

~~CLOSED-LOOP JET CONTROL FOR AERONAUTICAL APPLICATIONS~~

A YEAR INTO PATTERN-RECOGNITION ALGORITHMS AND REINFORCEMENT LEARNING

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Supervisors: Marco Raiola
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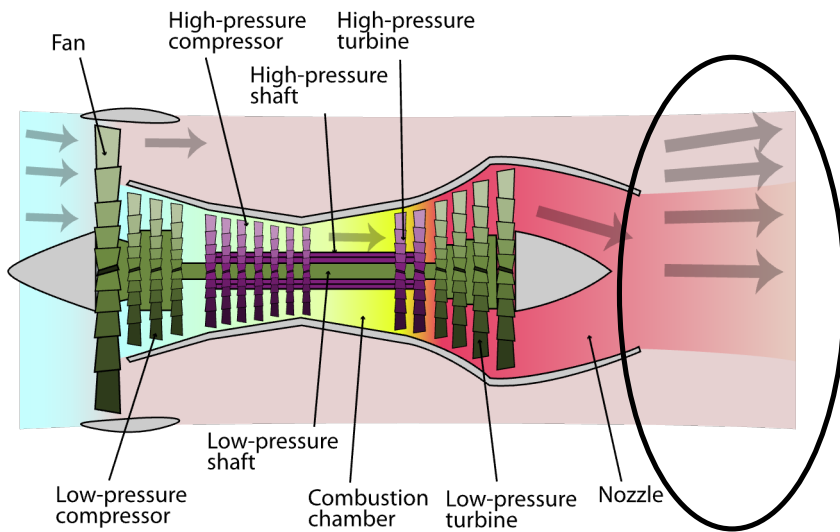
PhD Aerospace Engineering UC3M

Doctoral Meetings 2026

2nd and 3rd June 2026

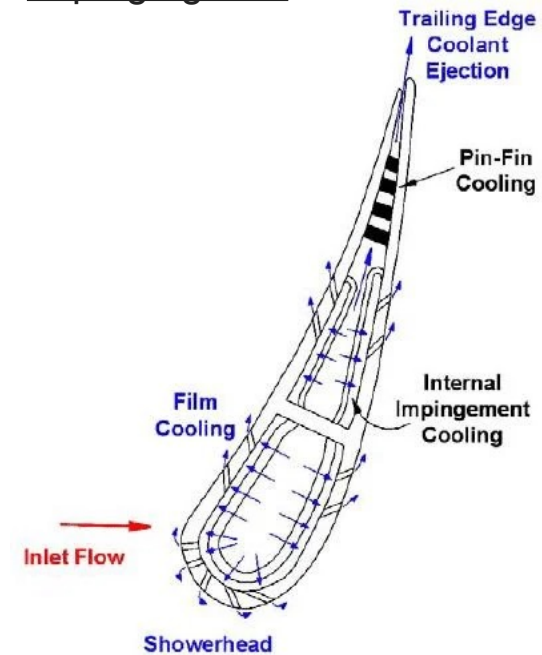
- Fluid jets are common in aerospace applications

Free Jets



Extracted from Wikipedia

Impinging Jets



Extracted from "Thermal analysis of cooling effect on gas turbine blade." by Al-Luhaibi, A. A. J. (2014), International Journal of Research in Engineering and Technology

- Fluid jets are common in aerospace applications

Pros

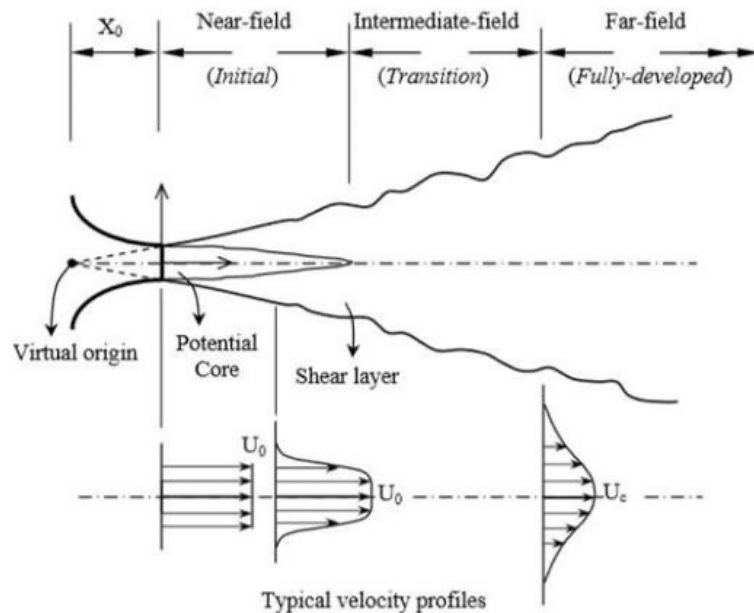
- Core of aircraft and rocket engines
- Allow advanced cooling tech
- Allow flow manipulation for aerodynamic control

Cons

- Acoustic pollution: Jet noise
- Efficiency losses: Uncontrolled turbulence
- Chaotic behaviour difficulting predictable implementations

Literature Review: Jet Structure

Free jet structure



Extracted from "Numerical Analysis of the Flow Behaviour of a Turbulent Round Free Jet" by Kooner P. (2017).

Some characteristics

- Advection-dominated → Delayed Feedback
 - Initially amplification
 - Evolves into dissipative
 - Chaotic
 - Broadband
- Sensing and Actuation Location
- Control Complexity

■ Passive Control

(No feedback, No energy input)



Boeing 787 Chevron Nozzle. Image extracted from Capt. Samarth Singh Wadalia LinkedIn.

■ Active Open-Loop Control

(No feedback, External energy input)



Article

Evaluation of Synthetic Jet Flow Control Technique for Modulating Turbulent Jet Noise

Jairo Murillo-Rincón *^{ID} and Carlos Duque-Daza ^{ID}

IOP Publishing

J. Phys. D: Appl. Phys. 47 (2014) 505201 (18pp)

Journal of Physics D: Applied Physics

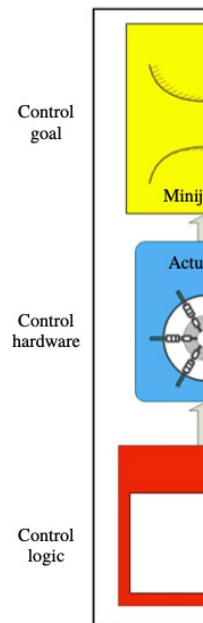
doi:10.1088/0022-3727/47/50/505201

Instability wave control in turbulent jet by plasma actuators

V F Kopiev^{1,5}, Y S Akishev^{2,6}, I V Belyaev^{1,5}, N K Berezhetskaya³,
V A Bityurin⁴, G A Faranosov^{1,5}, M E Grushin², A I Klimov⁴, V A Kopiev¹,
I A Kossyi³, I A Moralev⁴, N N Ostrikov^{1,5}, M I Taktakishvili³, N I Trushkin²
and M Yu Zaytsev^{1,5}

■ AI in Control

(Open-Loop, Genetic)

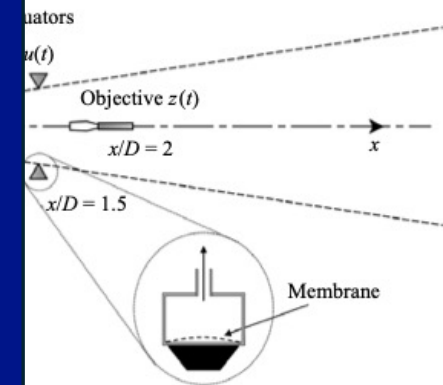


Extracted from "Artificial Intelligence in Control Systems" by Noack B.R. et al (2004)

The Question:

Can we expand data-driven techniques to enable closed-loop control of high-complexity objectives like noise reduction and enhanced heat transfer?

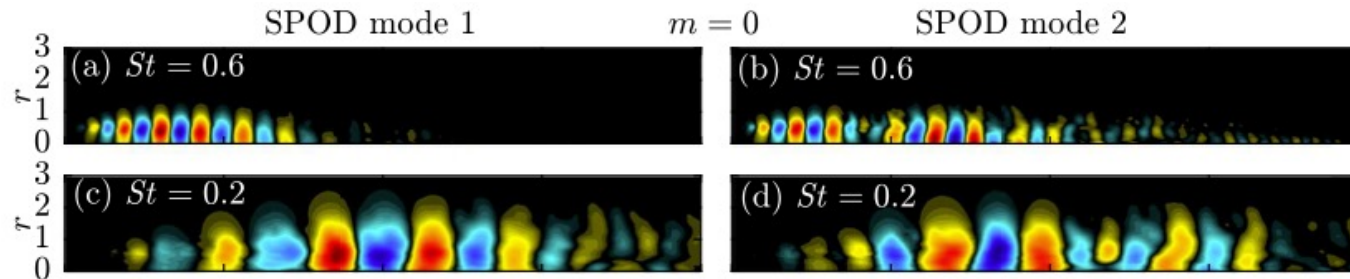
transfer functions)



Experimental control of turbulent jet noise, Journal of Fluid Mechanics

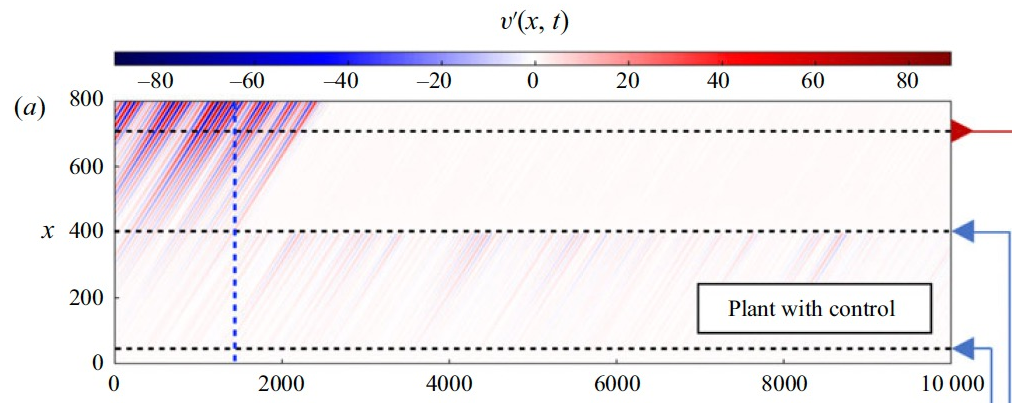
Research Opportunity: The gap

- Recurrent Behaviours: Despite chaos, jets exhibit recurrent coherent structures that can be identified and targeted.



Extracted from "Spectral analysis of jet turbulence." by Schmidt, Oliver T., et al. (2018), *Journal of Fluid Mechanics*.

- Reinforcement Learning (RL) successfully applied in other flow control scenarios. Can we work around feedback delays, multiscale and chaotic behaviour to achieve control?



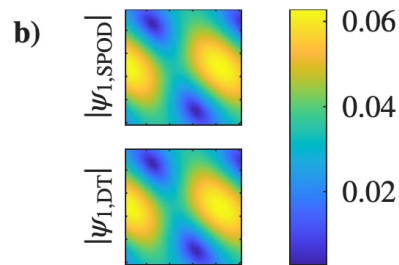
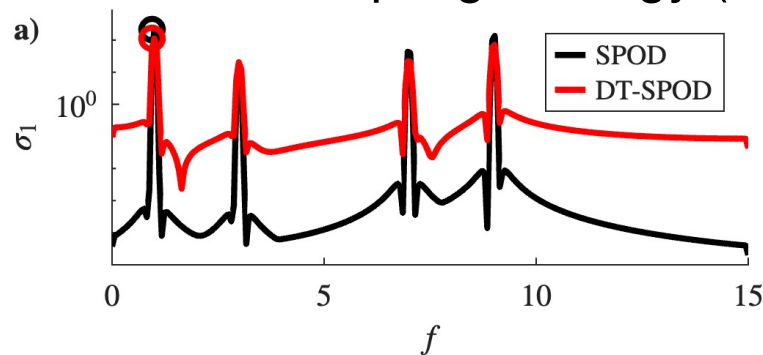
Extracted from "Reinforcement-learning-based control of convectively unstable flows." by Xu D. and Zhang M. (2023), *Journal of Fluid Mechanics*.

- There are several parts for this task:

1st: Identify Recurrent Structures (RS)

- SPOD is a powerful tool for extracting space-time structures, Limited to time-resolved data (Not available for us)

→ Different sampling strategy (Discontinuous sampling) and algorithm



“A dual-time implementation of the spectral proper orthogonal decomposition.” Navarro, M., et al. *AIAA Aviation Forum and Ascend* (2025), Las Vegas.

From theory to the lab:

- Testing the algorithm in experimental data
- Checking statistical properties of the implementation
- Enhancing computational speed
- An open-source implementation in MATLAB

A General Overview of Jet Control

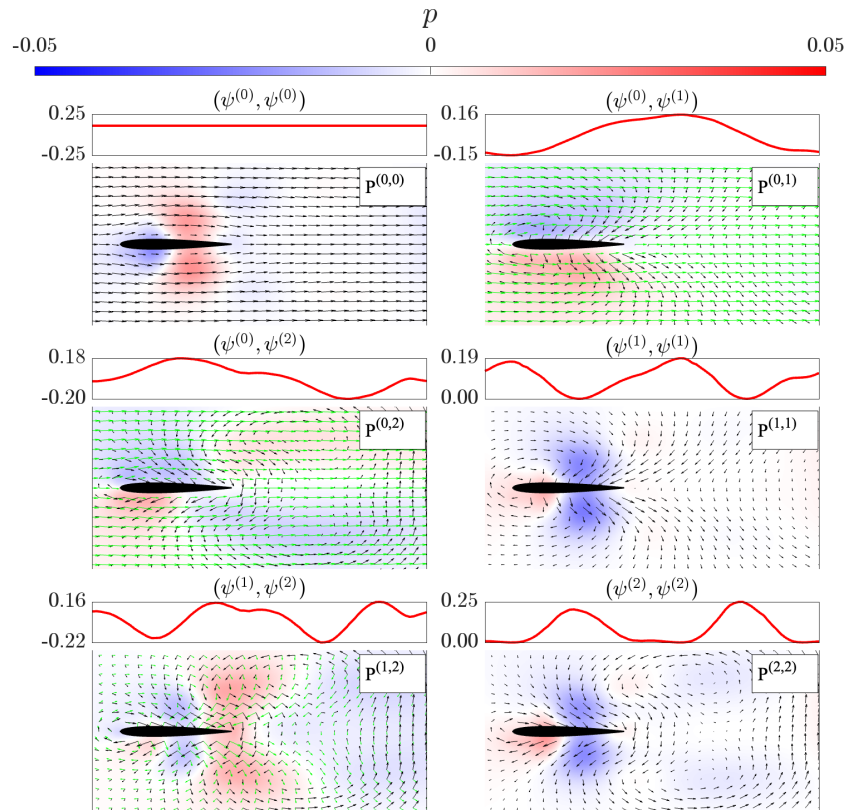
- There are several parts for this task:

1st: Identify Recurrent Structures (RS)

2nd: Relate RS with their impact to control objective.

Stochastic identification of quadratically-related modes

- Pressure is quadratically related with flow velocity. Can we exploit this relationship to identify flow structures related to pressure patterns?



- Statistical framework grounded in the physics.
- Identify flow patterns that drive force fluctuation

"A Stochastic Estimation Framework for interpretable force modelling in flapping wing aerodynamics" by M. Navarro and M. Raiola (2026), Journal of Fluid Mechanics

- The inverse problem: Can this framework be used to infer flow from pressure/acoustic measurements?

Particularly interesting for noise reduction applications!

A General Overview of Jet Control

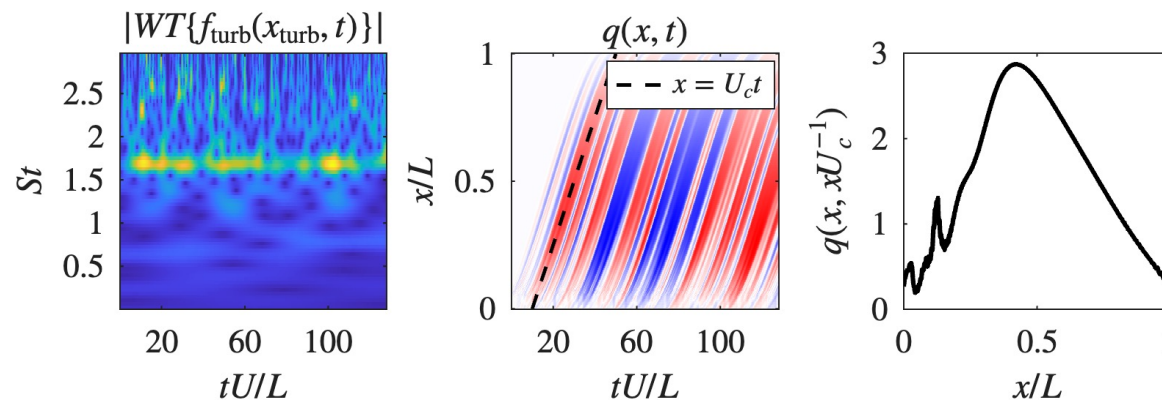
- There are several parts for this task:

1st: Identify Recurrent Structures (RS)

2nd: Relate RS with their impact to control objective.

3rd: Train a RL agent for Jet Control

- RL assumes Markovian property is fulfilled. In flow control it rarely is. Can we overcome this incompatibility?
- Built a stochastic environment to capture convective instabilities:



- Successfully controlled it in ideal Markovian scenarios
- Shown control fail in partial observability conditions

Can we leverage Taken's Embedding Theorem to recover the Markovian property under partial observability?

1st: Identify Recurrent Structures (RS)

2nd: Relate RS with their impact to control objective.

3rd: Train a RL agent for Jet Control

How can we build the flow-inference framework for spatio-temporal structures?

How to define the State and Rewards for RS targetting?

Achievements

■ Journal Papers

- M. Navarro-González and M. Raiola, “A stochastic estimation framework for interpretable force modelling in flapping-wing aerodynamics,” *Journal of Fluid Mechanics*, vol. 1025, p. A11, 2025. doi:10.1017/jfm.2025.10950

■ Conference Papers/Presentations

- “Reduced order modelling of flapping wing aerodynamics: linking flow kinematics to aerodynamic forces”. *Spanish Fluid Mechanics Conference 2025*, Malaga.
- “A dual-time implementation of the spectral proper orthogonal decomposition”. *AIAA Aviation Forum and Ascend 2025*, Las Vegas.
- “Dual-Time SPOD for experimental identification of spatio-temporal patterns”. *EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows – Modelling, Control and Interpretation*, 2026, Berlin (Incoming)

■ Imparted Coursework

- “Diseño de Turbohélices” laboratory sessions for the Bachelor in Aerospace Engineering, UC3M 2025/26 Course
- “Modelización en Ingeniería Aeroespacial” practical sessions for the Bachelor in Aerospace Engineering, UC3M, 2025/26 Course

■ Dissemination Activities

- “Ruido visible: La Ciencia de lo que no se ve” in *La Noche Europea de los Investigadores*, 2025, Leganés
- “Turbulencia: El arte científico del desorden” in *Semana de la Ciencia y de la Innovación*, 2025, Leganés

■ Coursework

- “An introduction to Statistical and Variational Methods for Assimilation and Real Time Modelling” organized by the *PhD Program in Aerospace Engineering of UC3M*, 2025, Leganés
- “Advanced Postprocessing Techniques” organized by the *European Academy of Aeroacoustics*, 2025, Turin



Thank you!
Questions?

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EXCALIBUR



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Support Slides

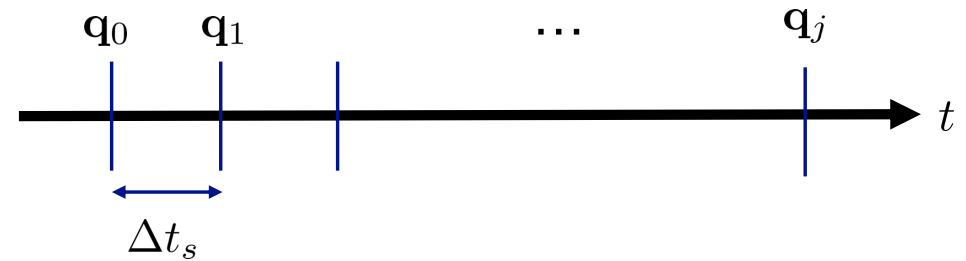
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For a general process $\mathbf{q}(\mathbf{x}, t)$:

- Continuous Sampling:

$$\mathbf{q}_j = \mathbf{q}(\mathbf{x}, t_j), \quad t_j = (j - 1)\Delta t_s$$



- Dual-Time Sampling

$$\begin{aligned} \mathbf{q}_{i,\tau}^{(1)} &= \mathbf{q}(\mathbf{x}, t_i), \\ \mathbf{q}_{i,\tau}^{(2)} &= \mathbf{q}(\mathbf{x}, t_i + \tau), \end{aligned} \quad t_i = (i - 1)\Delta t_s$$

