DigiPAD

Digital Twin for Advanced Design in the Aerospace Industry

A real-time, high-fidelity preliminary design workflow coupling parametric CAD, RBF mesh morphing, CFD, POD/SVD and machine learning

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1. Goal and concept

Objective. Develop a preliminary aeronautical design methodology able to reduce design time while improving the fidelity of early-stage aerodynamic assessment.

The project combines **JPAD** parametric aircraft modelling with **RBF Morph** shape parameterization to generate a Digital Twin from a compressed database of high-fidelity CFD solutions. The approach brings CFD-level information into the preliminary design stage, where conventional tools are faster but generally less accurate.

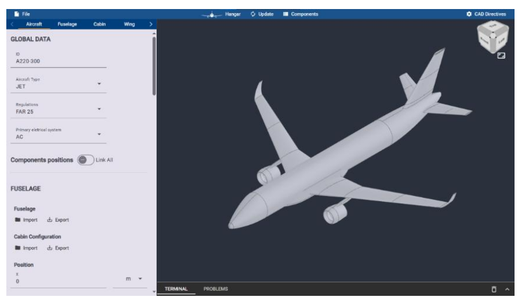
TRL 4 → 7
from technology validation to prototype demonstrated in an operational environment

Real time
interactive exploration of geometric parameters and aerodynamic fields

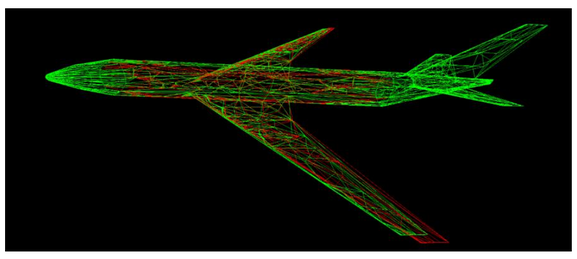
High fidelity
surrogate responses inherited from CFD snapshots

2. Parametric geometry & iso-topology

JPAD generates aircraft configurations and exports geometry suitable for automatic coupling. The workflow was refined to preserve the same topology across variants, a key requirement for robust CAD2CAD correspondence. The selected exchange representation is based on **BRep/STEP** data and uses OpenCASCADE procedures to produce a single united solid while retaining the sub-surfaces and intersection curves required by the downstream workflow.



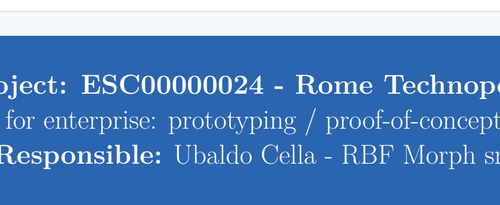
JPAD Modeller: interactive aircraft configuration and CAD generation.



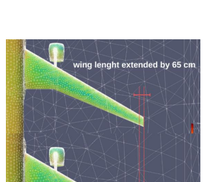
Baseline and modified iso-topological configurations.

3. CAD2CAD and mesh morphing

A dedicated RBF CAD2CAD module identifies homologous geometric entities, creates corresponding surface point sets and transfers the deformation from CAD to the numerical domain while preserving mesh connectivity. The process relies on iso-topological CAD variants, so entity indices and the number of surfaces, curves and edges remain consistent between baseline and modified geometries.



Local morphing effect on the high-fidelity CFD mesh.

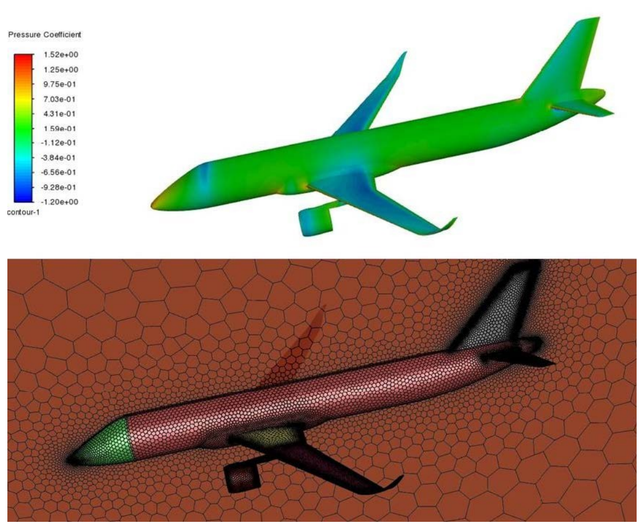


Example of a wing geometric variation propagated to the CFD domain.

- stand-alone ROC procedure for automatic CAD correspondence;
- RBF deformation transfer without full remeshing;
- original mesh topology and solver setup are preserved.

4. Automated CFD database

The numerical domain is automatically updated for each design point. Targeted spatial filtering modifies only the mesh regions affected by geometry changes, avoiding full remeshing. Mesh coordinates are manipulated directly in CGNS format, while the original file structure and CFD setup are preserved for the subsequent SU2 runs.



Surface pressure coefficient and polyhedral CFD mesh.

- approximately **5 million polyhedral cells**
- cruise condition at **Mach 0.75**
- CGNS HDF5 manipulation followed by ADF conversion for SU2
- automated SU2-ready setup with convergence monitoring
- **200 configurations** sampled with Latin Hypercube techniques
- computations executed on a 128-core Xeon Gold cluster

5. End-to-end DigiPAD workflow

JPAD parametric aircraft geometry

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Iso-topological CAD consistent entities across variants

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RBF CAD2CAD deformation transfer to CFD mesh

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High-fidelity CFD automated database generation

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POD / SVD + ML compressed surrogate model

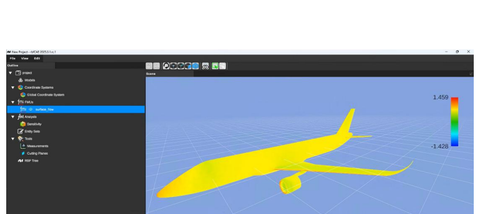
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ROM Explorer real-time Digital Twin

The workflow separates geometry generation, mesh update, high-fidelity simulation and model reduction into independent but automated blocks. This makes it possible to regenerate the complete aerodynamic database whenever the geometric design space is modified, while keeping the same end-to-end data structure.

6. Reduced-Order Model

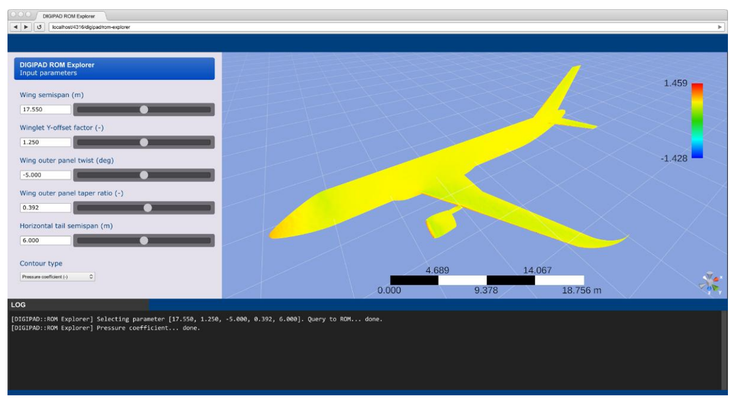
The CFD snapshot database is compressed using **SVD-driven Proper Orthogonal Decomposition (POD)**. Dedicated Python tools assemble mesh and field snapshots, compute the modal basis and evaluate reconstruction error as the retained number of modes increases. Machine-learning regression then maps aircraft design parameters to modal coefficients, allowing rapid reconstruction of geometry and aerodynamic fields.



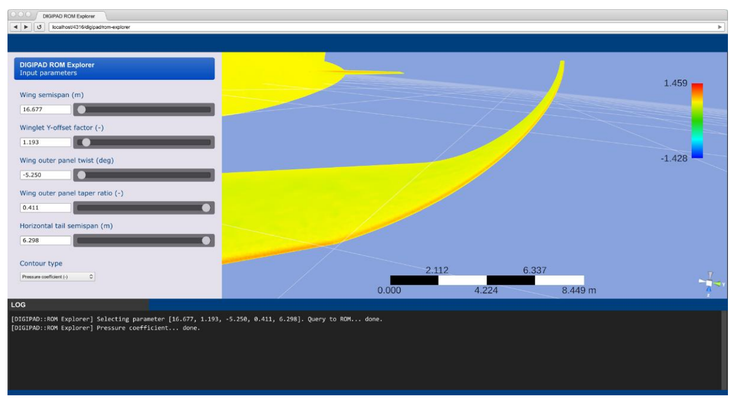
The final ROM met two key targets: **update time below 1 s** and **error below 5%**. It was verified in rbfCAE before integration into the final demonstrator.

7. Real-time Digital Twin demonstrator

The ROM is exposed through an interactive explorer. Users modify geometric design parameters with sliders; each parameter combination queries the surrogate model and immediately updates the aircraft geometry and pressure-coefficient field. The demonstrator complements JPAD Modeller with a dedicated web front-end, while the back-end exports STEP geometry enriched with component metadata, labels and colours.
In practice, the demonstrator allows designers to assess local and global aerodynamic trends during configuration changes, with immediate visual feedback on both the full aircraft and selected details such as the winglet region.



Full-aircraft real-time ROM exploration.



Winglet close-up for a different parameter combination.

8. Key achievements

The main quantitative and qualitative outcomes of DigiPAD are summarised below.

100×
meshing-time reduction vs. conventional workflow

<1 s
target ROM update time

<5%
target error vs. high-fidelity solution

- automatic generation of iso-topological aircraft variants;
- robust coupling between geometric and CFD parameterizations;
- automated high-fidelity database generation;
- compact ROM of full aerodynamic fields;
- interactive exploration of geometry and pressure results.

Together, these results demonstrate that DigiPAD can support faster preliminary design loops while maintaining a strong connection with high-fidelity CFD information.

9. Impact

DigiPAD brings CFD-level information into the preliminary design phase, enabling designers to explore a large aircraft design space with near-instant feedback. This supports faster configuration screening and the identification of more efficient aircraft concepts before committing to expensive high-fidelity analysis campaigns. The project therefore connects preliminary design, automatic geometry generation, CFD and data-driven surrogate modelling within a single reusable digital workflow.

Technology transfer outcome: a demonstrator evaluated in an operational environment, integrating parametric aircraft design, automatic mesh morphing and a data-driven Digital Twin.

PNRR project: ESC00000024 - Rome Technopole - Spoke 2
Cascade call for enterprise: prototyping / proof-of-concept
Scientific Responsible: Ubaldo Cella - RBF Morph srl

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