Active Flow Control with Data-Driven Reduced-Order Models

PhD Student: Alberto Solera-Rico

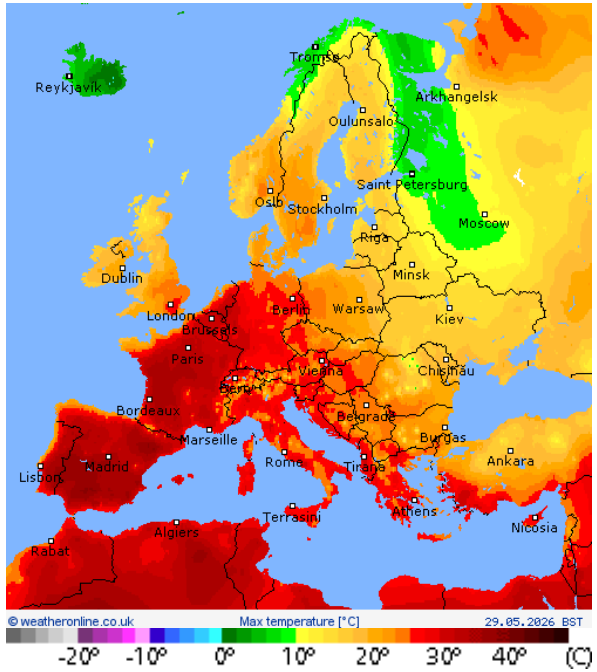
Supervisors:
Stefano Discetti & Carlos Sanmiguel Vila

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

Context & motivation

Turbulence-related inefficiencies: up to ~10%
of global greenhouse-gas emissions

Transport-sector aerodynamic drag ~5%
of EU greenhouse-gas emissions



Max temperatures last Friday

nature communications

Article

https://doi.org/10.1038/s41467-026-68929-9

Human-induced climate change amplification on storm dynamics in Valencia's 2024 catastrophic flash flood

Received: 20 May 2025

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Carlos Calvo-Sancho[1,2], Javier Díaz-Fernández[1], Juan Jesús González-Alemán[3], Amar Halifa-Marín[4,5], Mario Marcello Miglietta[6], Cesar Azorin-Molina[2], Andreas F. Prein[7], Ana Montoro-Mendoza[1,8], Pedro Bolgiani[9], Ana Morata[3] & María Luisa Martín[1,10]

Hoyas & Vinuesa, **The role of turbulence in climate mitigation and sustainable engineering.** Results in Engineering 30, 110666 (2026)

Transportation Research Board. **Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles**. Washington: National Academies Press, 2010

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Classical geometrical optimization (1981)

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: E-38096 Date: 1981

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Active flow control (2015)

Hoyas & Vinuesa, **The role of turbulence in climate mitigation and sustainable engineering.** Results in Engineering 30, 110666 (2026)

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Research questions and objectives

Active Flow control still needs to solve obstacles with practical implementation
We focus on Reduced Order Models (ROMs) for control

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RQ1

Can a nonlinear ROM capture chaotic wake dynamics with a compact, near-orthogonal latent space?

→ **Paper 1: β-VAE + transformer ROM**

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RQ1

Can a nonlinear ROM capture chaotic wake dynamics with a compact, near-orthogonal latent space?

→ **Paper 1: β-VAE + transformer ROM**

RQ2

How do compression and prediction architectures trade off compactness versus forecast accuracy?

→ **Paper 2: POD vs autoencoder compression, single-step vs sequence predictor**

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We focus on Reduced Order Models (ROMs) for control

RQ1 Can a nonlinear ROM capture chaotic wake dynamics with a compact, near-orthogonal latent space?

→ **Paper 1: β-VAE + transformer ROM**

RQ2 How do compression and prediction architectures trade off compactness versus forecast accuracy?

→ **Paper 2: POD vs autoencoder compression, single-step vs sequence predictor**

RQ3 Can a controller trained only on offline, sparse data deliver safe, realizable drag reduction?

→ **Paper 3: MPC with offline-learned latent dynamics**

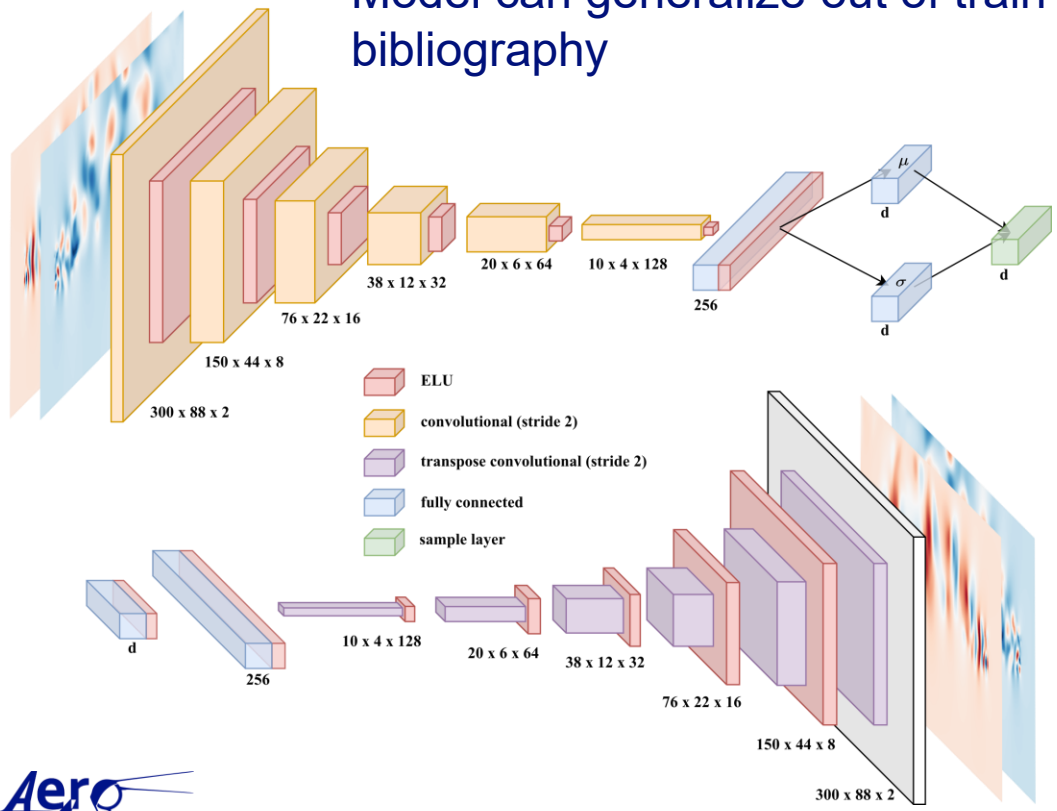
Paper 1: β-VAE and transformer for ROM

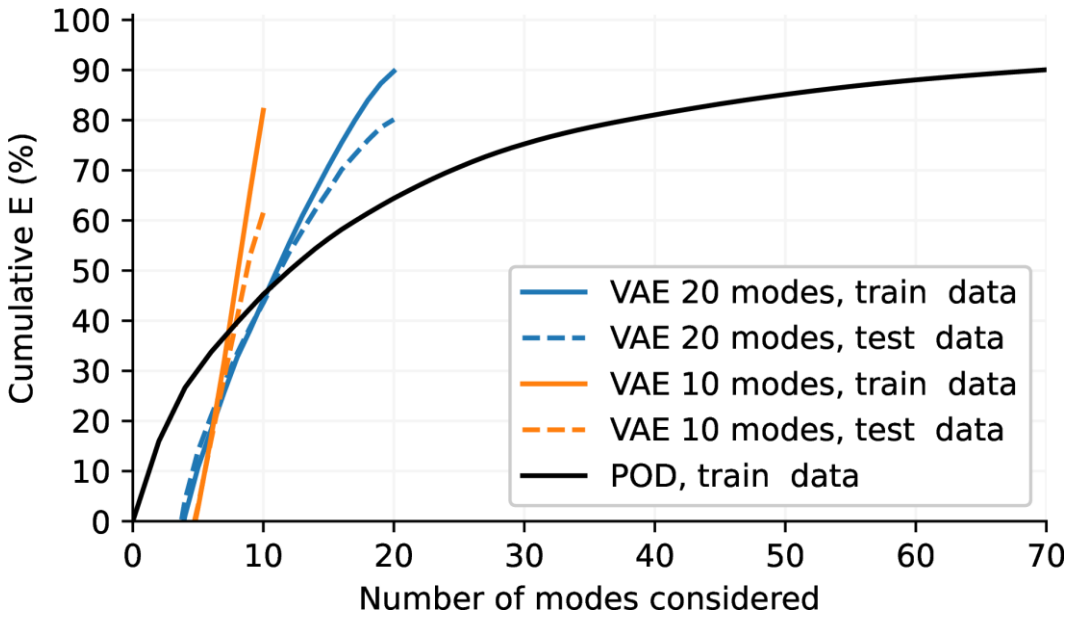
Solera-Rico, A., Sanmiguel Vila, C., Gómez-López, M. et al. **β-Variational autoencoders and transformers for reduced-order modelling of fluid flows**. Nat Commun 15, 1361 (2024).

Link to paper
Code and data available

β-Variational Autoencoder for modal decomposition and transformer for prediction:

- State compressed to a nearly-orthogonal 10-20 size latent-space
- Nonlinear model: better reconstruction error than POD, keeping some desirable properties
- Model can generalize out of train data for chaotic flow: not previously found in related bibliography



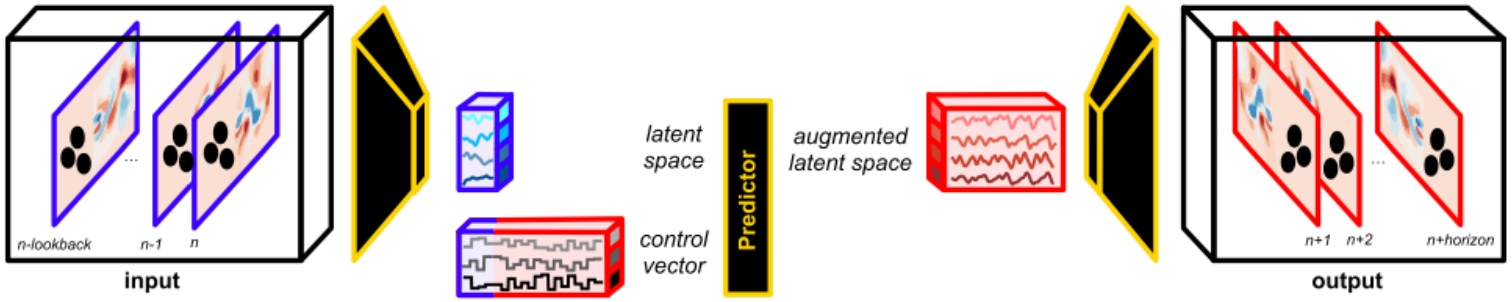


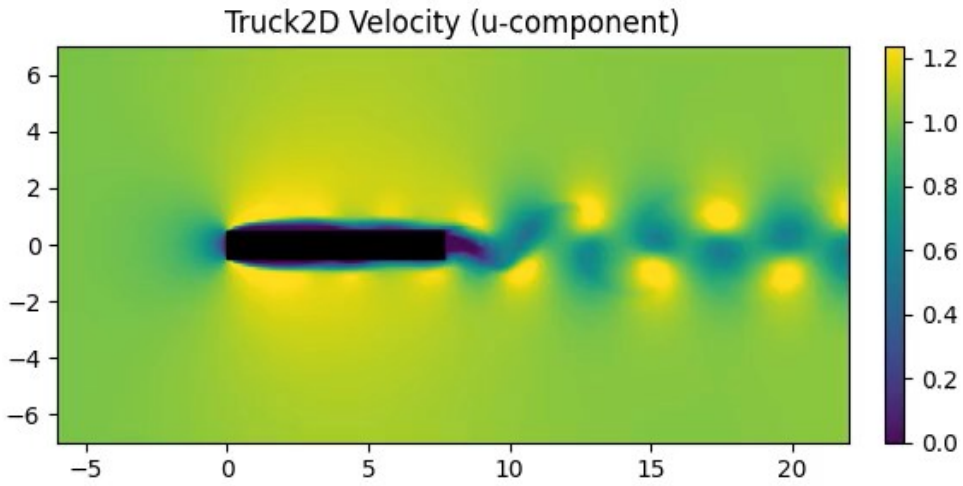
Paper 2: Analysing models for prediction of controlled wake flows

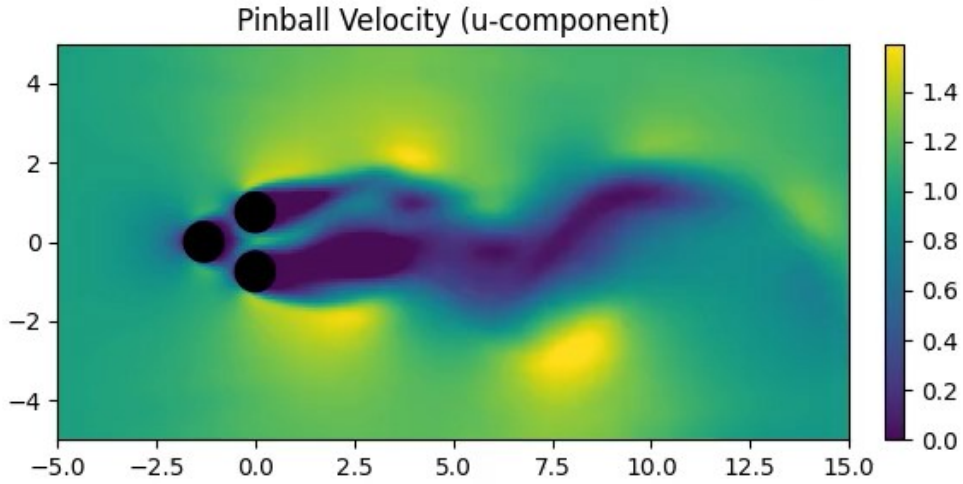
Under review (JFM)

uc3m PHD

Are nonlinear compression methods better for control?







What we compare

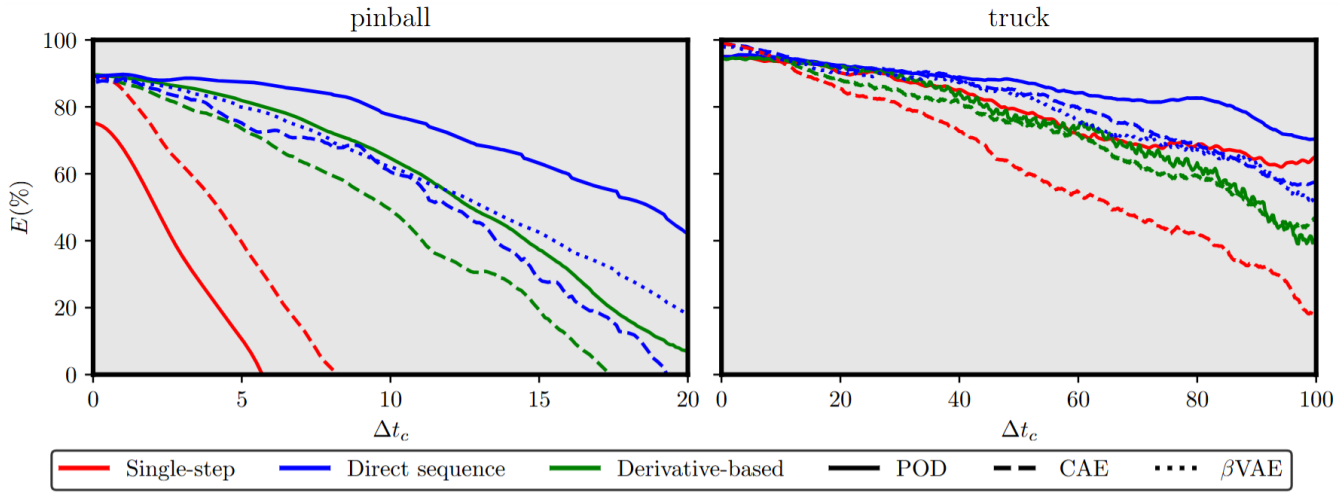
- Encoders: POD (linear) vs CAE and β-VAE (nonlinear).
- Predictors: single-step, direct-sequence and derivative-based LSTMs.
- Test cases: truck (Re 500, single jet) and pinball (Re 150, rotating cylinders).

Thanks to Patricia García Caspueñas for her contribution!

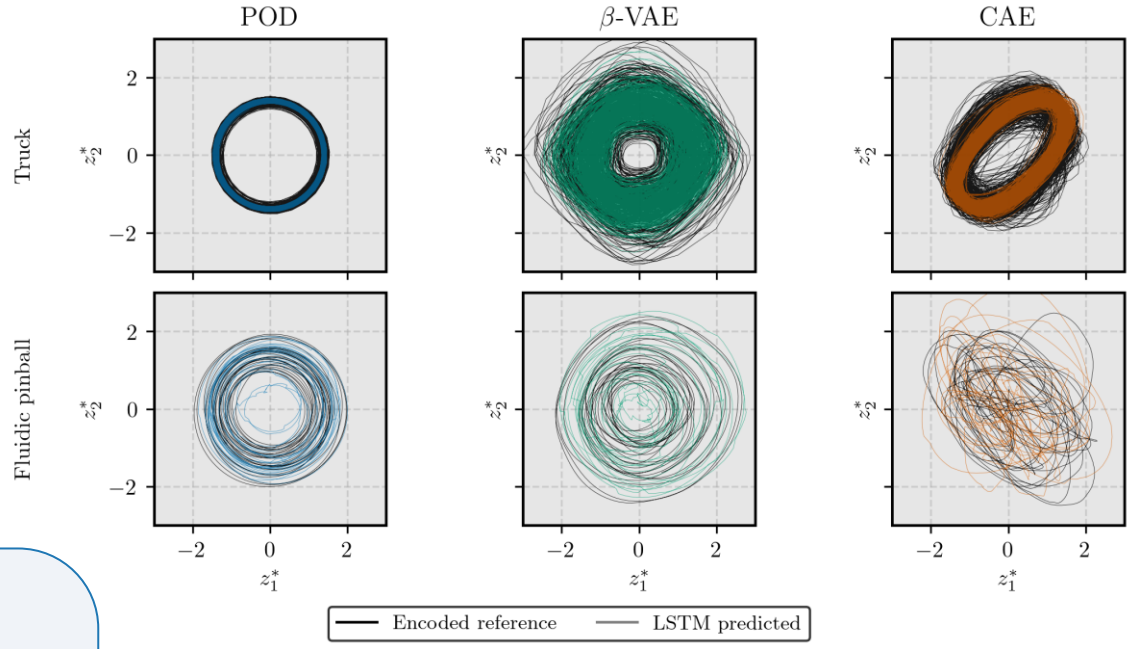
Paper 2: compactness vs forecast accuracy

Under review (JFM)

Forecast accuracy vs prediction horizon



Why: latent-space geometry (phase portrait)



Key findings

- **AEs compress more and reconstruct sharper short-term fields. But AEs need regularization.**
- **Yet POD forecasts are more accurate in the long term.**
- **For control: a slightly larger but simpler latent space increases the reliable MPC horizon.**

- POD traces a clean ring the LSTM reproduces
- CAE fills a broad, irregular region the predictor cannot track

Paper 3: Controller from offline data

Under review (EAAI)

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1. **Open-loop actuation dataset: not trivial for unstable objective regions and delayed systems**

Open-loop data generation:
Sensors, control and forces

STEP 1

Paper 3: Controller from offline data

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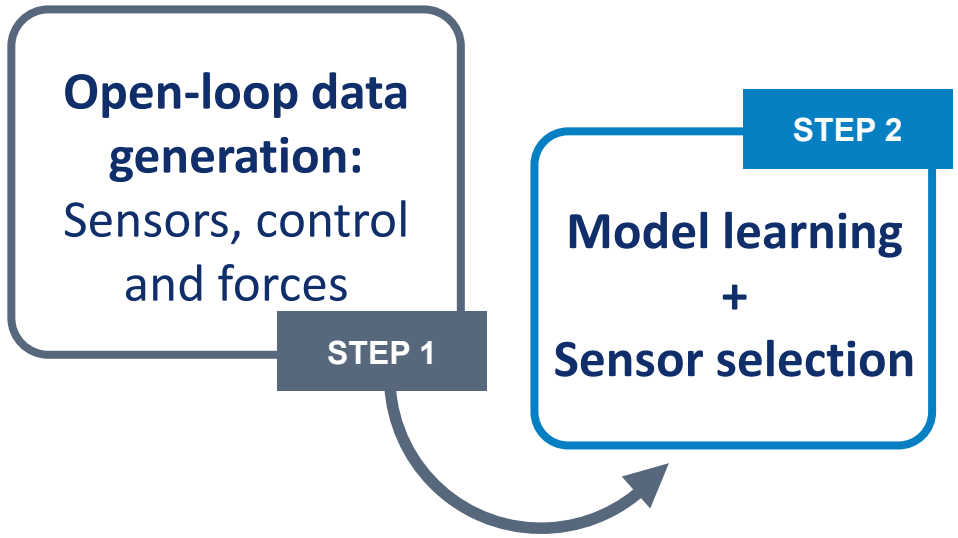
2. **Data-driven dynamics model from dataset using surface pressure sensors**



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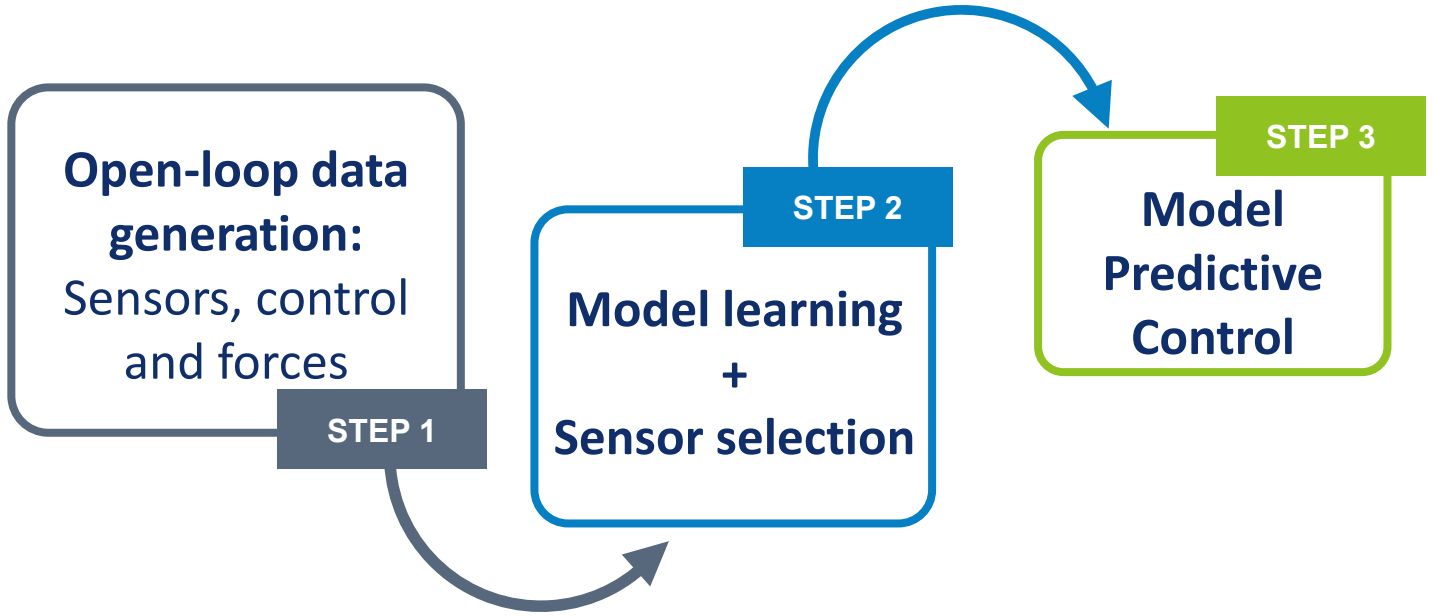

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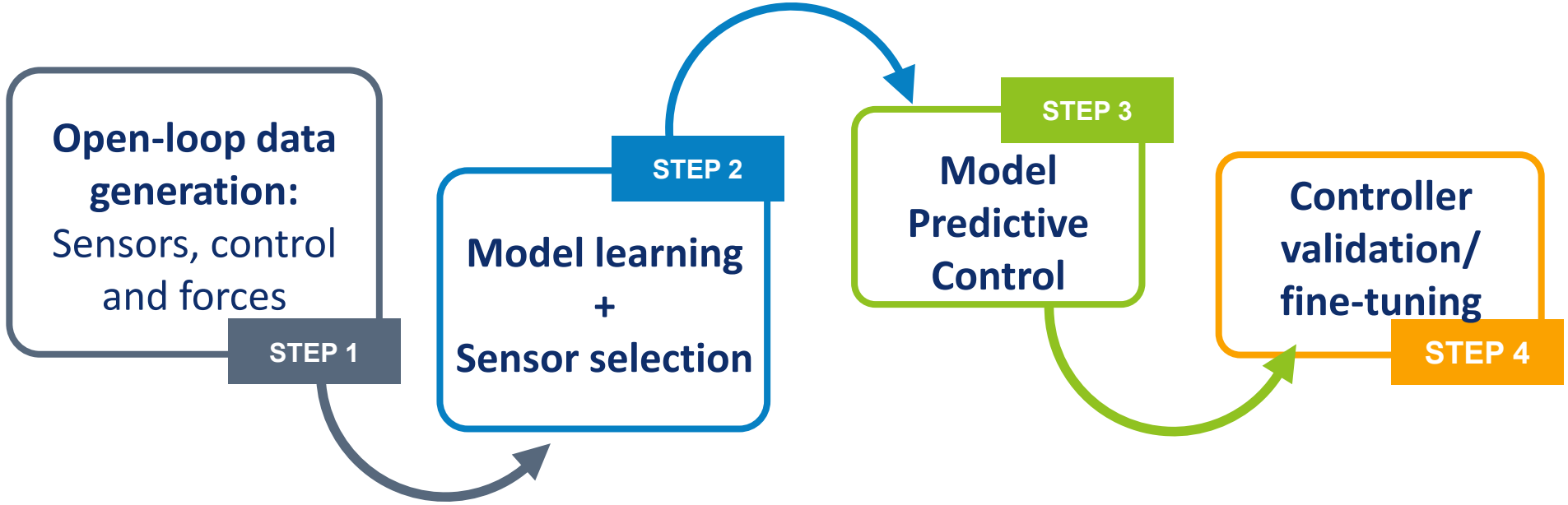
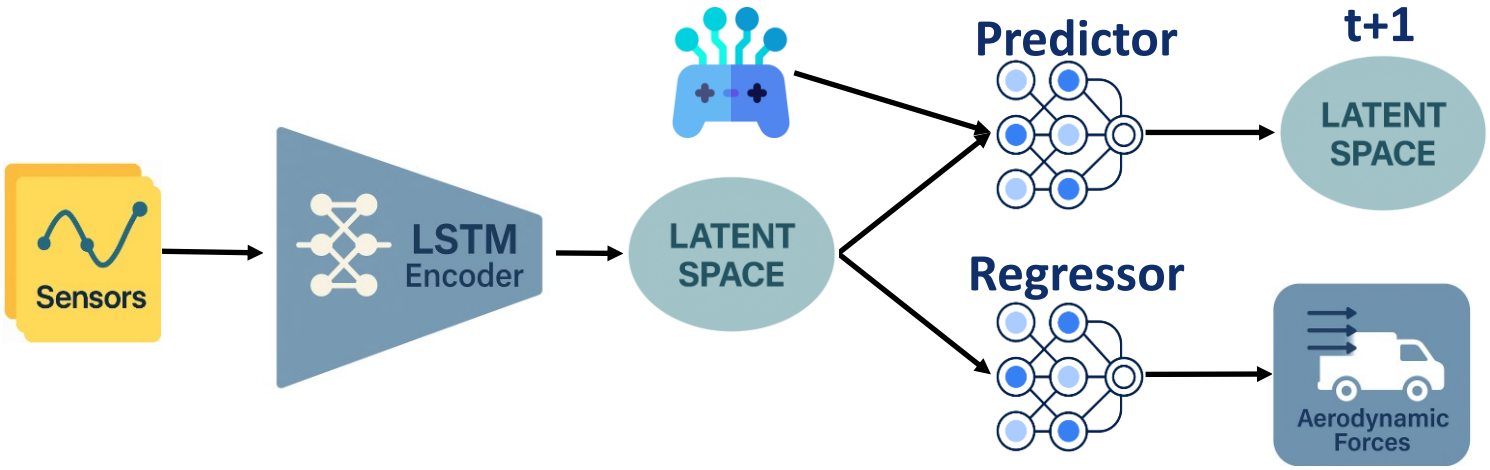
3. **Model-based controller**

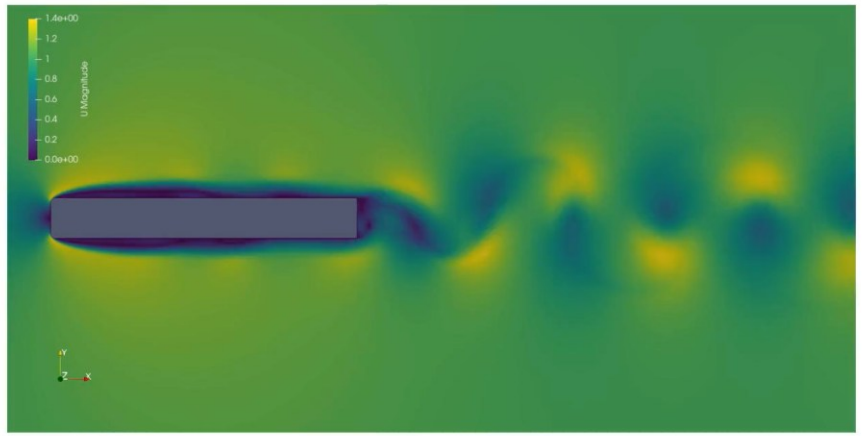
- **Simpler offline training**
- **Safe and deterministic pre-trained controller**
- **Learns from a rich, carefully crafted dataset**

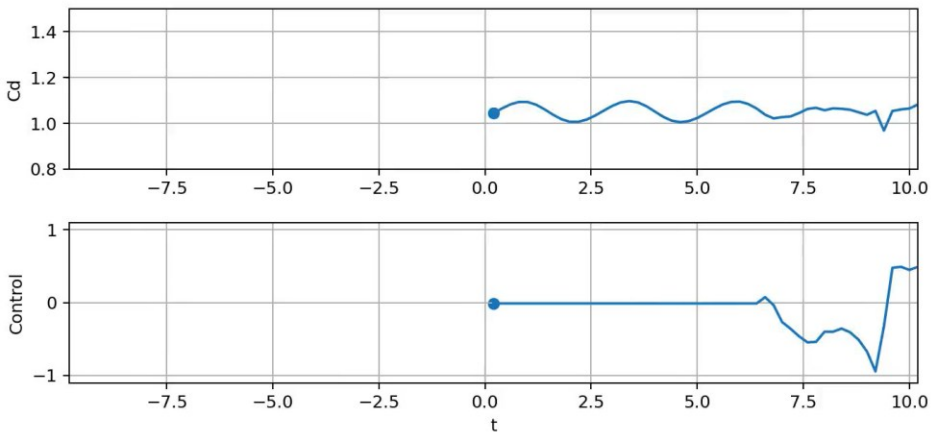


Paper 3: Controller from offline data: Model

Under review (EAAI)







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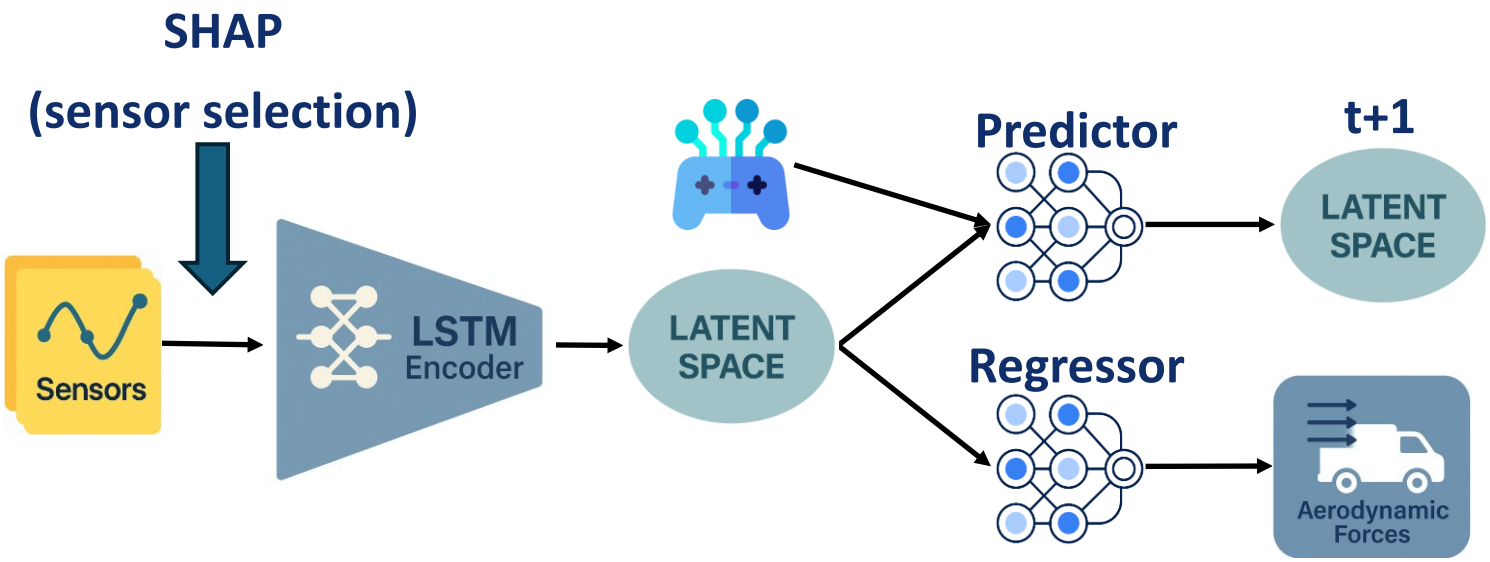

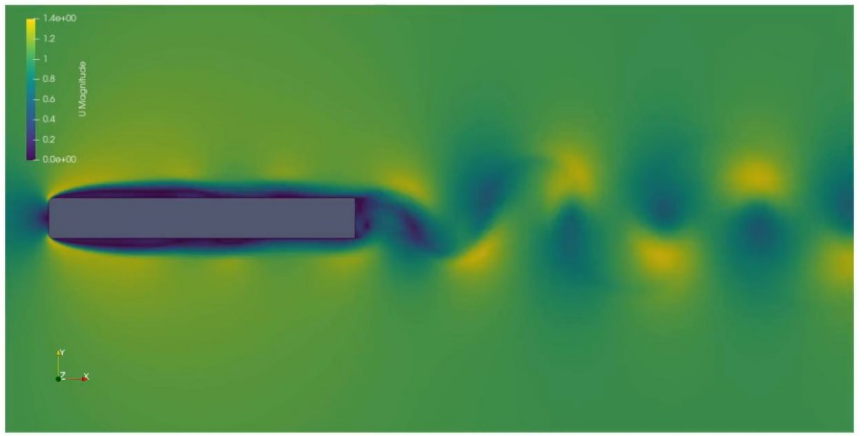

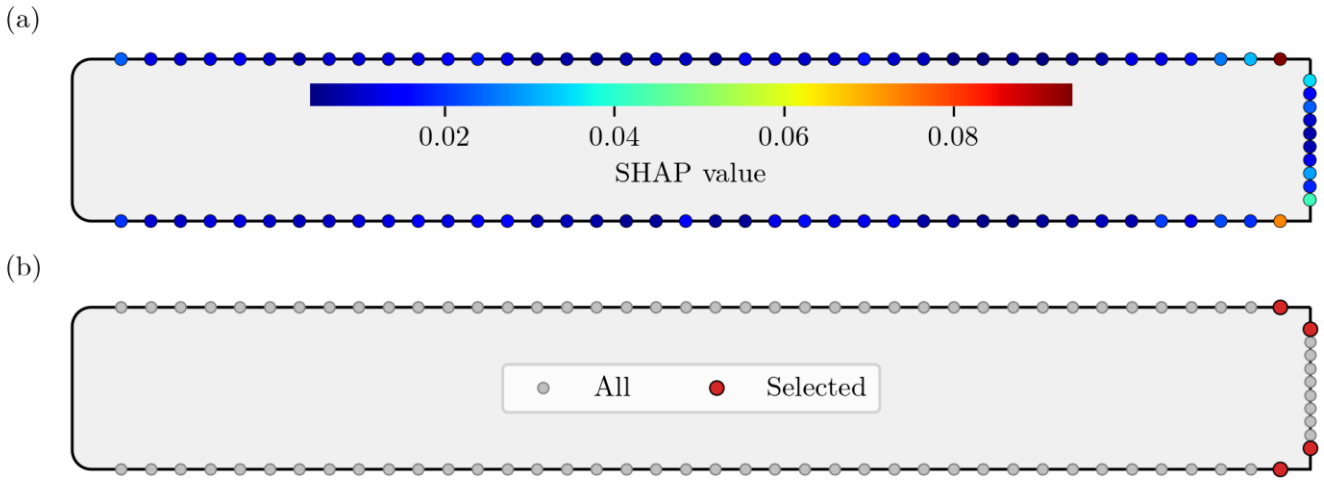

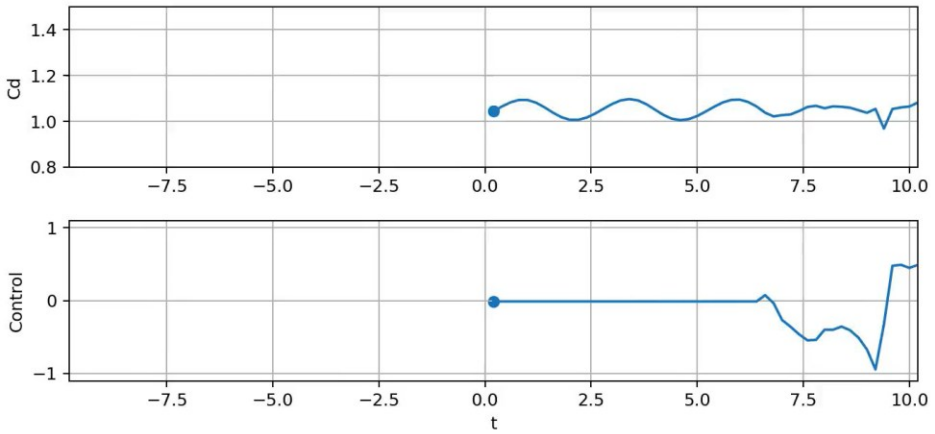

Paper 3: Controller from offline data: Closed-loop results

Under review (EAAI)

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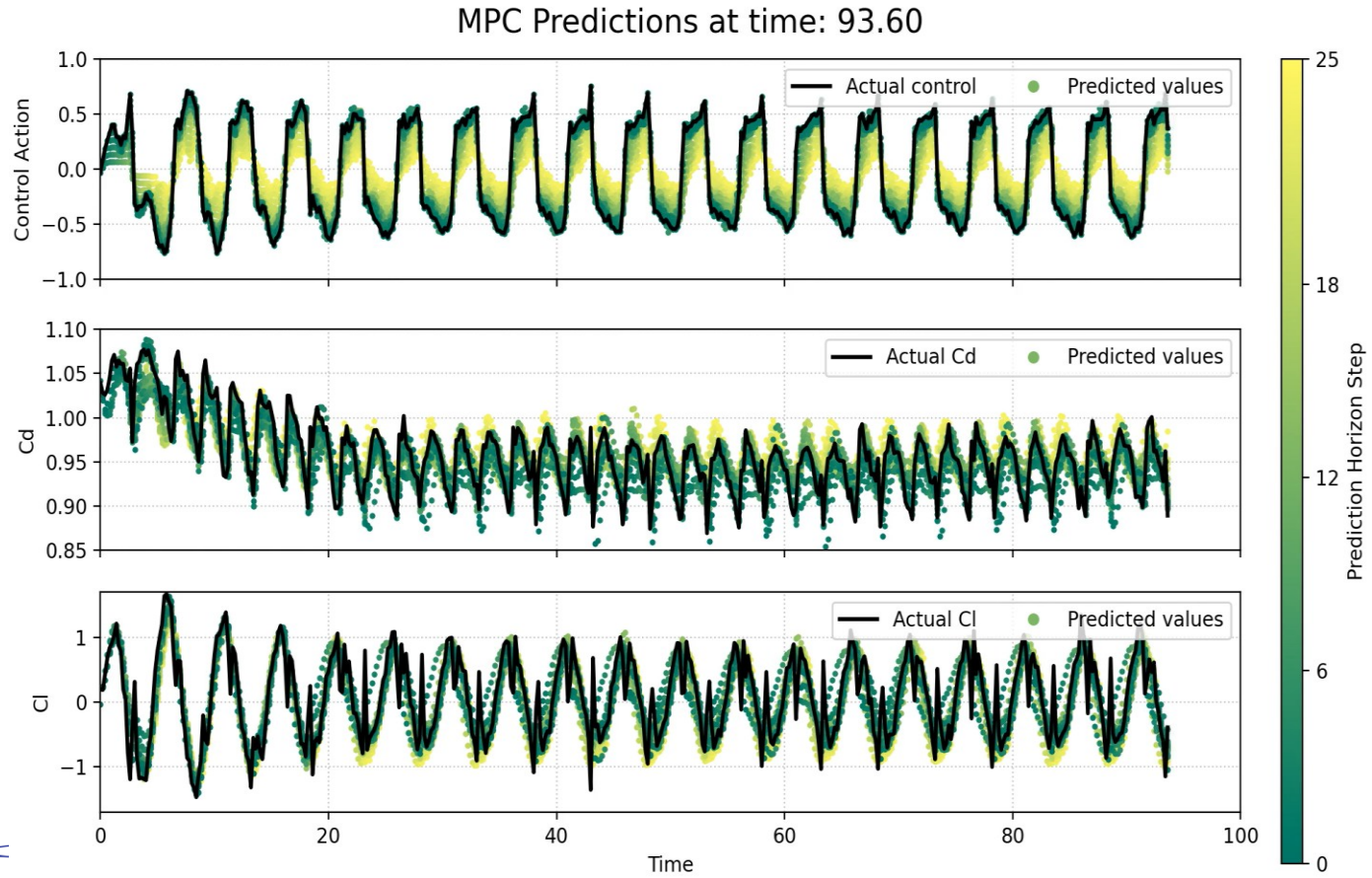
13%
Drag reduction

33%
Lift amplitude reduction

4
Sensors used (from 90)

MPC predictions vs. actual (control, drag, lift)



How it works

- Control is robust to delay in sensing
- Control is robust to Gaussian noise in sensors
- Model shows gradual degradation outside the training dynamics distribution

Current limitations

- Accuracy degrades far from the unactuated dynamics region

Planning: Year 4

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- **Finish paper reviews**

Planning: Year 4

- **Finish paper reviews**
- **Final PhD thesis defence**

Achievements to date

Journal papers

P1 — **Published**

Solera-Rico, Sanmiguel Vila, Gómez-López et al.

β-Variational autoencoders and transformers for reduced-order modelling of fluid flows.

Nat. Commun. 15, 1361 (2024).

P2 — **Under review**

Solera-Rico, García-Caspueñas, Sanmiguel Vila, Discetti.

Balance between compactness and forecast accuracy of data-driven latent-space ROMs in controlled wakes.

Under review at J. Fluid Mech.

P3 — **Under review**

Solera-Rico, Sanmiguel Vila, Discetti.

A framework for realisable data-driven AFC using model predictive control applied to a simplified truck wake.

Under review at Eng. Appl. Artif. Intell — arXiv:2510.11600

Conferences

EDRFCM 2024 European Drag Reduction and Flow Control M.
Turin, Italy — 10–13 Sep 2024
LSTM-Based predictive modelling for AFC of a wake.
(Presented by C. Sanmiguel)

SFMC 2025 Spanish Fluid Mechanics Conference
Málaga, Spain — 24–27 Jun 2025
LSTM-based predictive modelling for ML control of a simplified truck wake.

EFDC 2025 2nd European Fluid Dynamics Conference
Dublin, Ireland — 26–29 Aug 2025
Modeling the dynamics of controlled wake flows with machine learning.

Euromech 665 Data-driven active control in flows
8-10 June 2026, Paris, France
Sparse-sensing-state estimation of vortex-gust airfoil interactions.
(Presented by C. Sanmiguel)

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P2

Solera-Rico, García

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Under review at J…

P3

Solera-Rico, Sanm…

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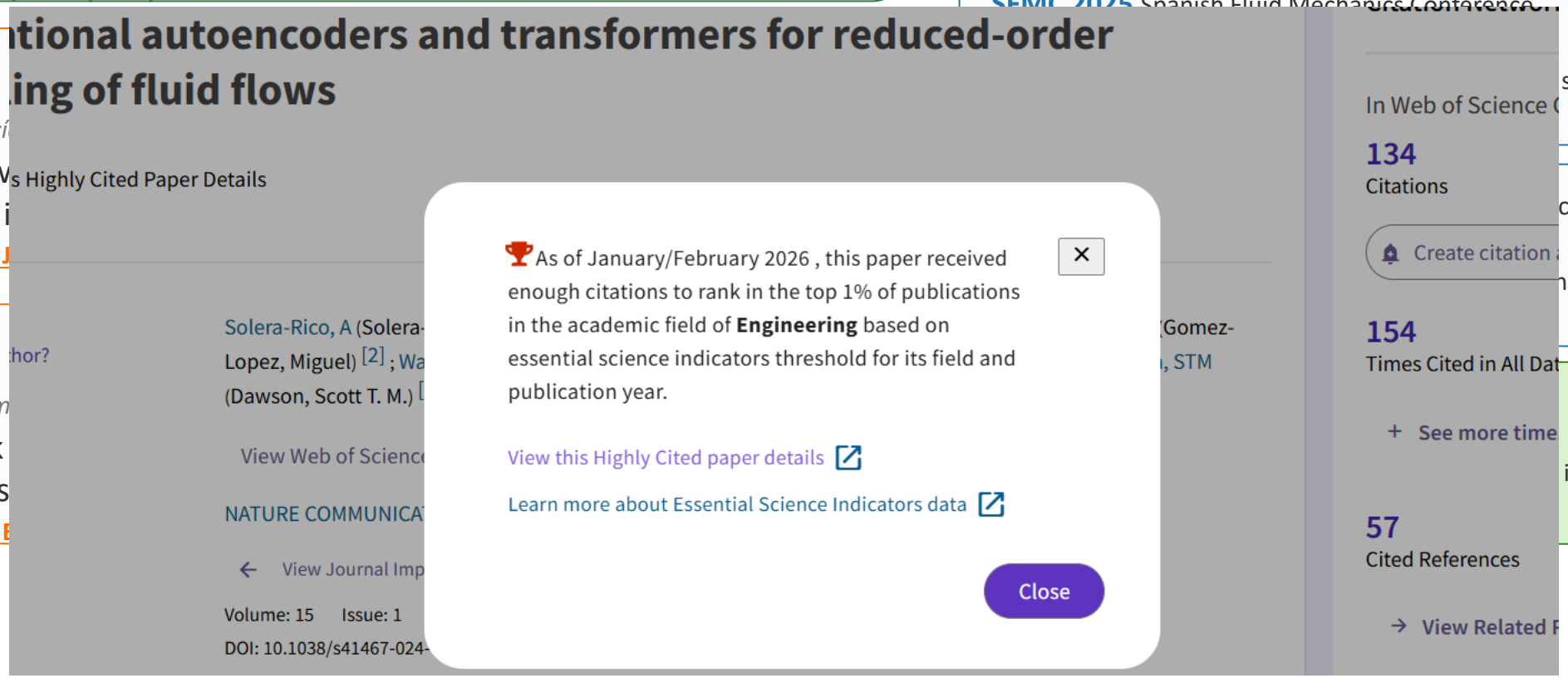
SEMC 2025 Spanish Fluid Mechanics Conference…

…simplified

…ce

…machine

…interactions.



Thank you!
Questions?

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- A. Solera-Rico, P. García-Caspueñas, C. Sanmiguel Vila, S. Discetti. The balance between compactness and forecast accuracy of data-driven latent-space reduced-order models in controlled wake flows. Under review
- A. Solera-Rico, C. Sanmiguel Vila, S. Discetti. A framework for realisable data-driven active flow control using model predictive control applied to a simplified truck wake. Under review, Preprint arXiv: 2510.11600

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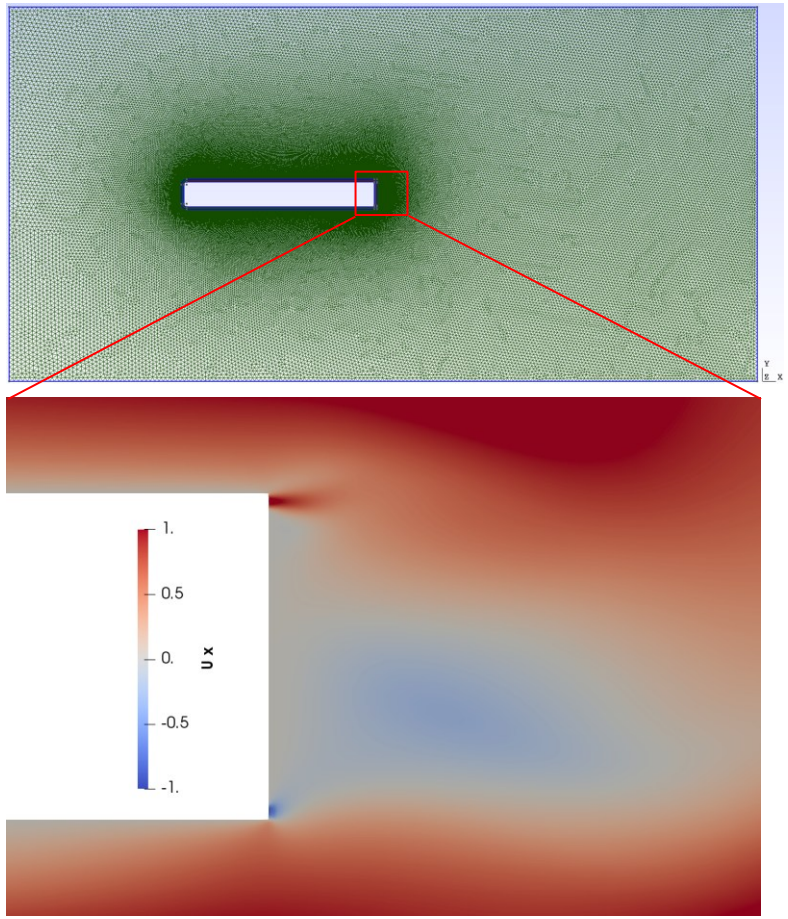
- Solera-Rico, A., Sanmiguel Vila, C., Discetti, S. LSTM-Based predictive modelling for active flow control of a wake. European Drag Reduction and Flow Control Meeting (EDRFCM) 2024, 10−13 September 2024, Turin, Italy.
- Solera-Rico, A., Sanmiguel Vila, C., Discetti, S. LSTM-based predictive modelling for machine learning control of a simplified truck wake. Spanish Fluid Mechanics Conference 2025 (SFMC25). 24−27 June 2025, Málaga, Spain.
- Solera-Rico, A., García-Caspueñas, P., Sanmiguel Vila, C., Discetti, S. Modeling the dynamics of controlled wake flows with machine learning. 2nd European Fluid Dynamics Conference (EFDC2). 26−29 August 2025, Dublin, Ireland.
- Solera-Rico, A., Miró, A., Lehmkuhl, O., Sanmiguel Vila, C. Sparse-sensing-state estimation of vortex-gust airfoil interactions. Euromech Colloquium 665: Data-driven active control in flows: from model-based to reinforcement learning methods. 8-10 June 2026, Paris, France.

Test case

- Simplified 2D truck model
- OpenFOAM DNS, Re=500
- Actuation with zero-net-mass flow jets at the base
- Pressure sensing at the wall
- Gym-precice coupling with Python
- Pytorch implementation of NNs

$$t_c = \frac{width}{U_\infty} \qquad \bar{U}_{jet} \in [-U_\infty, U_\infty]$$
$$\Delta t = 0.2 t_c$$

M. Shams and A. H. Elsheikh. Gym-precice: Reinforcement learning environments for active flow control. *SoftwareX*, 23:101446, 2023.



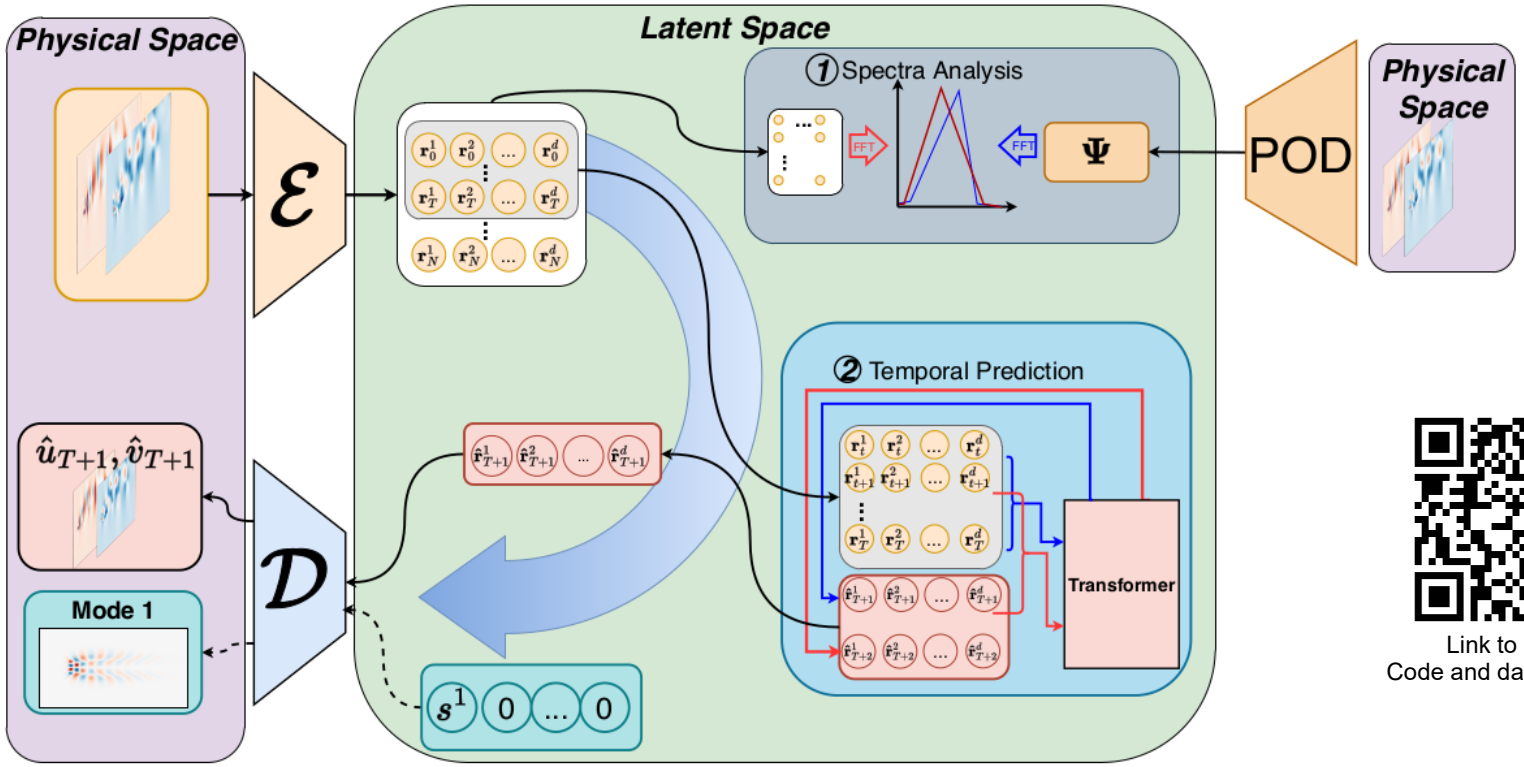
Publication: β-VAE and transformer for ROM

Solera-Rico, A., Sanmiguel Vila, C., Gómez-López, M. *et al*. β-Variational autoencoders and transformers for reduced-order modelling of fluid flows. *Nat Commun* **15**, 1361 (2024). https://doi.org/10.1038/s41467-024-45578-4

Reduced order model of chaotic flow dynamics

- Data compression by projection to latent-space with β-VAE, **dimension ~ 10**
- Recursive temporal prediction in low-dimensional space using transformer

Achieves generalization and learns the long-term system dynamics



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Transformer for prediction:

- Predictions diverge over time, as expected
- Long-term system dynamics are maintained