial displacement interpolator.
- A Domain Encap bounds the region affected by morphing.
- Each MPI partition evaluates the same global meshless RBF on its local mesh nodes.
- One complete volumetric displacement field is stored per mode and partition.

Initialization cost: approximately one full-grid morphing evaluation per mode.

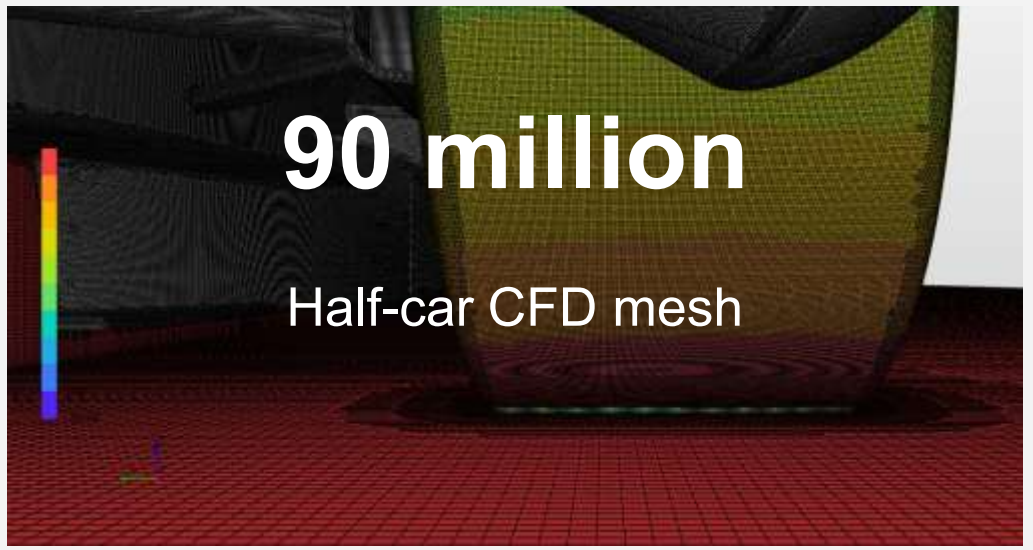
Runtime: modal superposition with native HELYX motion

$$\mathbf{u}(\mathbf{x},t) = \sum_{k=1}^{6} a_k\left(\boldsymbol{\mu}(t)\right)\boldsymbol{\Phi}_k(\mathbf{x})$$

- The maneuver prescribes the time history of the CAD parameters / modal weights.
- HELYX combines six precomputed displacement fields.
- ALE handles the moving mesh during transient CFD.
- No FastRBF evaluation is required inside the time-stepping loop.

The same control model, different CFD resolutions of the ENGYS F1 car model



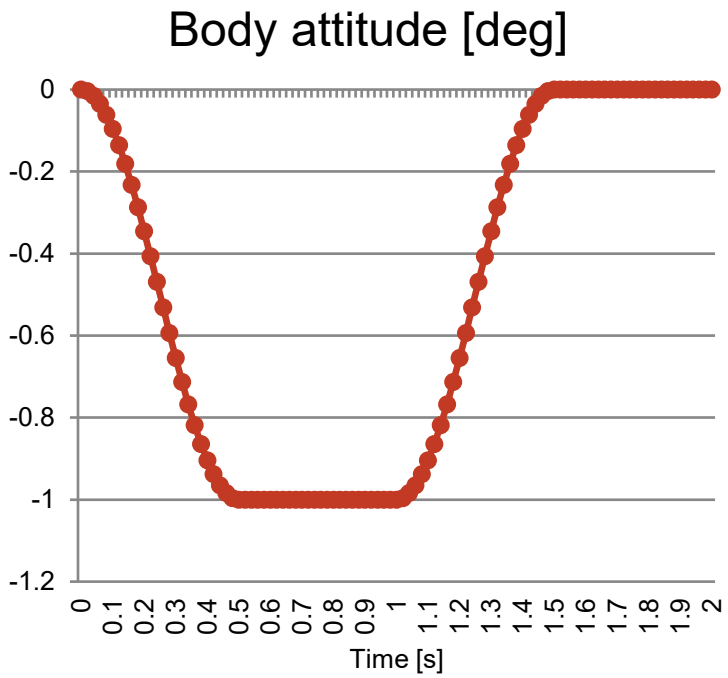


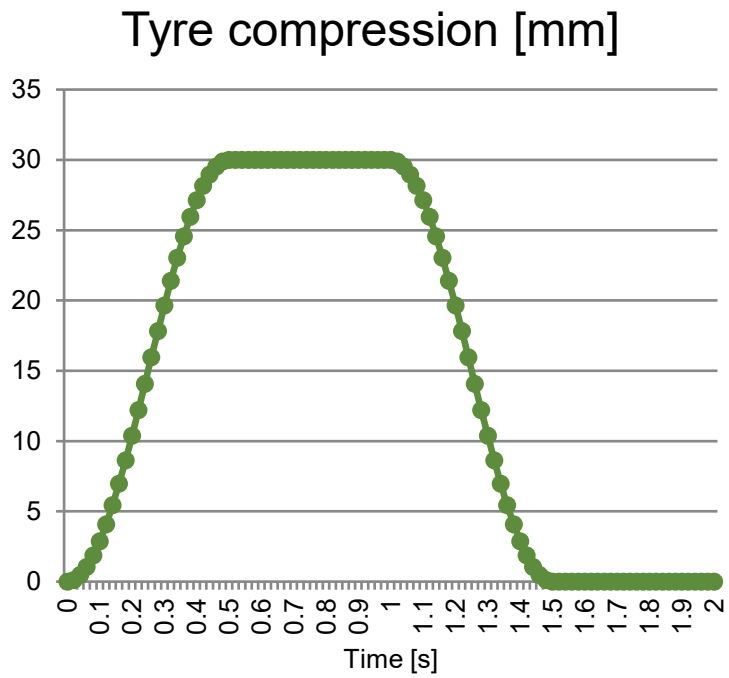
Reusable: CAD parametrization, control-cloud spacing and reduced model.

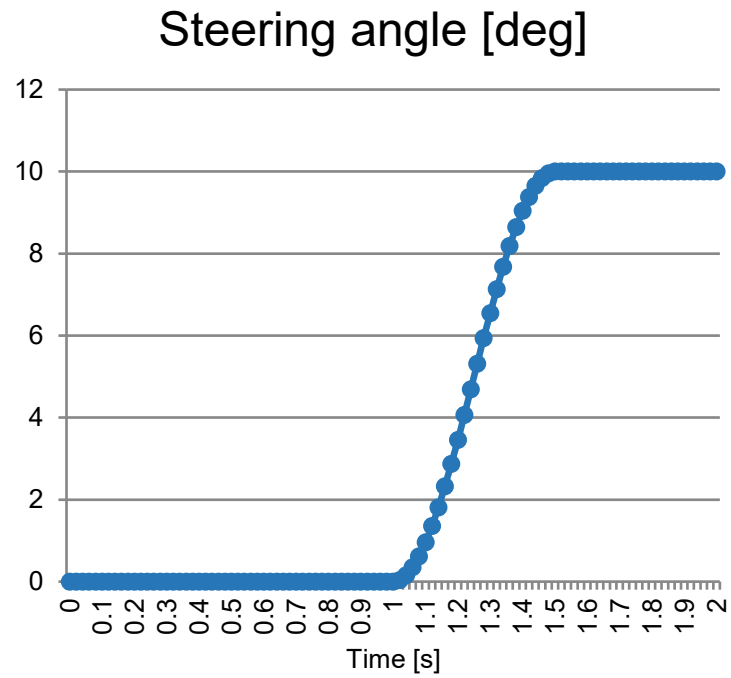
Regenerated for each mesh: six volumetric fields and their partition storage.

Prescribed manoeuvre: CAD parameter histories

This is an exercise intended to put the workflow at work, track data could be used



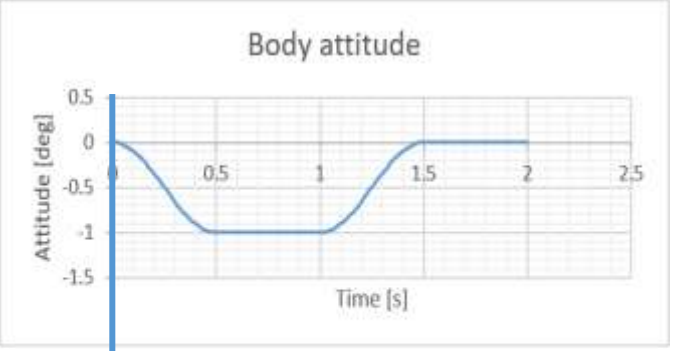


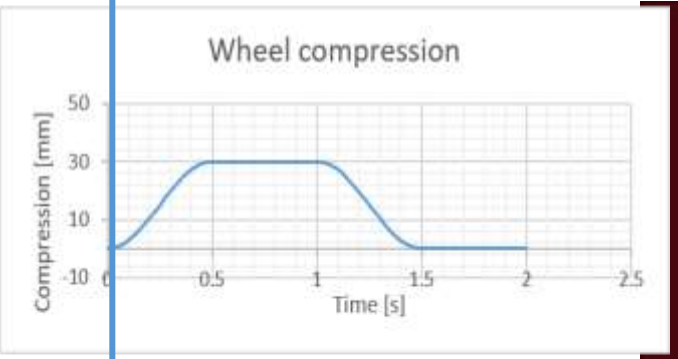


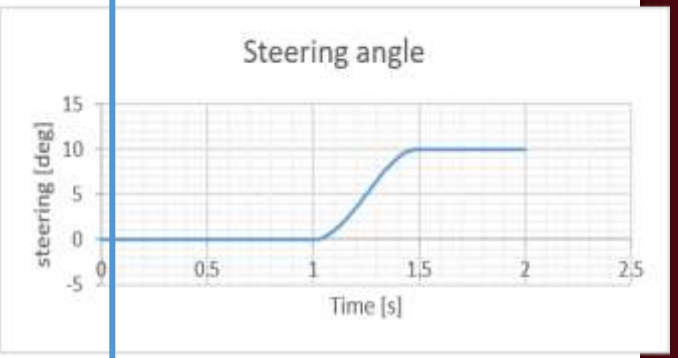
The same prescribed parameter trajectory drives the reduced model and, through modal superposition, HELYX mesh motion.

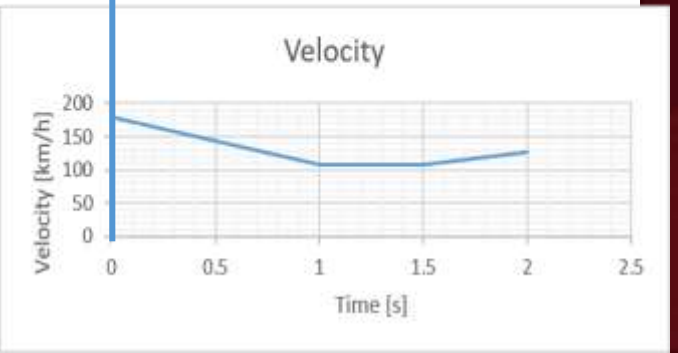
5 million - half car

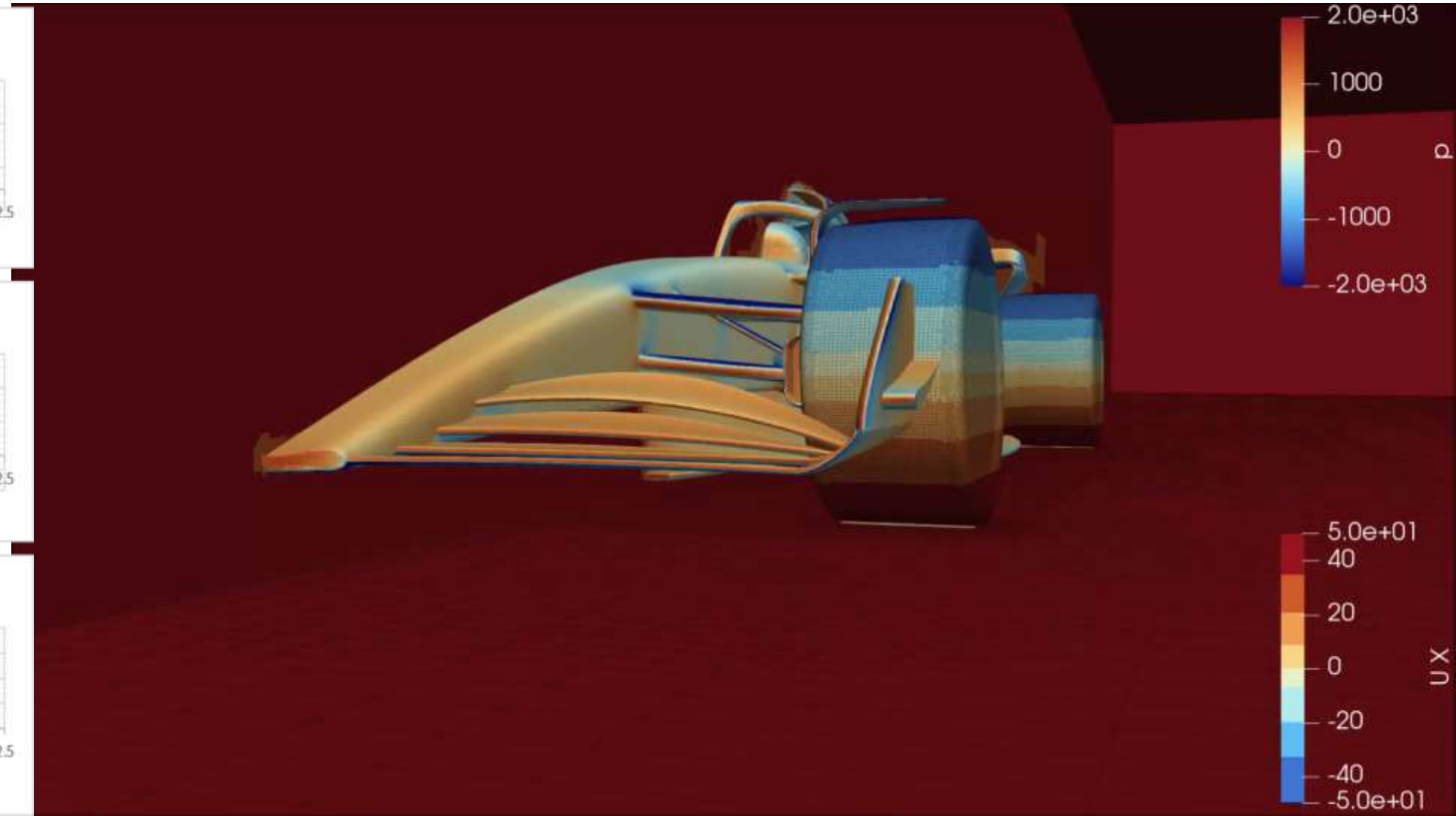
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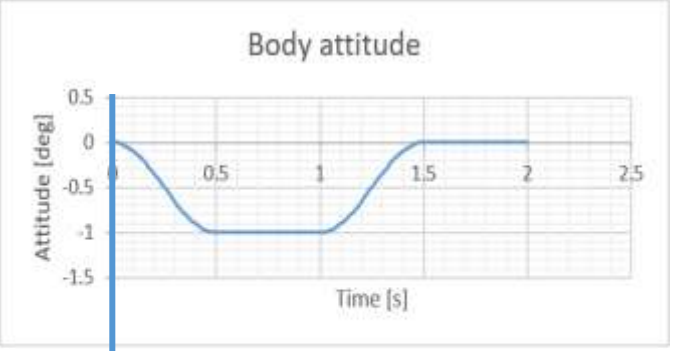


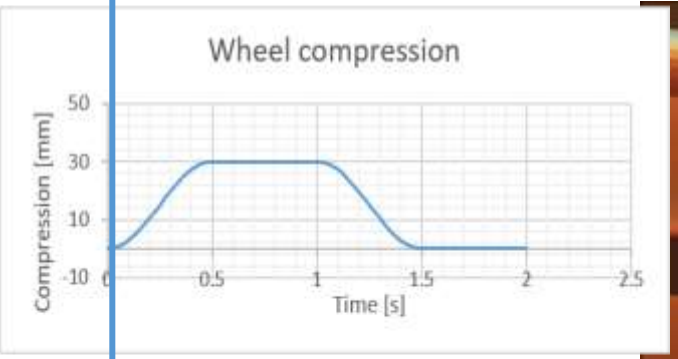


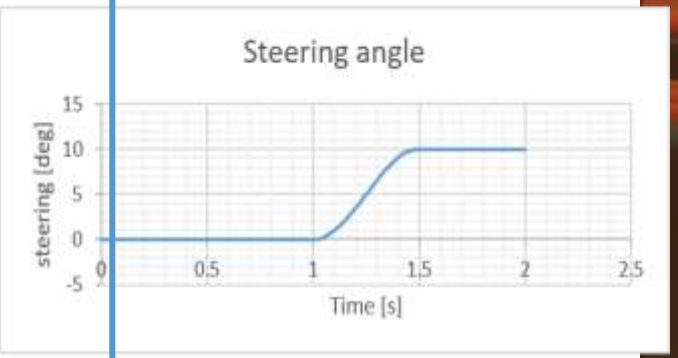


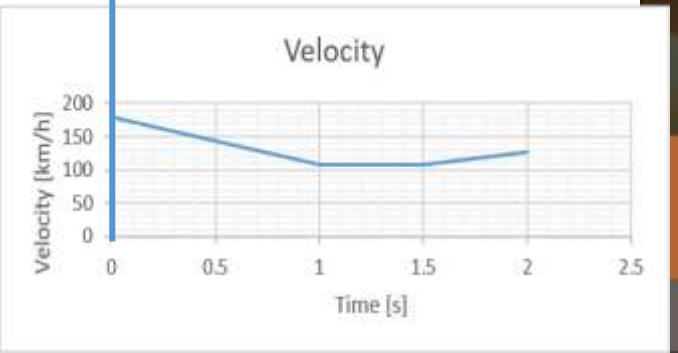
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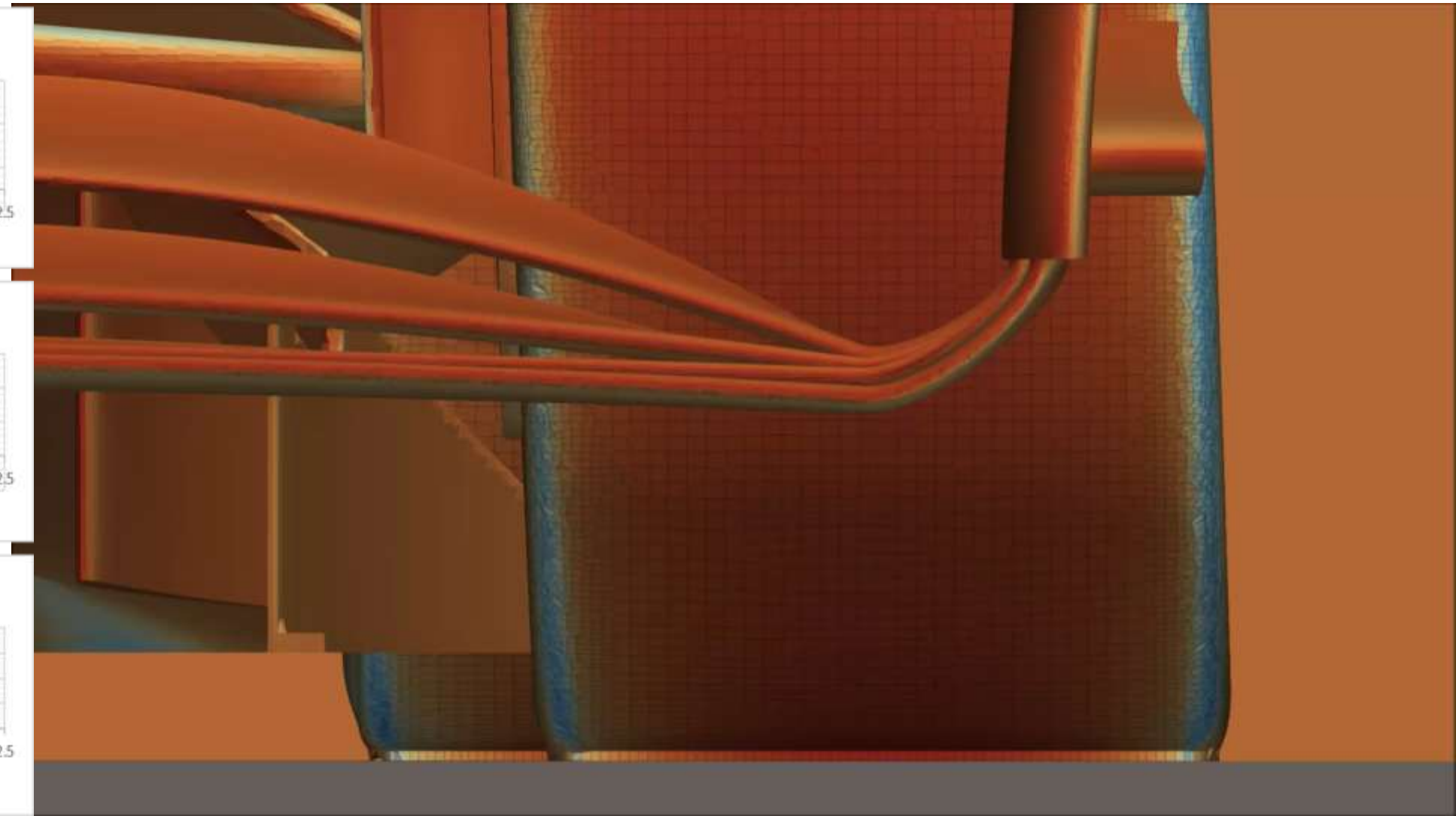
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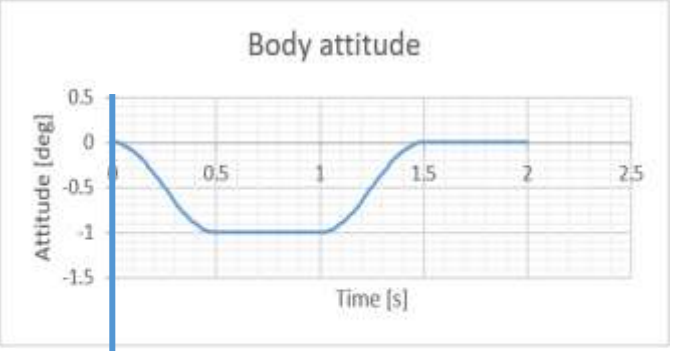


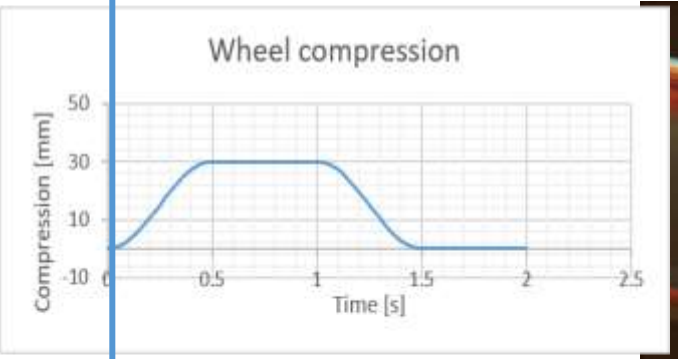


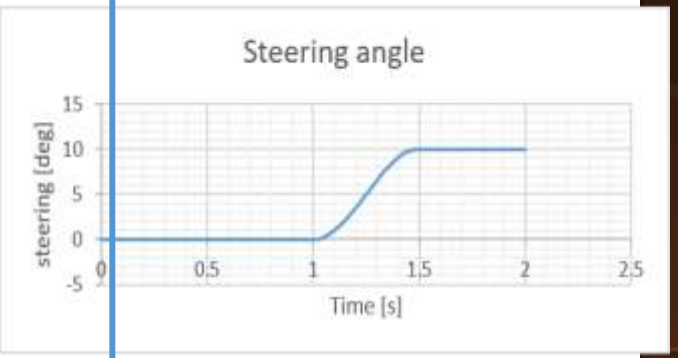


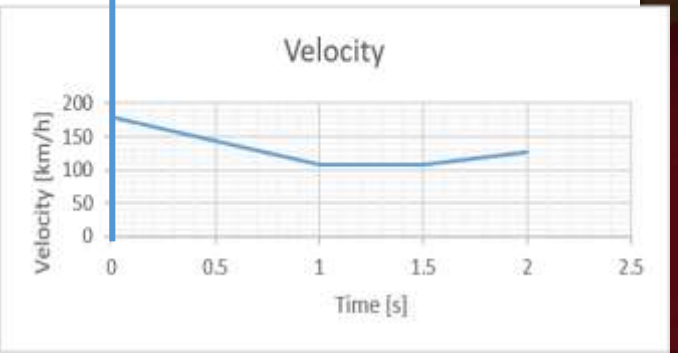


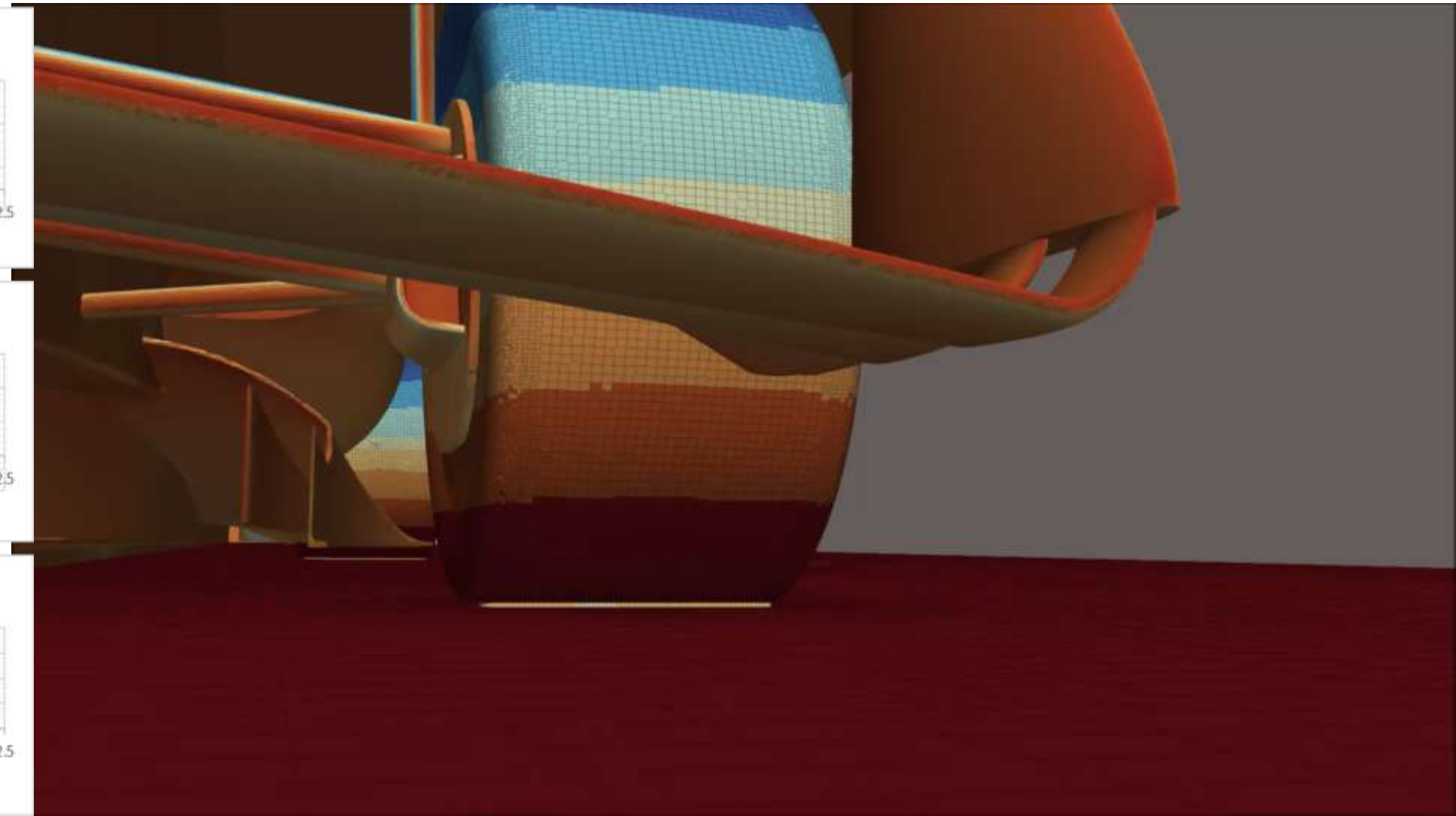
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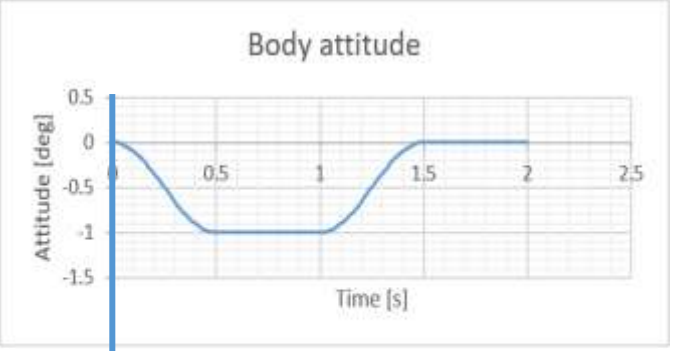


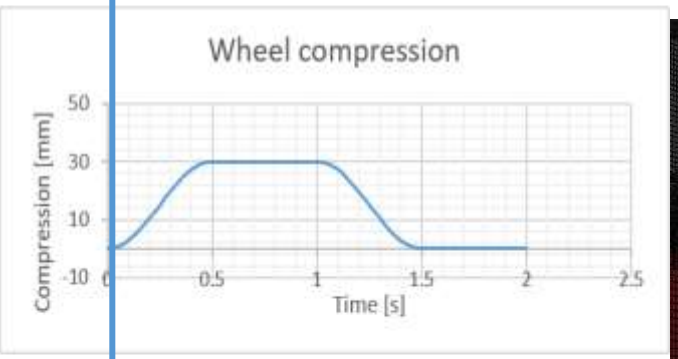


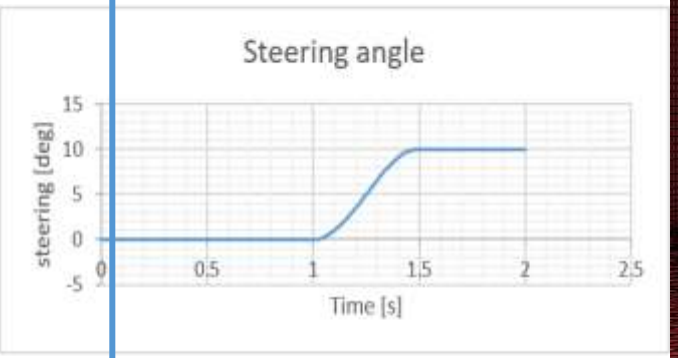


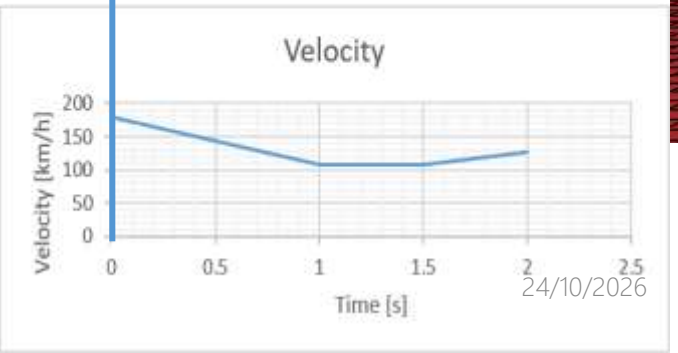
90 million - half car

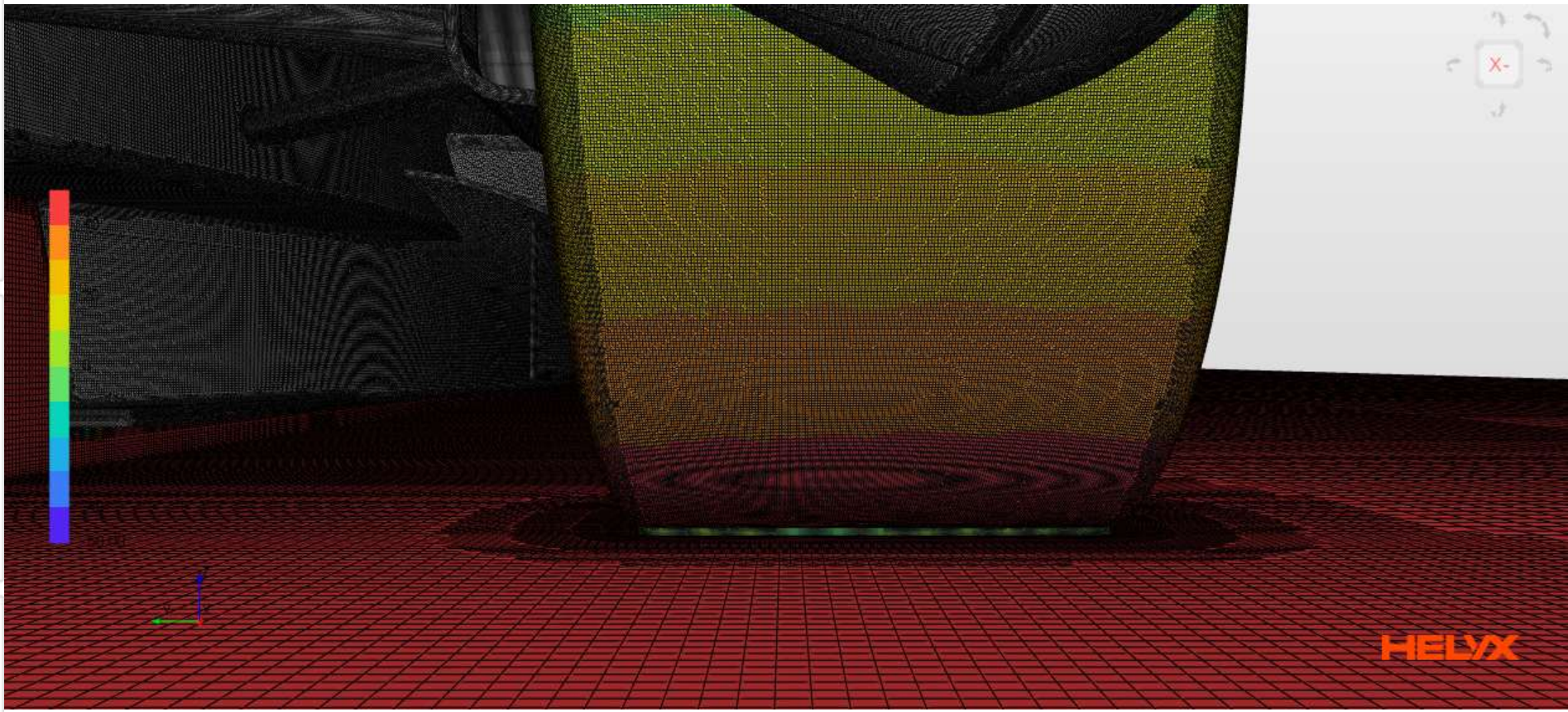
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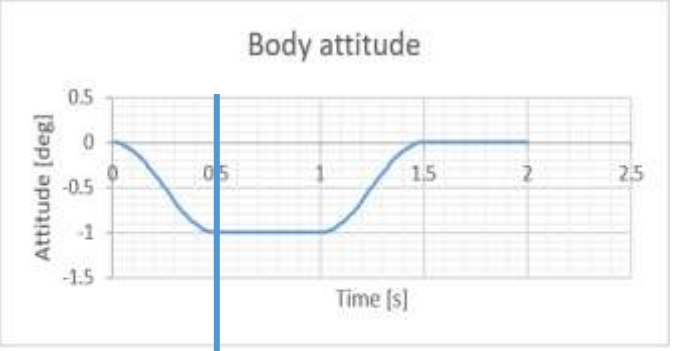


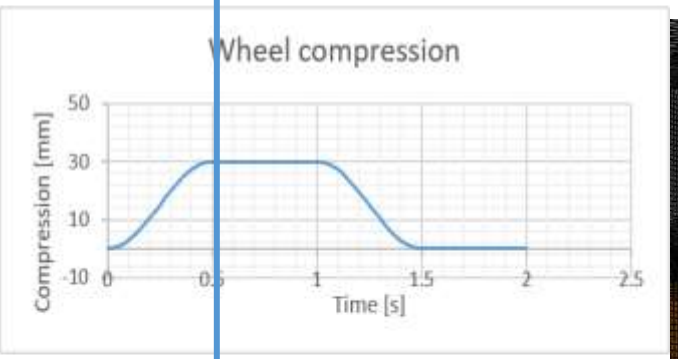


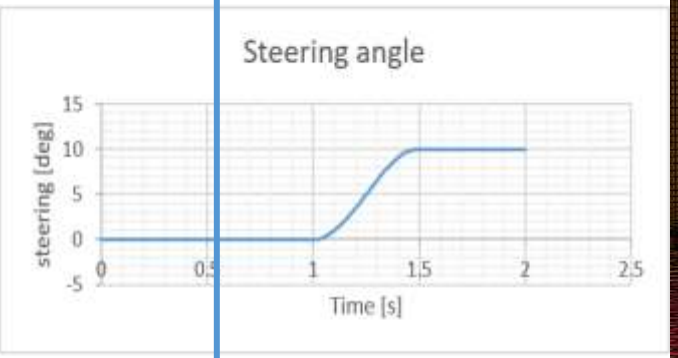


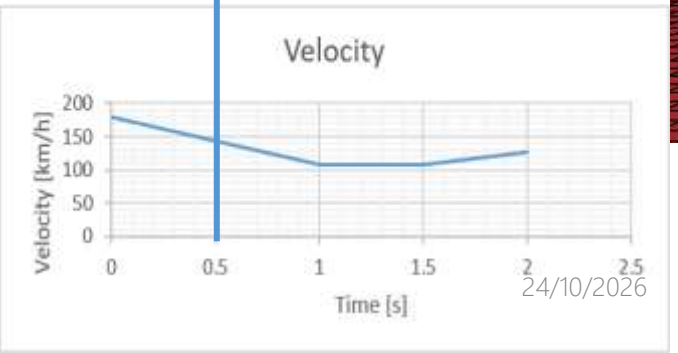
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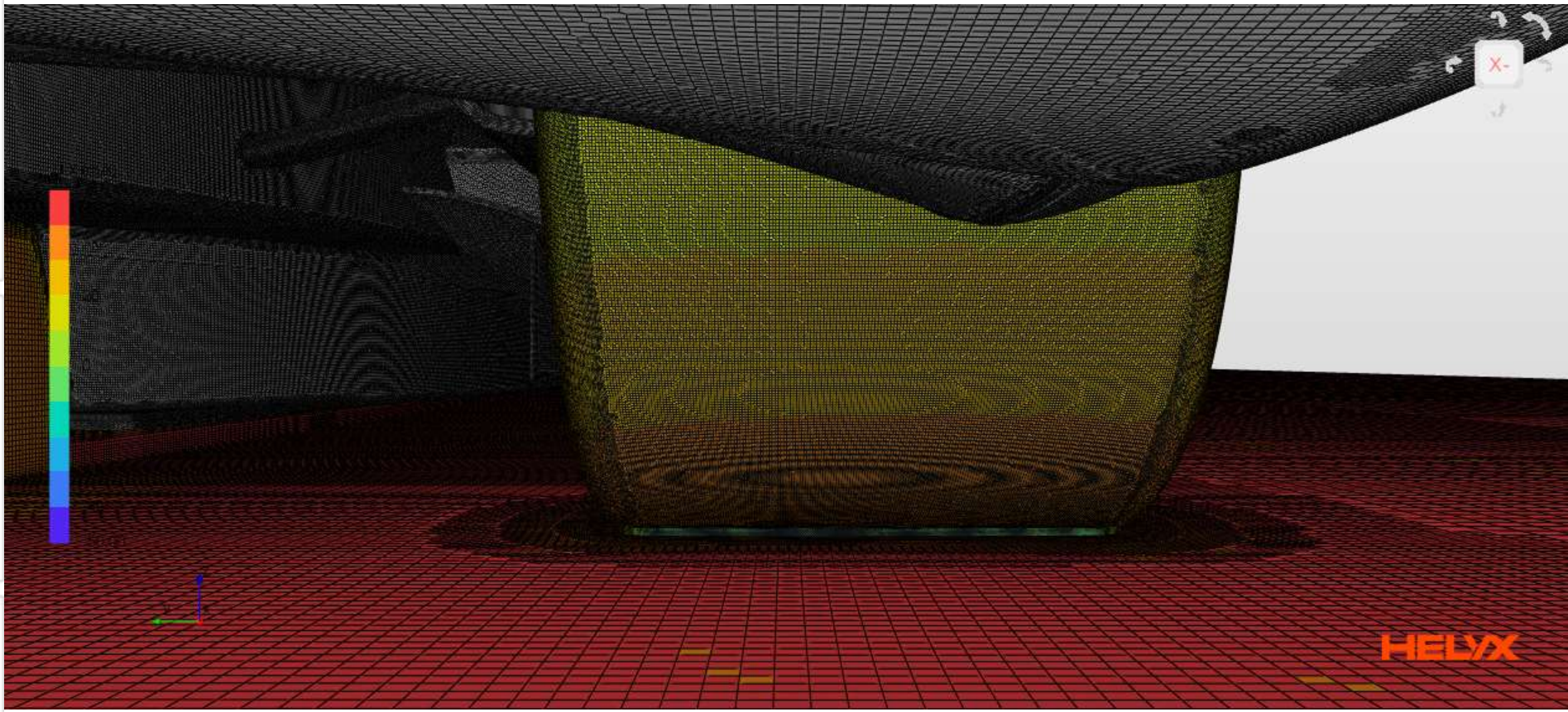
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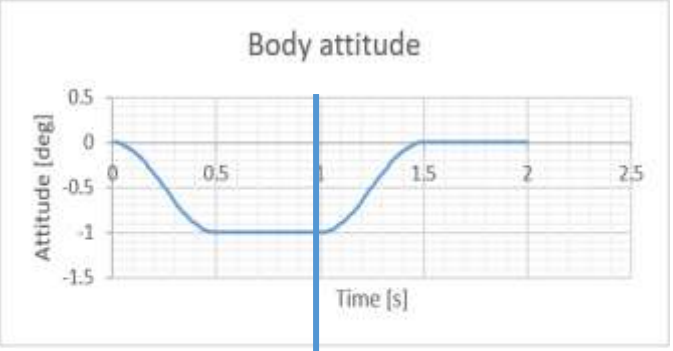


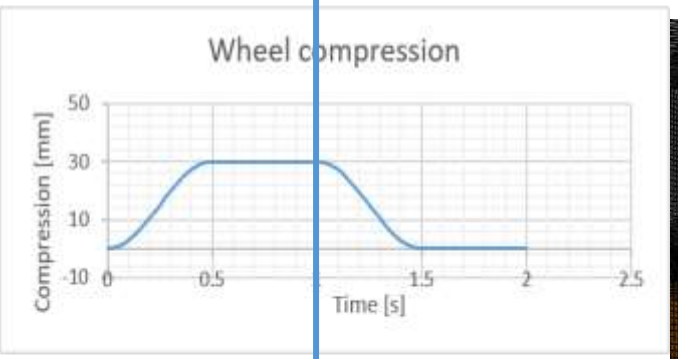


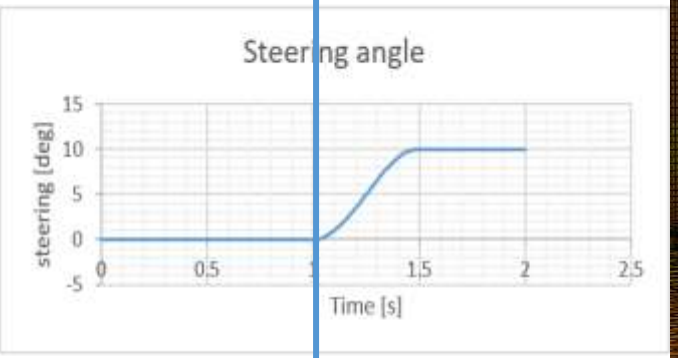


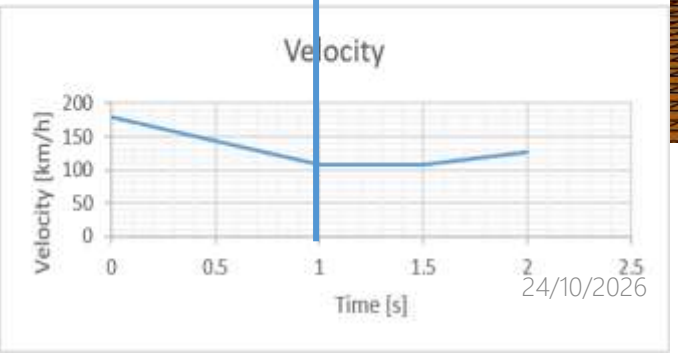
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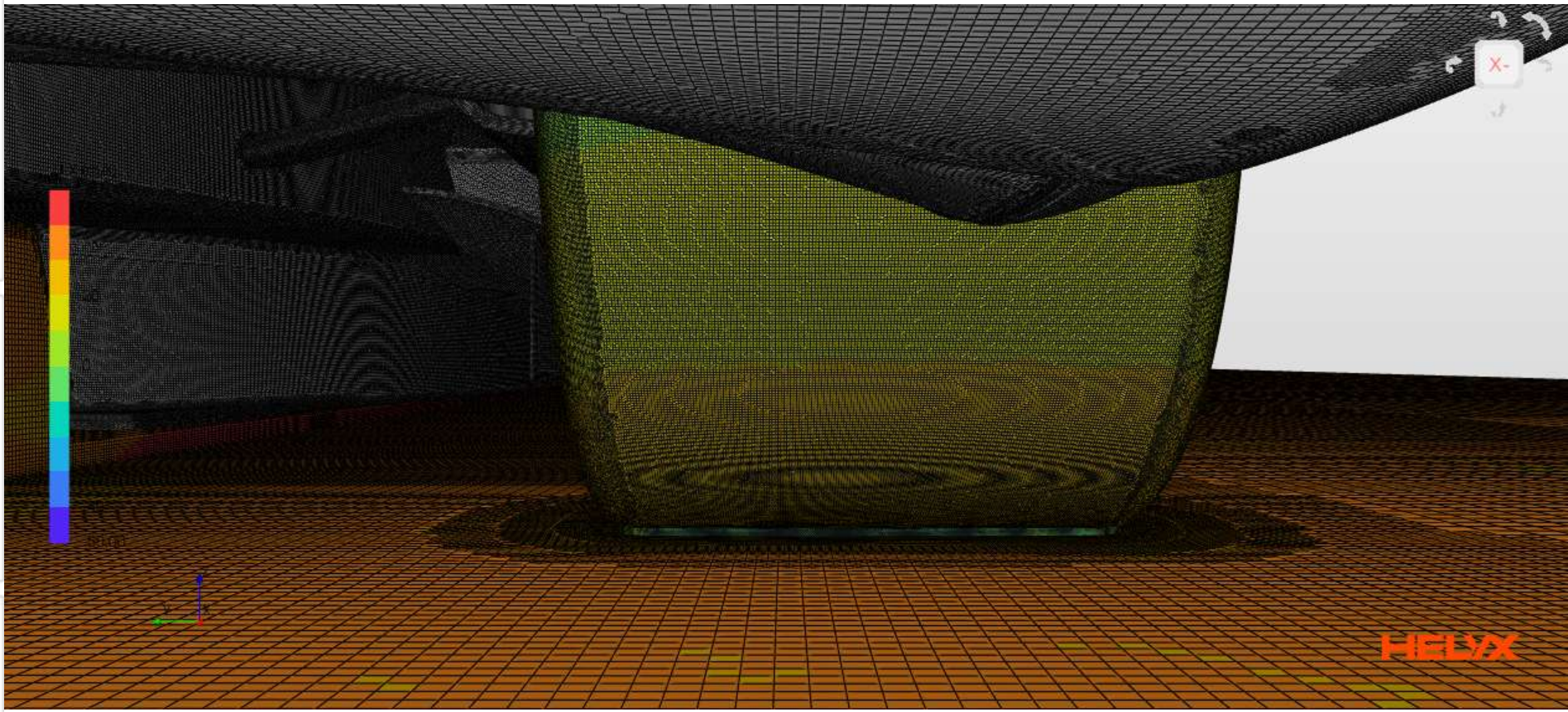
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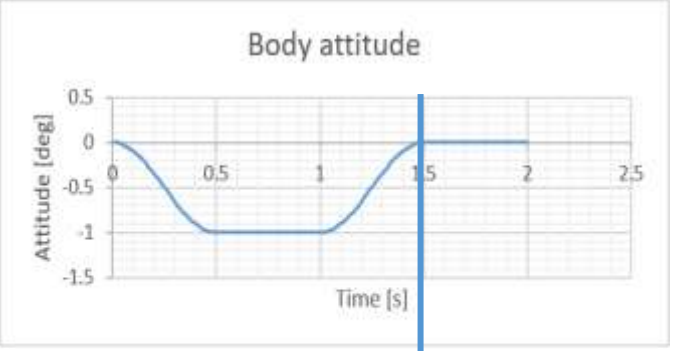


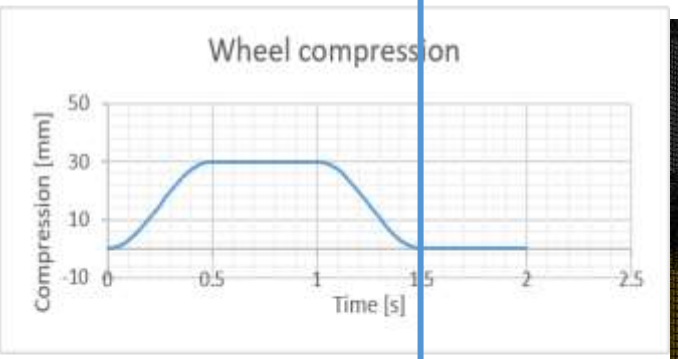


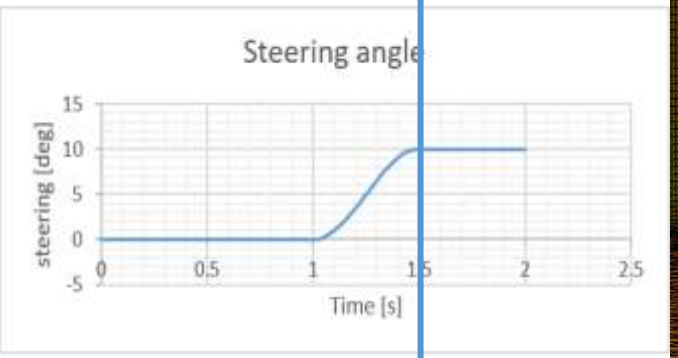


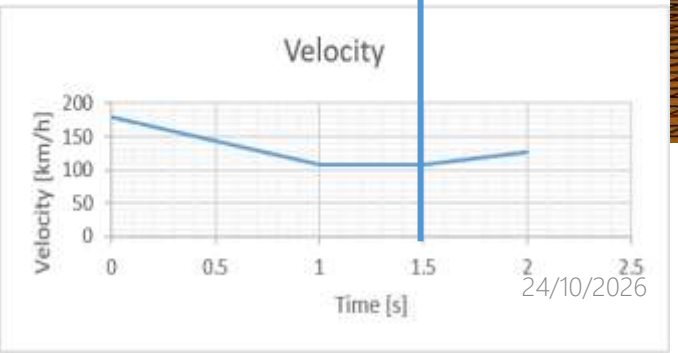
90 million - half car

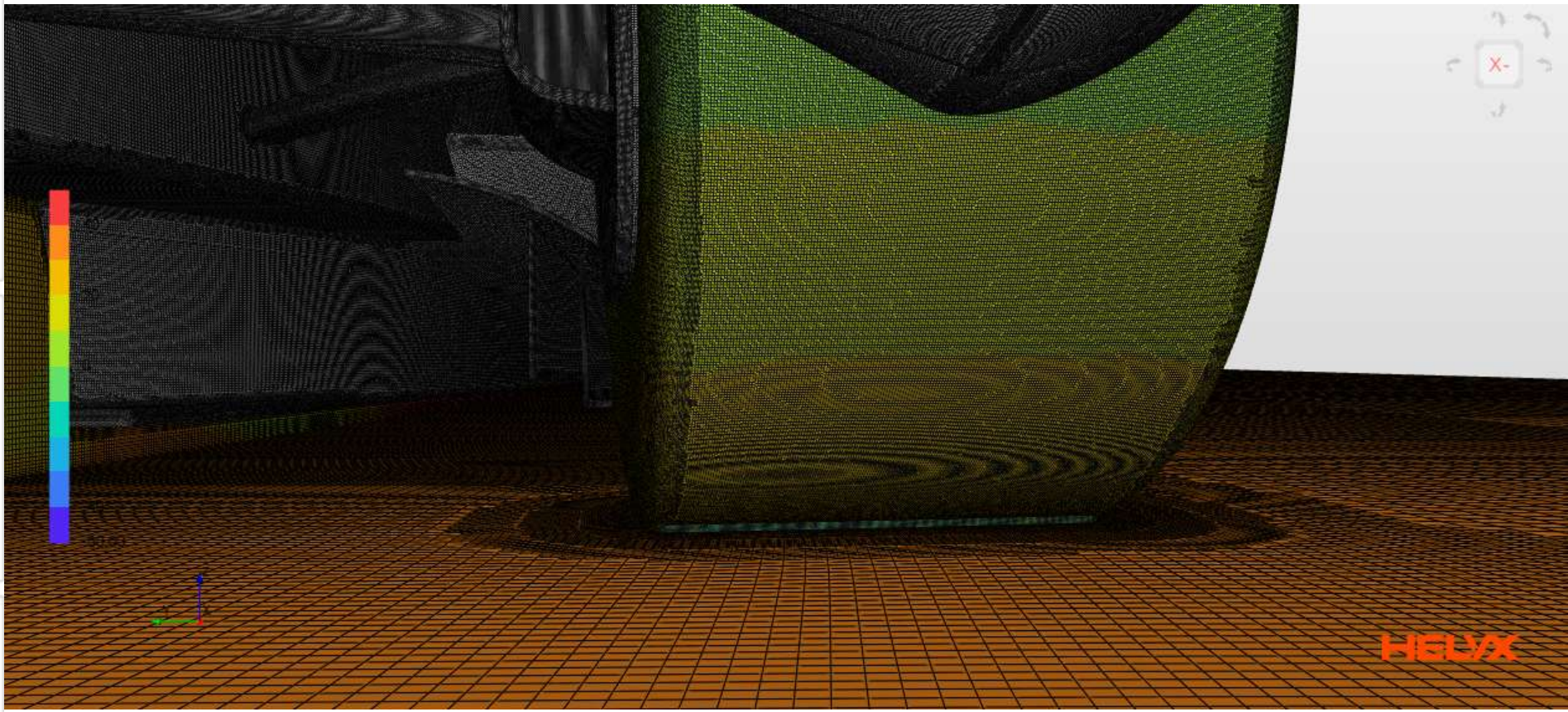
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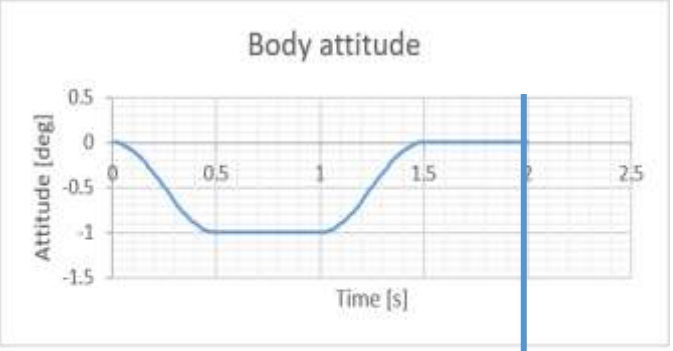


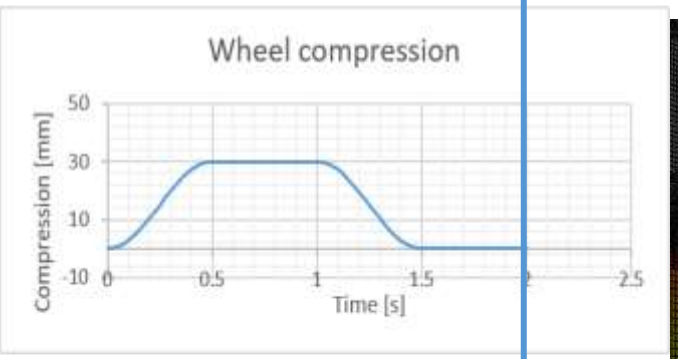


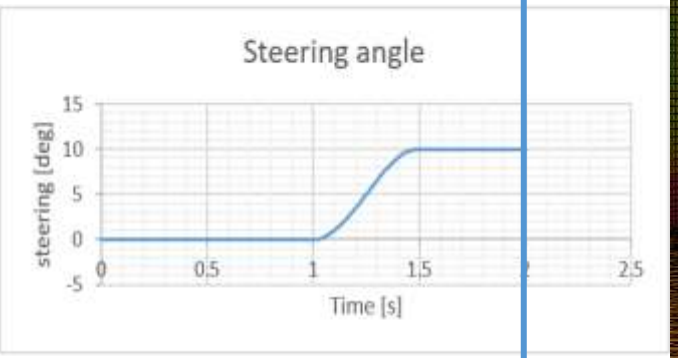


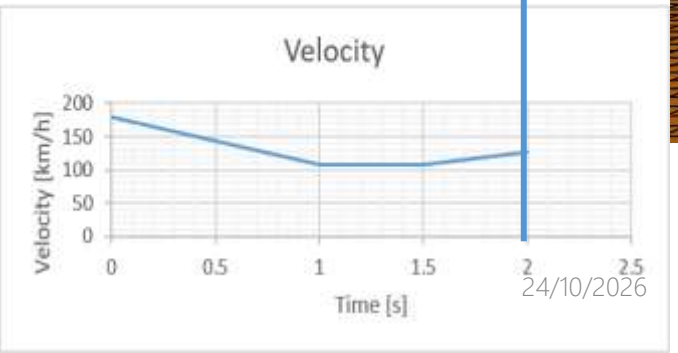
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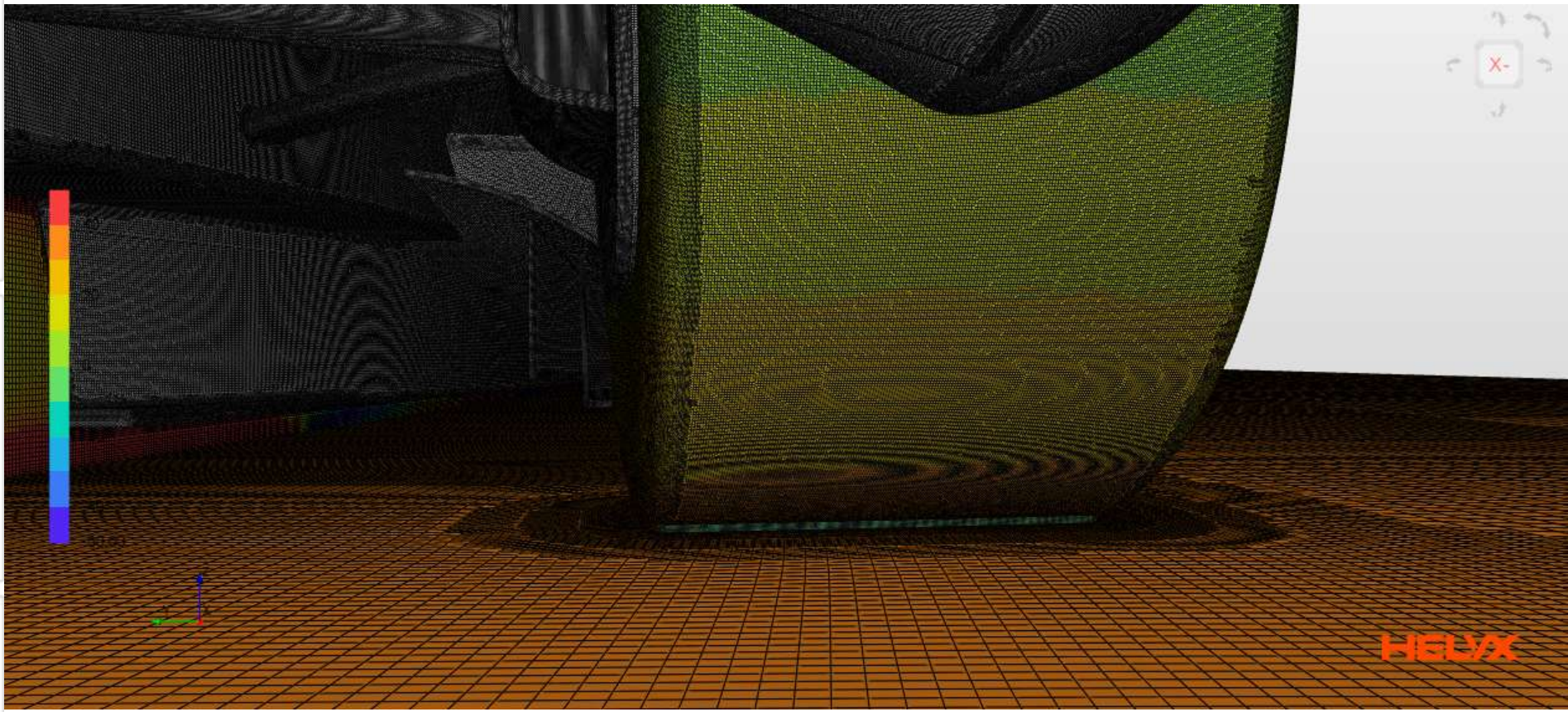
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Results and limitations

What we have achieved

- A **complete and effective** workflow that brings **CAD-level geometric accuracy** to HPC CFD simulations.
- A solution built on **out-of-the-box tools**, coordinated through a Python-based orchestration framework.
- Successfully demonstrated on both a **small-scale mesh** and an **industrial-scale mesh**, achieving stable CFD solutions and maintaining good mesh quality.

What to be addressed (WIP)

- **Realistic vehicle manoeuvres** and **tyre deformation**, with CAD geometry driven by FEA predictions and/or experimental data.
- **Comprehensive surface-motion verification** to ensure that nominally rigid surfaces remain within the prescribed geometric tolerances.
- **Further refinement of CFD settings**, including full-vehicle modelling, time-step selection and the treatment of deceleration effects.

Beyond braking: CAD parametrization inside HELYX

CONTINUOUS / TRANSIENT

Follow a prescribed parameter trajectory with HELYX ALE active.

STATIC / PARAMETRIC

Bring the CFD grid to a selected CAD-defined configuration using native motion.

One geometric intelligence layer, multiple HELYX workflows.

rbfCAE platform

https://engys.com/rbfcae/

rbfCAE

RBF-Based Geometry Morphing for Simulation and Design

Your gateway to advanced geometry control and simulation-ready mesh morphing with HELYX and ELEMENTS.

rbfCAE is a solver-independent platform built to accelerate design iterations, optimise shapes, and enable adjoint and FSI workflows — all without remeshing.

BENEFITS

Why choose rbfCAE with HELYX and ELEMENTS to enhance your simulation workflow?

- Mesh Morphing Without Remeshing
- Solver Independence
- Parametric shape control
- Adjoint-Driven Optimisation
- Real-Time FSI Morphing
- Ready for ROM and VR

Mesh morphing without remeshing

Apply complex geometric deformations directly to existing HELYX and ELEMENTS grids to ensure a robust and repeatable workflow across iterative design processes, preserving topology and avoiding remeshing.

Contact us



BENEFITS

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- Mesh Morphing Without Remeshing
- Solver Independence
- Parametric shape control
- Adjoint-Driven Optimisation
- Real-Time FSI Morphing
- Ready for ROM and VR

Solver independence

rbfCAE works seamlessly with HELYX, ELEMENTS and other solvers. From CFD to FEA, rbfCAE supports a wide range of mesh formats and integrates smoothly into your CAE software pipeline.

Contact us



BENEFITS

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- Real-Time FSI Morphing
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Parametric shape control

Turn any static geometry into a flexible parametric model. Control geometry with design variables linked to CAD or mesh points.

Contact us



BENEFITS

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- Adjoint-Driven Optimisation
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Adjoint-driven optimization

Integrate adjoint sensitivities from HELYX-Adjoint or ELEMENTS-Adjoint into your morphing process for high-fidelity optimisation. Combine surface sensitivities with interactive design sculpting.

Contact us



BENEFITS

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- Solver Independence
- Parametric shape control
- Adjoint-Driven Optimisation
- Real-Time FSI Morphing
- Ready for ROM and VR

Real-Time FSI Morphing

Apply structural mode shapes dynamically to CFD meshes from HELYX and ELEMENTS for one-way FSI simulations, ideal for flexible body designs.

Contact us



BENEFITS

Why choose rbfCAE with HELYX and ELEMENTS to enhance your simulation workflow?

- Mesh Morphing Without Remeshing
- Solver Independence
- Parametric shape control
- Adjoint-Driven Optimisation
- Real-Time FSI Morphing
- Ready for ROM and VR

Ready for ROM and VR

Generate design snapshots for reduced-order models. Explore geometry variation and performance in immersive VR environments.

Contact us

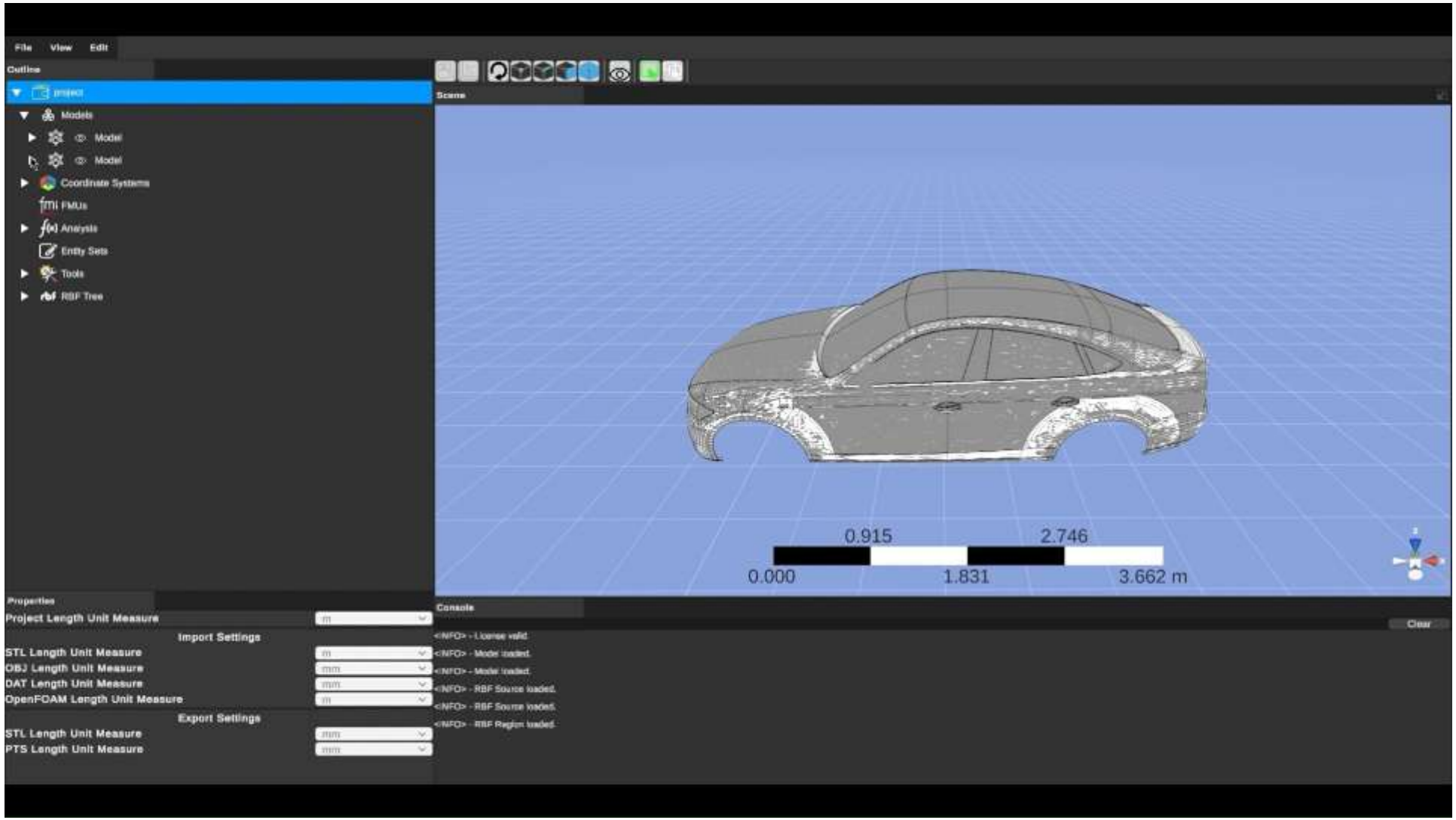


✔ Interactive Parametric Setup

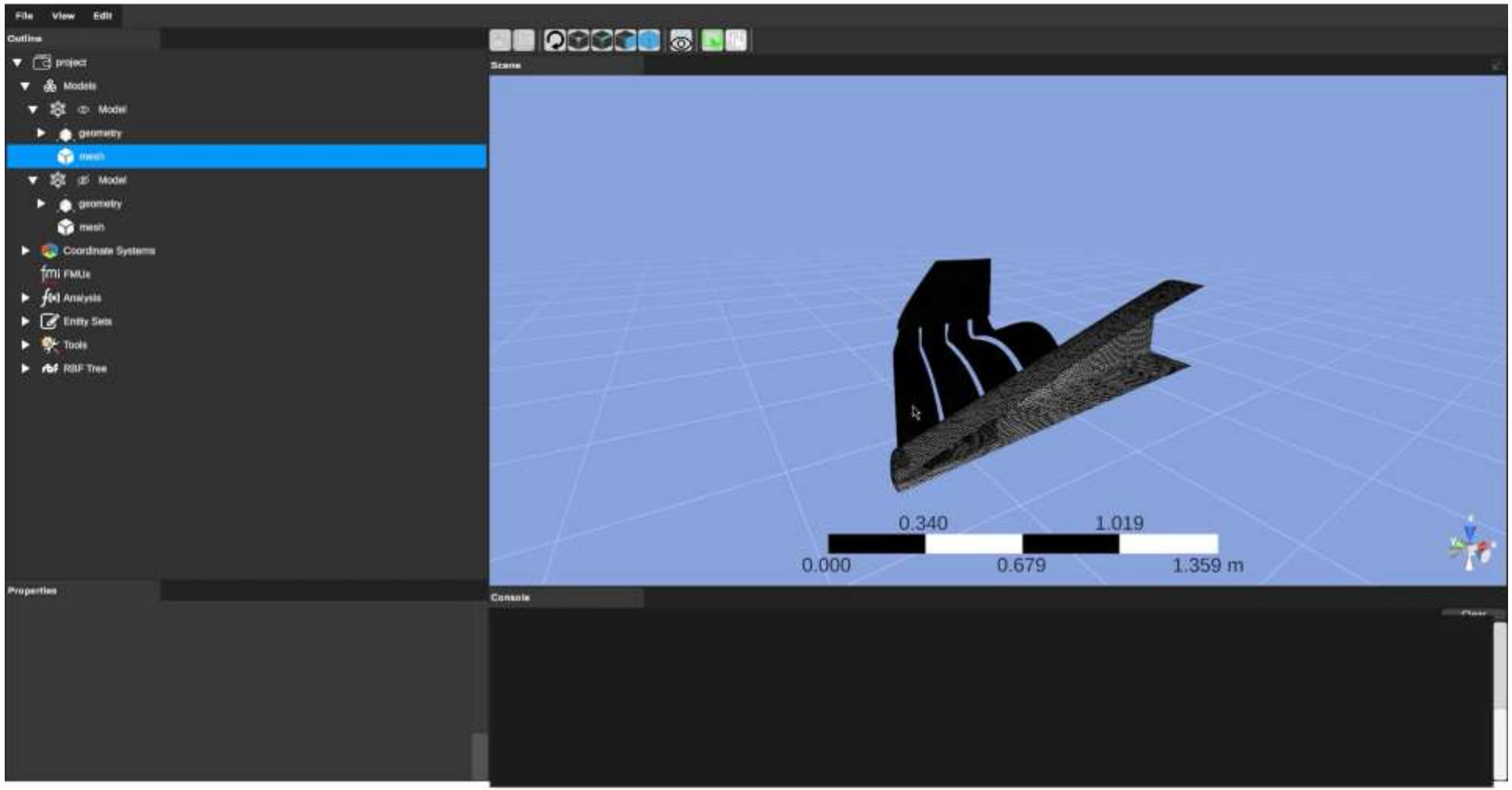
✔ Adjoint-driven Optimization

✔ Fluid-Structure Interaction

✔ Real-time ROM Interaction



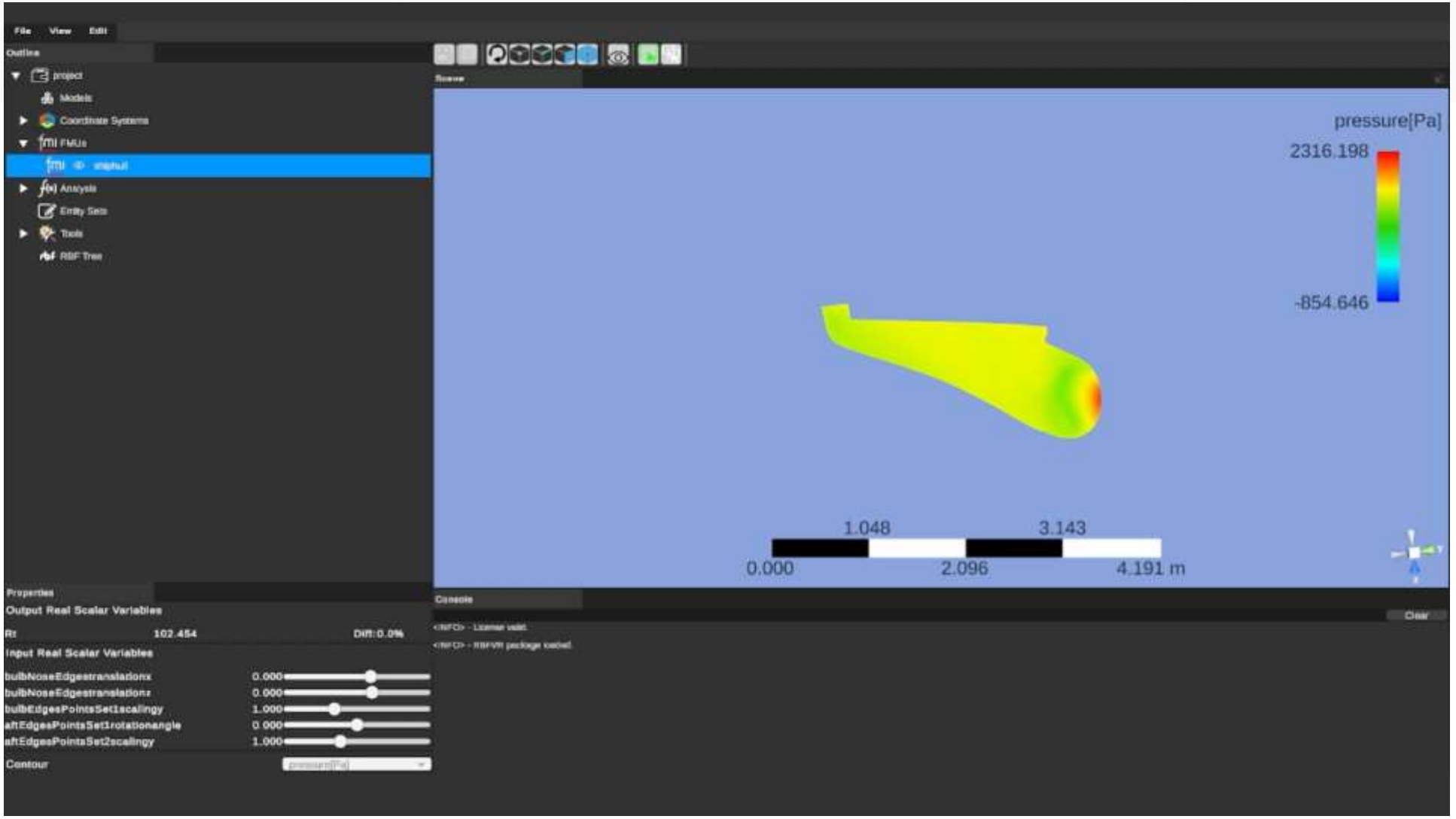
✔ Interactive Parametric Setup | ✔ Adjoint-driven Optimization | ✔ Fluid-Structure Interaction | ✔ Real-time ROM Interaction



✔ Interactive Parametric Setup ✔ Adjoint-driven Optimization ✔ Fluid-Structure Interaction ✔ Real-time ROM Interaction



✔ Interactive Parametric Setup ✔ Adjoint-driven Optimization ✔ Fluid-Structure Interaction ✔ Real-time ROM Interaction



✔ Interactive Parametric Setup

✔ Adjoint-driven Optimization

✔ Fluid-Structure Interaction

✔ Real-time ROM Interaction

✔ Immersive VR Visualization



Conclusions

- An advanced **prescribed-motion CFD simulation** has been presented, addressing transient vehicle manoeuvres in motorsport.
- The proposed strategy **decouples geometric complexity from transient HPC CFD** simulations, leveraging reduced-order models to deform the computational mesh while preserving CAD-level geometric accuracy.
- The **feasibility and effectiveness** of the approach have been demonstrated on an **industrial-scale CFD case**, although further refinements are needed for the specific application.
- An overview of the **rbfCAE (https://engys.com/rbfcae/) platform** and its integration with HELYX has been provided.

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Thank you!

marco.biancolini@rbf-morph.com

linkedin.com/company/rbfcae/

engys.com/rbfcae/

rbfcae.com



Marco Evangelos Biancolini
RBF Morph Founder - Associate Professor of Machine Design
Rome, Latium, Italy · Contact info