Instituto Nacional de Técnica Aeroespacial

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

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AGENCIA ESTATAL DE INVESTIGACIÓN

Design of smart geometry variation morphing wing for optimized drone performance

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PhD Aerospace Engineering UC3M
Doctoral Meetings 2026
2nd and 3rd June 2026

uc3m PHD

Motivation

- The challenge: **gusts in non-conventional regimes.**
  - UAVs in urban canyons, ridges, wakes → G > 1.
  - A full flow reorganization, not a perturbation.
  - Transient lift loss, separation, vortices, nonlinearity.
  - Active solutions to cancel disturbances.

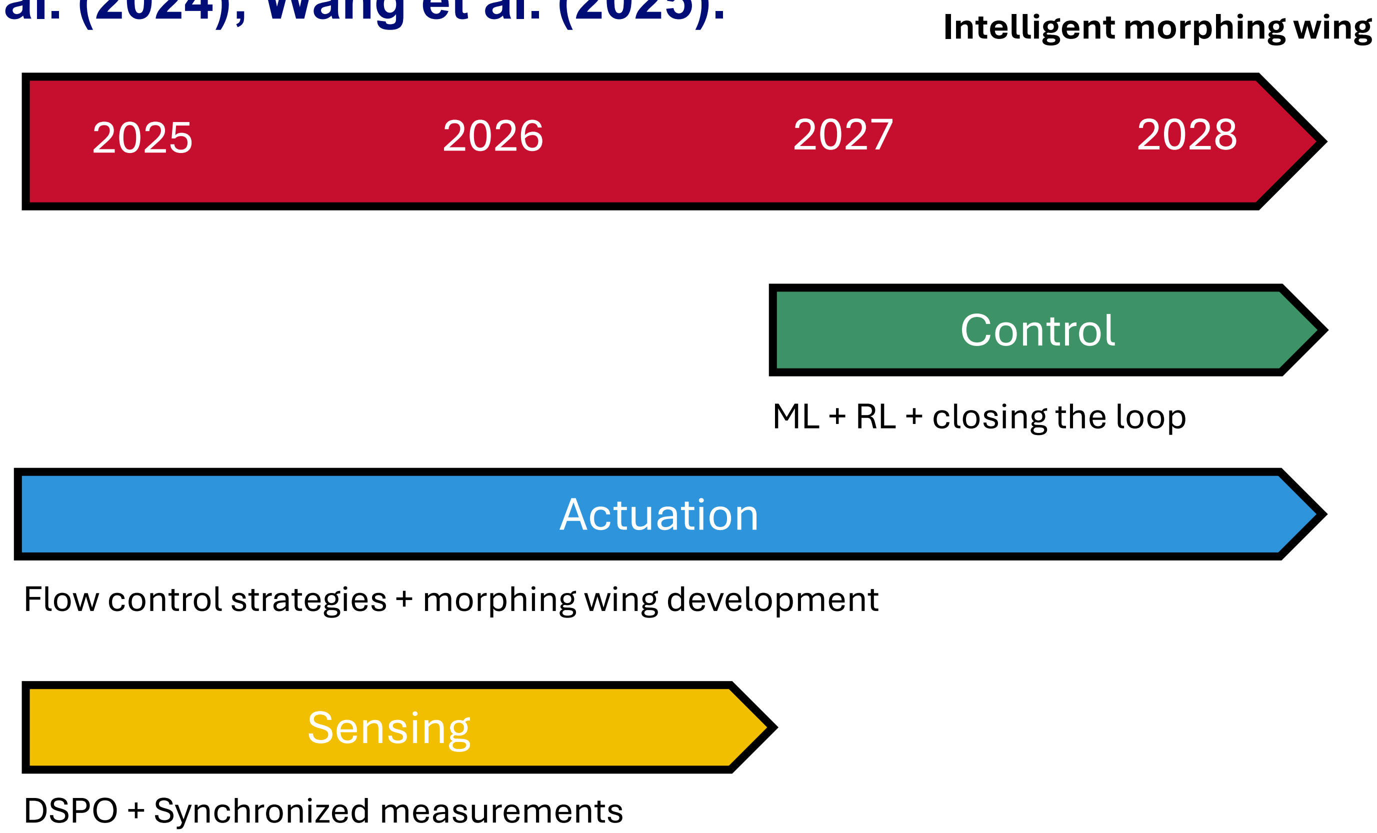
Source: Turbulence Solutions

Source: Youtube

Introduction and Objectives

- What is the target? **A smart wing that adapts in real time to changing flight conditions.**
  - Continuous camber morphing for smooth shape change. **Woods & Friswell (2012); Rivero et al. (2022).**
  - Closed-loop gust load alleviation pressure sensing and deep reinforcement learning. **Fitzgerald et al. (2024); Wang et al. (2025).**

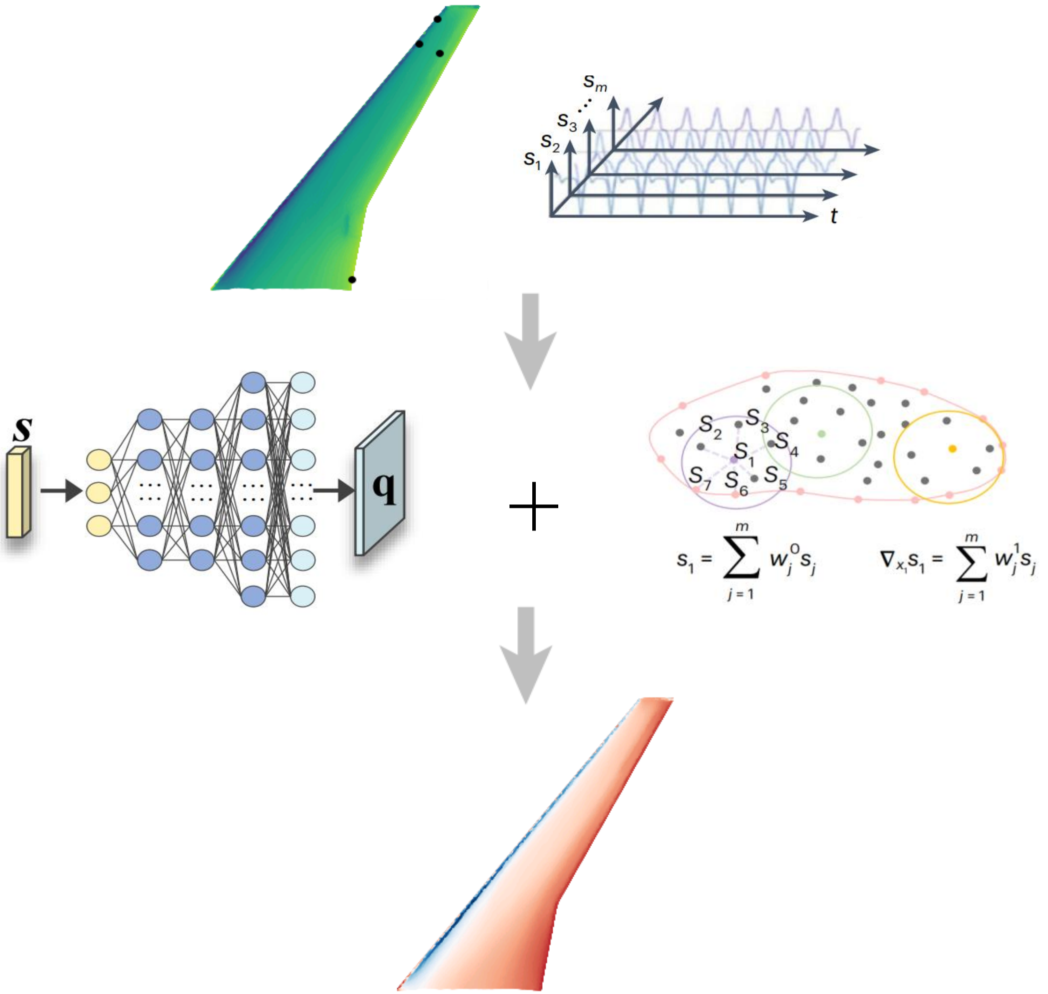
- What are the three main pillars?
  - **Sensing:** where and how to measure.
  - **Actuation:** flow and geometry control.
  - **Control:** ML/RL closing the loop.

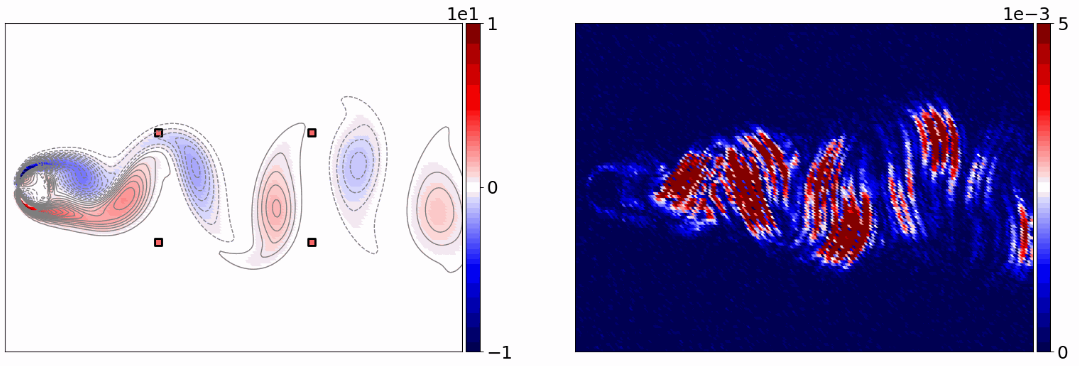


Sensing: where and how to measure

- No model sees more than its sensors reveal.
  - Take advantage of minimum information.
  - In experiments, sensor placement is crucial.

- Solution: **Differentiable Sensor Placement Optimization (DSPO).**
  - An MLP reconstructs the full field while model and sensor locations are co-optimized.
  - First numerical approach, for later wind tunnel validation.





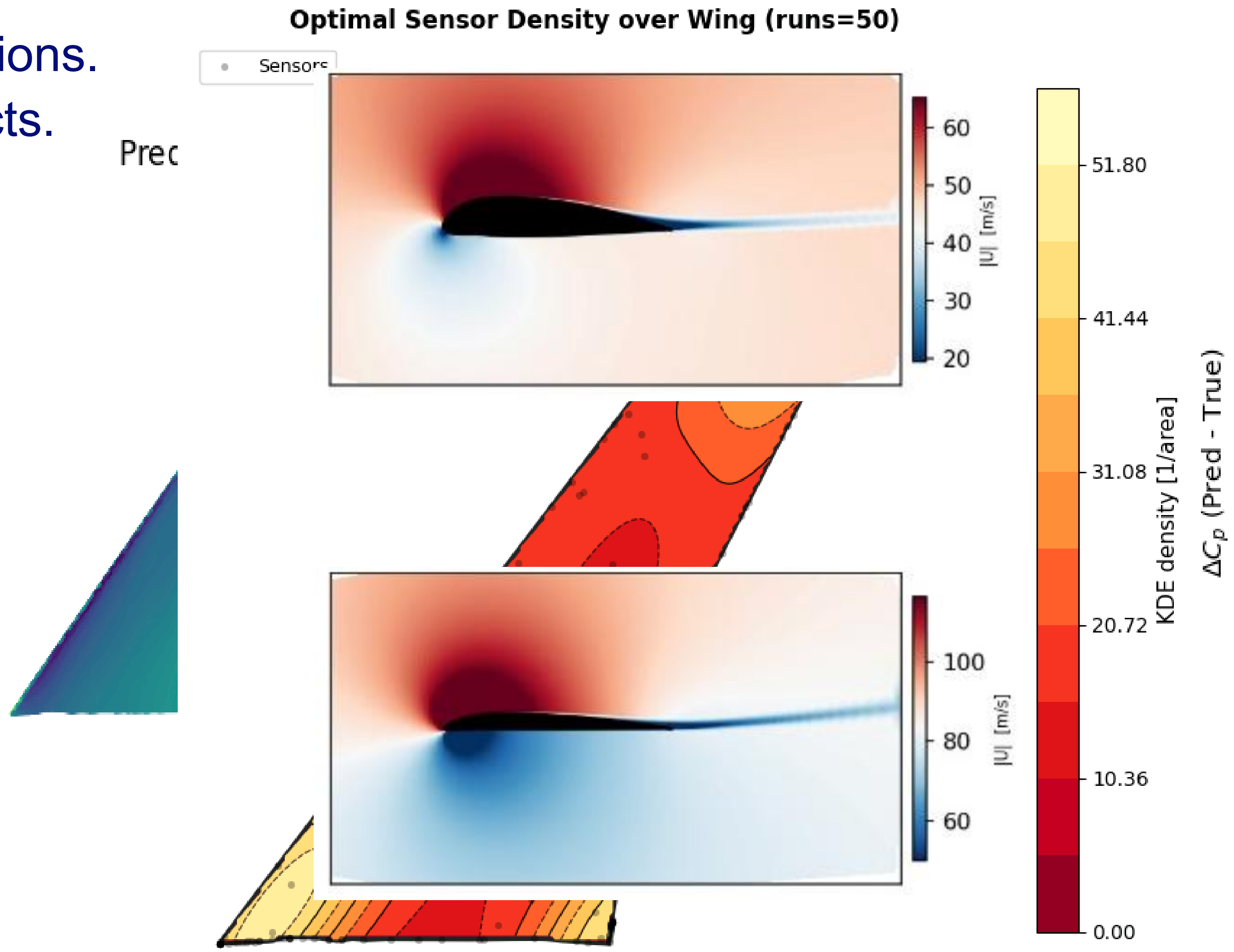
Liu *et al.* (2024)

Sensing: DSPO results

- Optimal sensor maps (NASA CRM).
  - 50 runs – 4 sensors – random initializations.
  - Final positions revealing dominant effects.

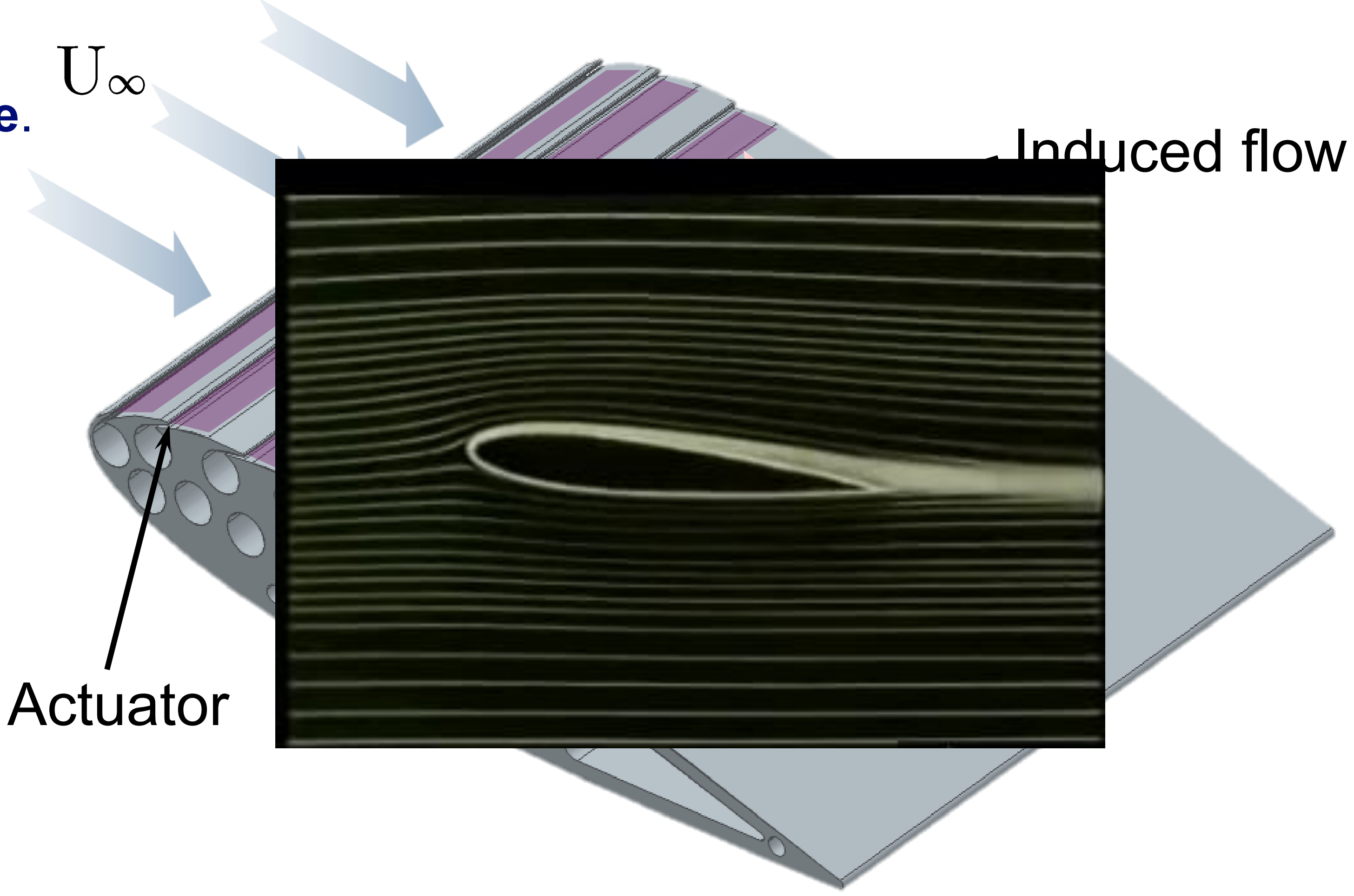
- Field reconstruction.
  - Full Cp recovered across multiple flight conditions.
  - Global error drops as ns = 4 → 8 → 16.

- Future steps
  - Extend to 3D flow-field reconstruction.
  - Target more complex datasets.
  - Move towards gust environments.



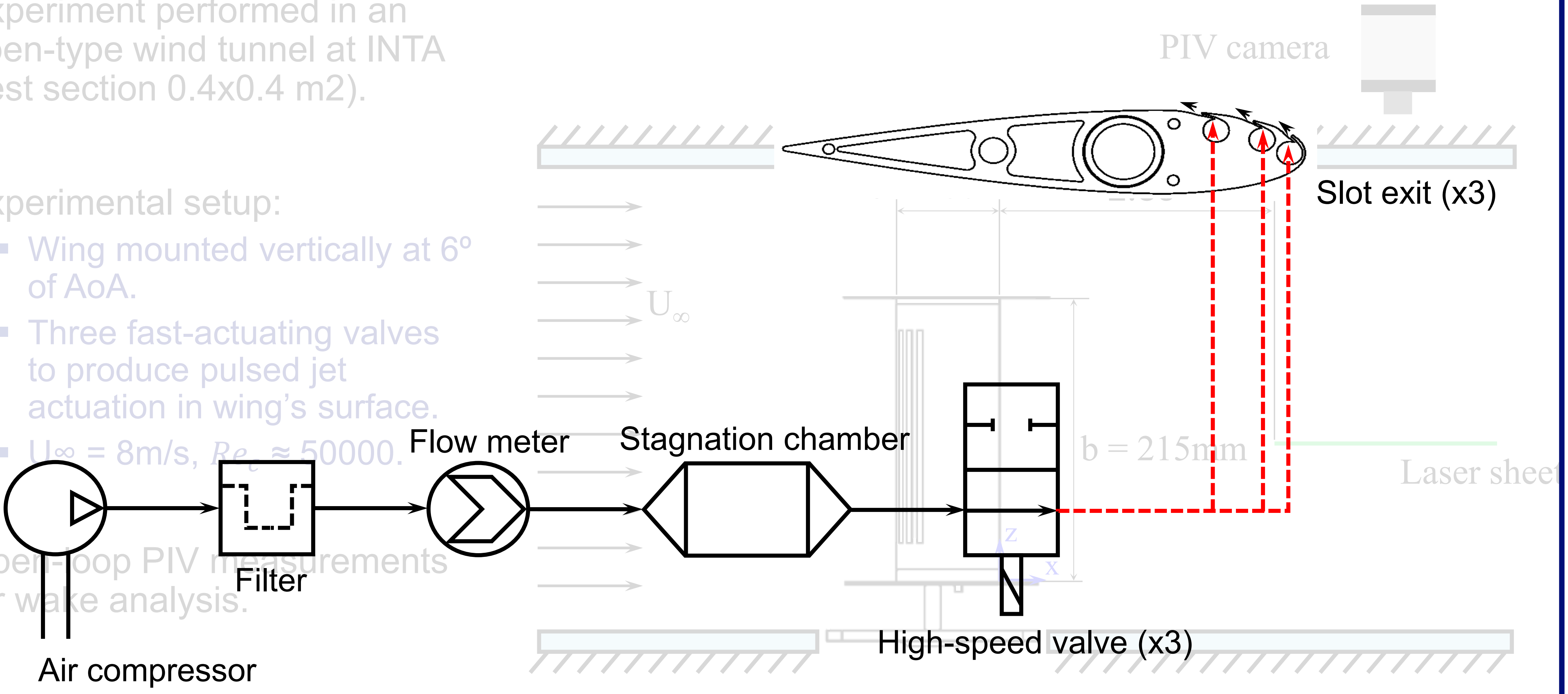
Towards flow control

- The problem
  - Low Re airfoils separation at moderate AoA, creates wake momentum deficit → **drag increase**.
- The approach:
  - Pulsed jets to re-energize the separated shear layer fast and locally.
  - Actuation parameters are non-intuitive → data-driven optimization needed.
- Why flow control?
  - Pulsed jets act directly and fast on the separated shear layer.



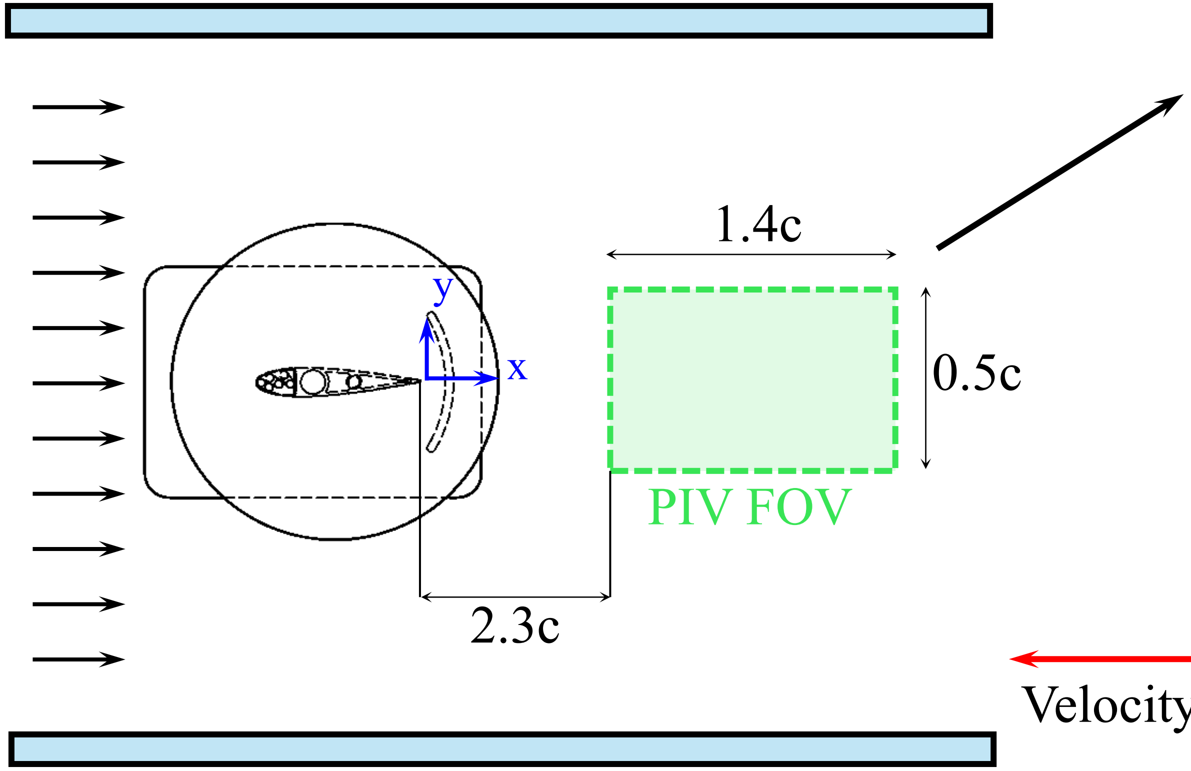
Experimental setup

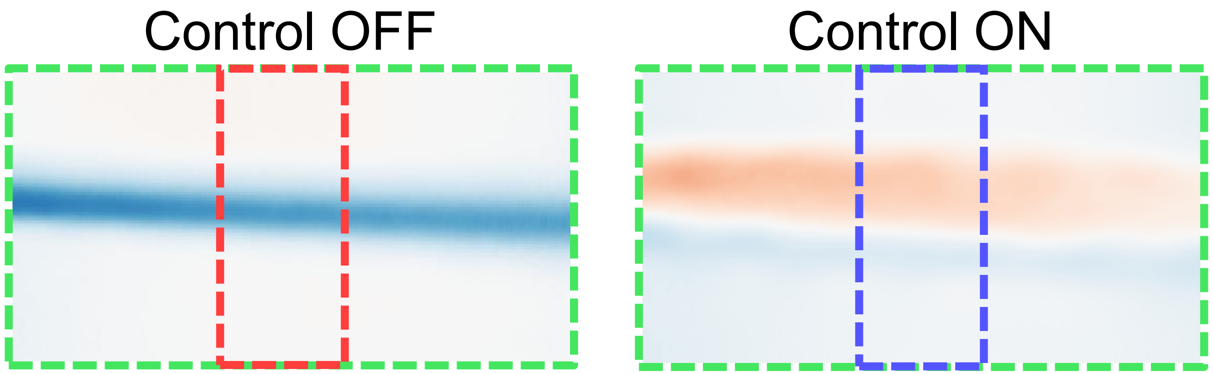
- Experiment performed in an open-type wind tunnel at INTA (test section 0.4x0.4 m2).
- Experimental setup:
  - Wing mounted vertically at 6º of AoA.
  - Three fast-actuating valves to produce pulsed jet actuation in wing's surface.
  - U_∞ = 8m/s, $Re_c \approx 50000$.
- Open-loop PIV measurements for wake analysis.

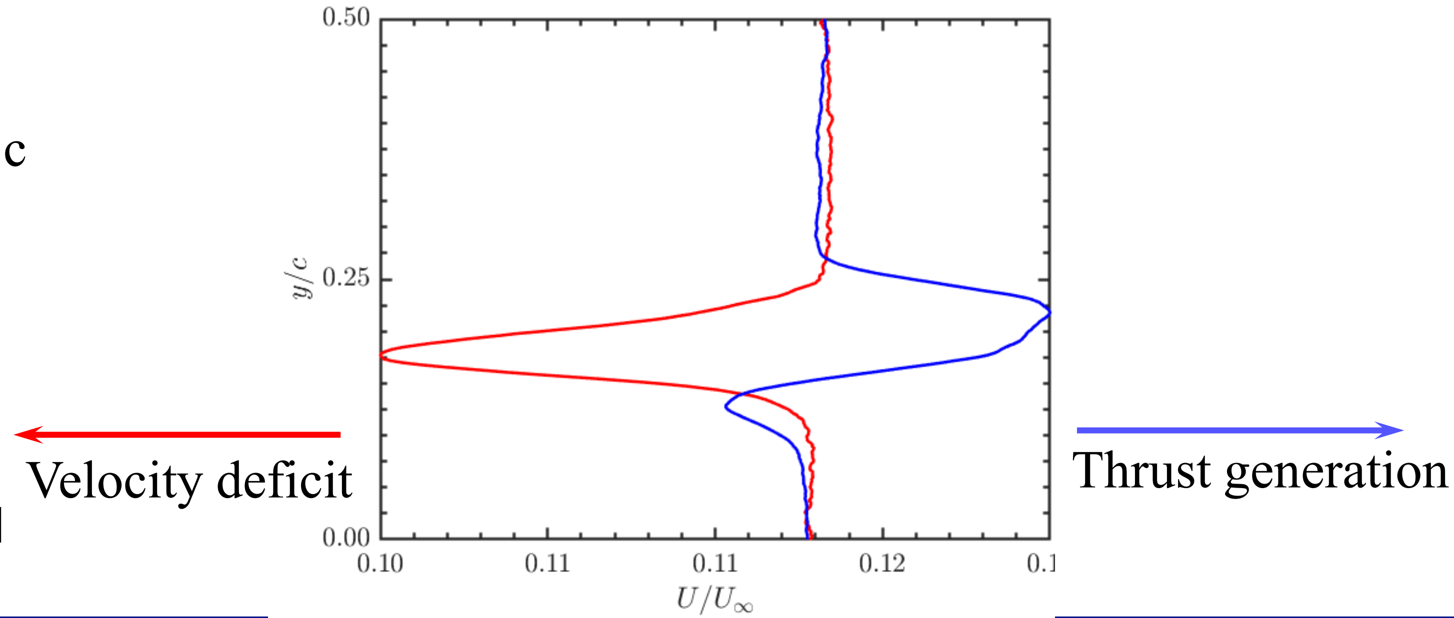


Flow field measurements

- Particle image velocimetry was used to study the wake profile at a distance 3c from the wing's TE.
  - Wake difference with control ON/OFF.
  - Velocity profile used as metric.

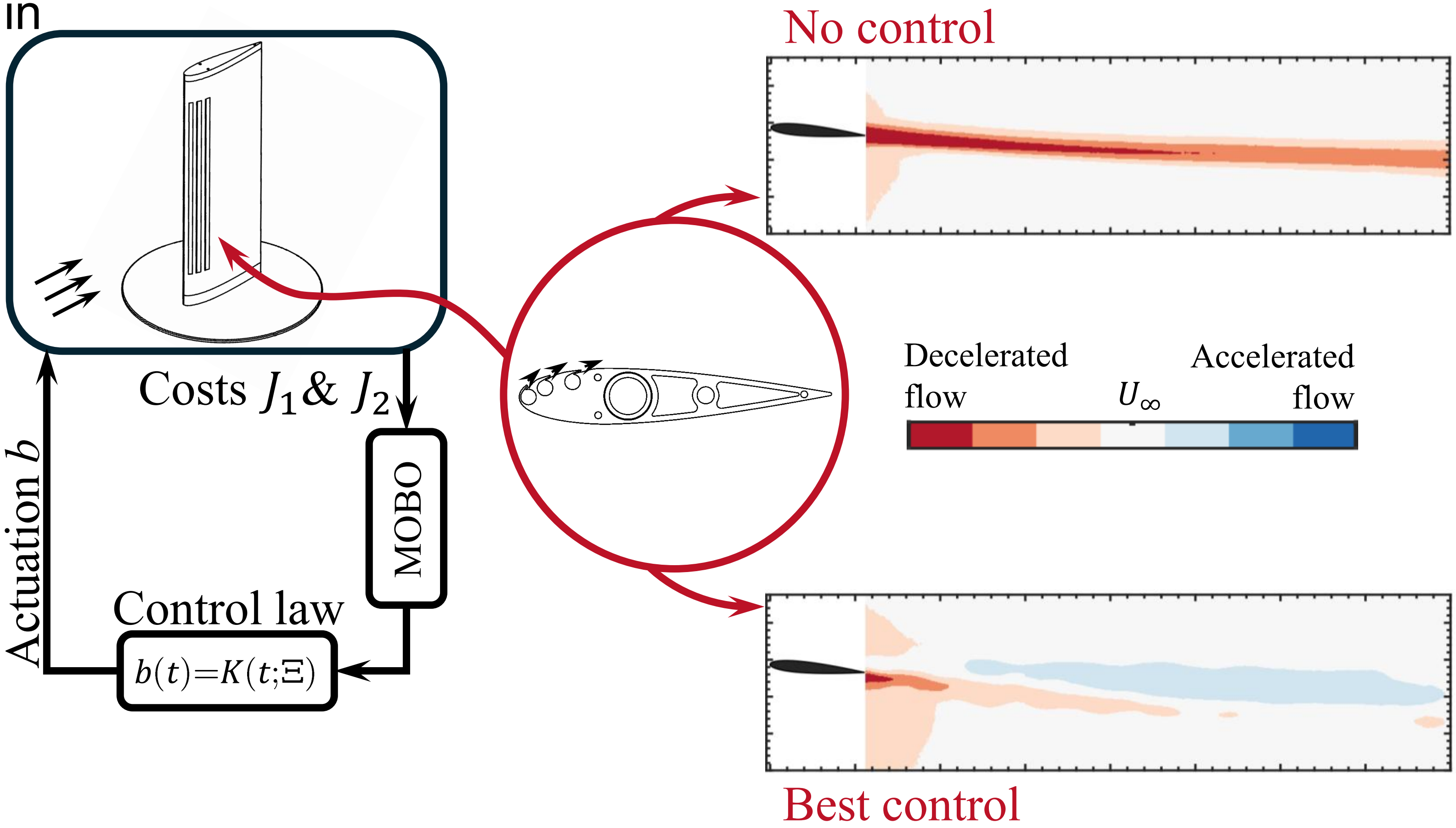






Solving the flow control problem…

- Apply machine-learning algorithm in an experimental environment.
  - Multi Objective Bayesian Optimization (MOBO).
  - 75 LHS control laws.
  - 329 evaluated individuals.
  - Goal → minimize **J**.



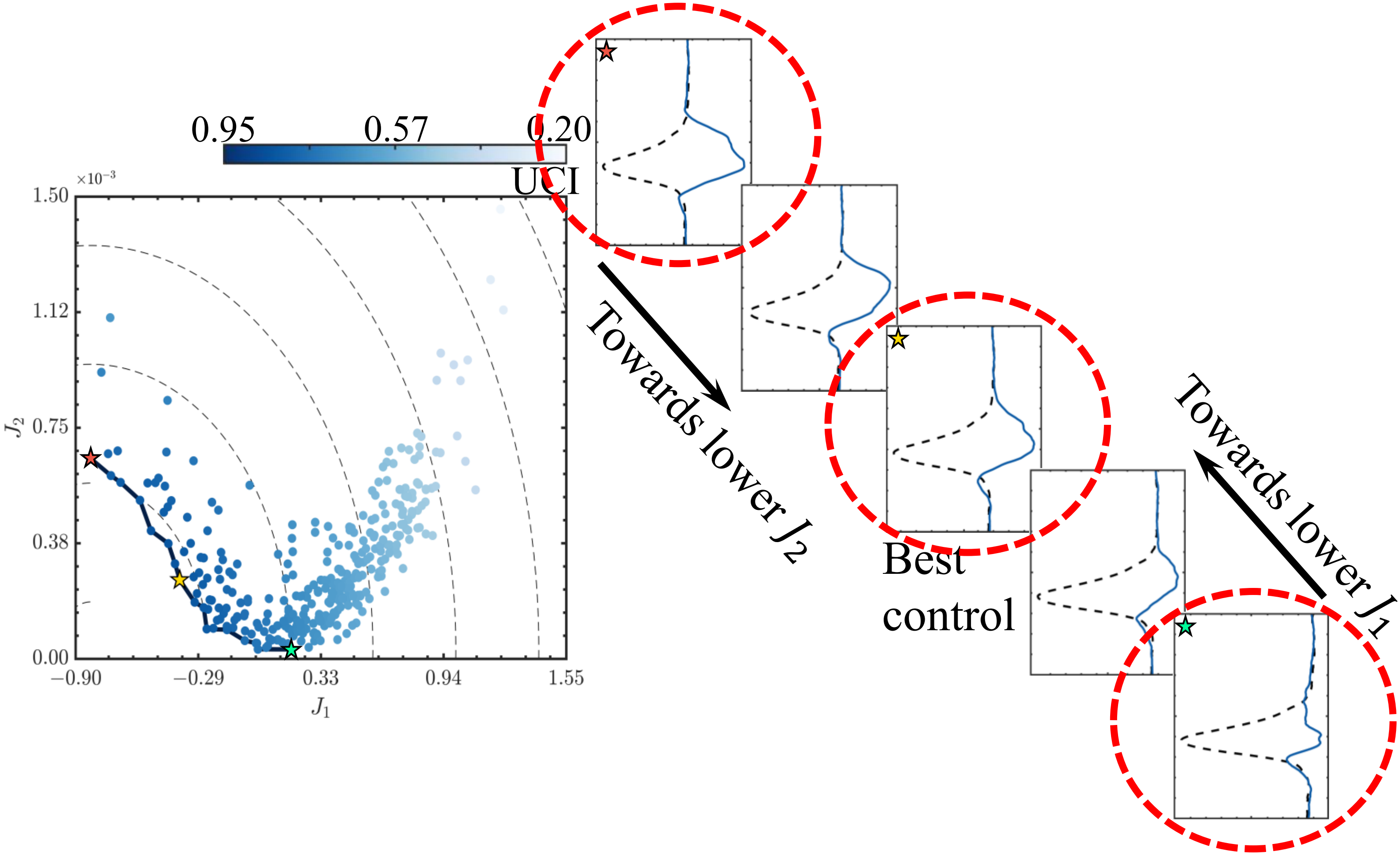
- Control parameters → $\Xi = [\,f_1, f_2, f_3, DC_1, DC_2, DC_3]$
  - $f_i \in [5 - 500]Hz$
  - $DC_i \in [0] \cup [10 - 90] \cup [100]\%$

$$\boldsymbol{J} = \Bigg[\underbrace{\frac{C_d}{C_{d,0}}}_{J_1}, \underbrace{\frac{1}{L_y}\int_{\Gamma_y}\left(\frac{u(y)-U_\infty}{U_\infty}\right)^2 \mathrm{d}y}_{J_2}\Bigg] \qquad C_d = \frac{2}{c}\int_{\Gamma_y}\frac{u(y)}{U_\infty}\left(1-\frac{u(y)}{U_\infty}\right)\mathrm{d}y$$

Training evolution and results

- A well-defined Pareto front of non-dominated control laws identified.
  - J1 induces wake-profile overcompensation.
  - J2 forces free-stream conditions.
  - Best control law represents a tradeoff between J1 and J2.

- Work in progress:
  - PIV stitching + Patch POD.
  - Wake analysis with hot wire.



Next steps: global morphing

- Beyond actuation: **a wing that reshapes itself. Morphing + sensing.**

- **FishBAC morphing wing** *(work in progress)*
  - Compliant trailing-edge design inspired by *Woods et al*.
  - 3D-printed in rigid + flexible materials, driven by a tendon-pulley mechanism.
  - In final prototyping stage.

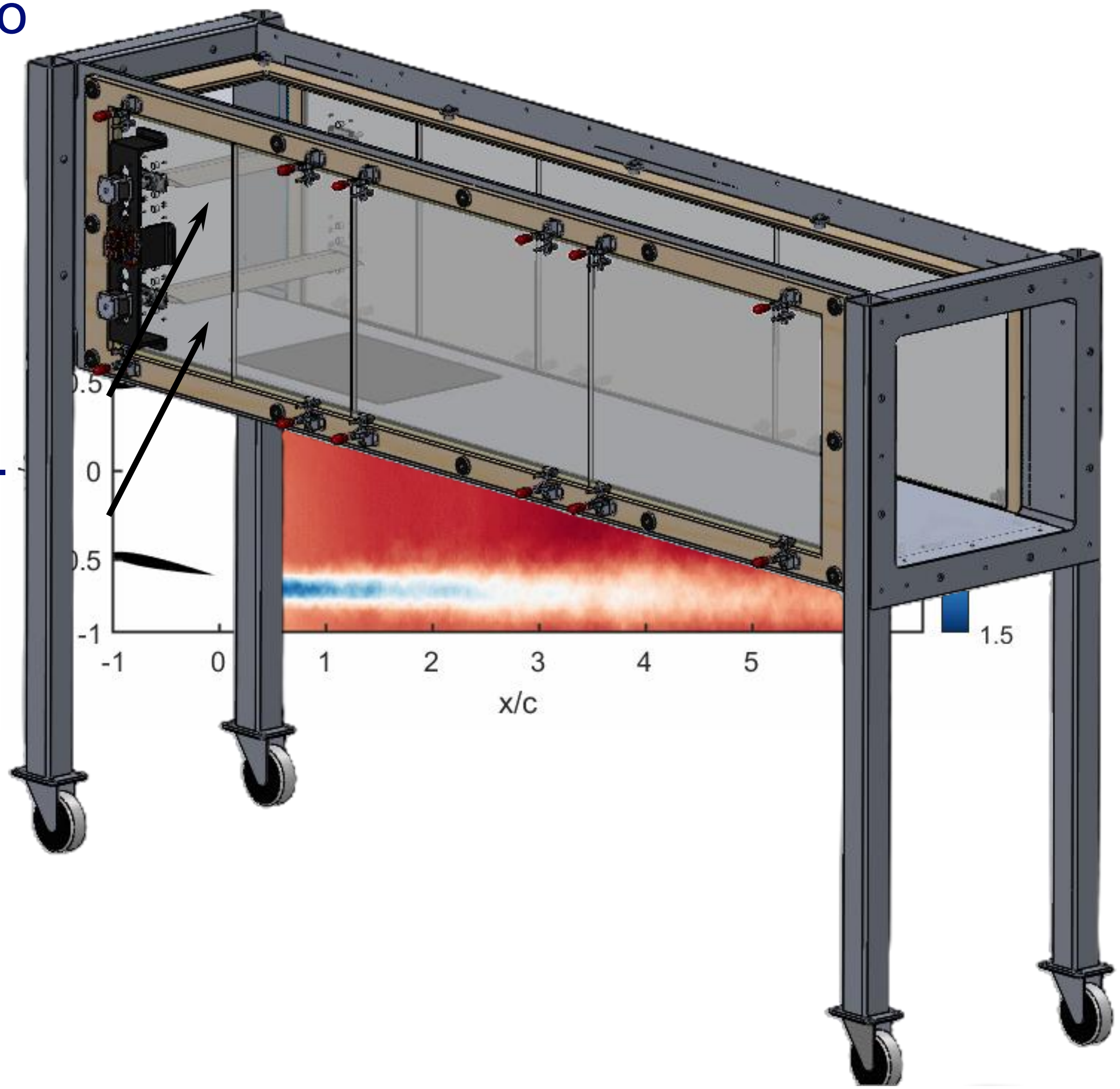
- Modular **leading edge**, the sensing and actuation zone:
  - Hosts pressure ports, slots for actuation, or other local actuators in development.

Next steps: experimental gust generation

- **Goal**: reproduce the disturbance to learn how to reject it.

- In-house **gust generator** (operational).
  - Two NACA 0012 vanes oscillating.
  - 1-cos gusts at low gust ratios (< 0.1).
  - Characterized by hot-wire anemometry and PIV.

- **Next steps**: closing the loop.
  - Integrate the morphing wing (or flapped wing) downstream of the generator.
  - **Goal**: closed-loop gust rejection combining sensing, actuation and geometry change.



Scientific dissemination

- Two journal papers as first author in progress, soon to be submitted (DSPO + Pulsed Jet).

- Journal papers contributions:
  - I. Robledo, **J. Alfaro**, C. Sanmiguel Vila, R. Castellanos, "Unsteady convective heat transfer of an impinging sweeping jet: A discussion on the effect of spatiotemporal filtering", Experimental Thermal and Fluid Science, (2025).
  - I. Robledo, **J. Alfaro**, V. Duro, A. Solera-Rico, R. Castellanos & C. Sanmiguel Vila, "Reducing base drag on road vehicles using pulsed jets optimized by hybrid genetic algorithms", Physics of Fluids, 38, 4, 1 (2026).
  - A. Rodríguez-Asensio, L. Marra, I. Andreu-Angulo, A. Meilán-Vila, **J. Alfaro**, G. Y. Cornejo Maceda, B. R. Noack, A. Ianiro & S. Discetti, "On the turbulent wake of the actuated fluidic pinball: dynamics, bifurcations and control authority", Experimental Thermal and Fluid Science, (submitted).
  - V. Duro, I. Robledo, **J. Alfaro**, R. Castellanos, C. Sanmiguel Vila, & A. Ianiro. "Enhancing impinging-jet heat transfer with pulsed mini-jets: optimization and low-dimensional analysis", International Journal of Flow and Heat Transfer (in preparation).

Scientific dissemination

- Conference contributions:
  - **J. Alfaro,** I. Robledo, V. Duro, R. Castellanos & C. Sanmiguel Vila, “Open-loop optimization of jet mixing for convective heat transfer using genetic algorithm control”, in Spanish Fluid Mechanics Conference 2025, Málaga
  - V. Duro, **J. Alfaro,** I. Robledo, R. Castellanos & C. Sanmiguel Vila, “Open-loop optimization of jet mixing for convective heat transfer using genetic algorithm control”, in 17th International Conference on Fluid Control, Measurements, and Visualization 2025, Delft.
  - V. Duro, I. Robledo, **J. Alfaro**, R. Castellanos & C. Sanmiguel Vila, “Impinging jet convective heat transfer enhancement using genetic algorithm control”, in 16th 21st International Symposium on Flow Visualization 2025, Tokyo.
  - **J. Alfaro**, R. Castellanos & C. Sanmiguel Vila, “ Differentiable sensor placement optimization for aerodynamic wing pressure field reconstruction”, in 10th European Congress on Computational Methods in Applied Sciences and Engineering, 2026, Munich.

- Conferences to be confirmed:
  - **J. Alfaro**, R. Castellanos, S. Discetti & C. Sanmiguel Vila, “Low-Reynolds-number separation control on an airfoil using multi-objective Bayesian optimization of pulsed jet actuation”, in European Drag Reduction and Flow Control Meeting – EDRFCM 2026, Madrid.
  - V. Duro, **J. Alfaro**, I. Robledo, R. Castellanos, Andrea Ianiro & C. Sanmiguel Vila, Data-driven low-dimensional interpretation of pulsed impinging-jet heat-transfer control, in European Drag Reduction and Flow Control Meeting – EDRFCM 2026, Madrid.

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Questions?

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Ackowledgments:

- Grant **EXCALIBUR** (No PID2022-138314NB-I00), funded by MCIU/AEI/10.13039/501100011033 and by 'ERDF A way of making Europe'.
- **TIFON** – Tecnologías Inteligentes para la Fabricación, el diseño y las Operaciones en entornos industriales PLEC2023-010251 (MIG-20232039).
- Instituto Nacional de Técnica Aeroespacial (**INTA**).