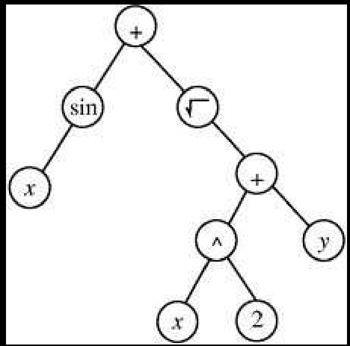
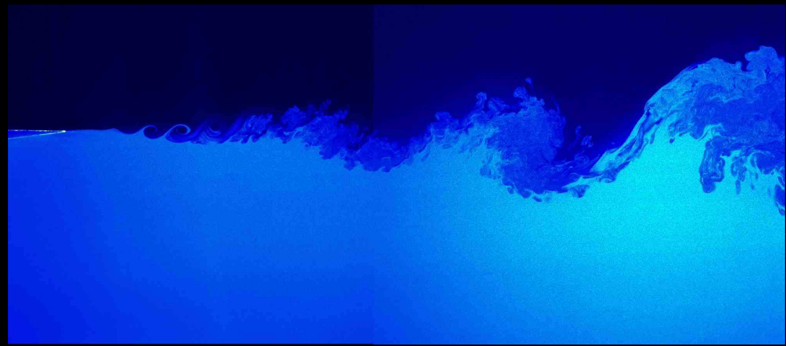
Closed-loop turbulence control using machine learning

Stop thinking and let your PC and experiment do the hard work!



→



B. Noack[3], T. Duriez[1,3], L. Cordier[3], K. von Krbek[3], E. Kaiser[3,4], V. Parezanovic[3], J.-P. Bonnet[3], M. Segond[3], M. Abel[3], N. Gautier[3], J.-L. Aider[3], C. Raibaudo[3], C. Cuvier[3], M. Stanislas[3], A. Debien[3], N. Mazellier[3], A. Kourta[3], S. Brunton[1], R. Niven[2] &

. . . . [1]Argentinia, [2]Australia, [3]Europe & [4]USA

— supported by ANR, DFG, ERC & ADFA@UNSW —

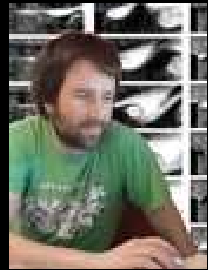
Wither Turbulence and Big Data for the 21st Century Workshop
honoring Bill in his starting Neptun decade, Corsica, France, 2015-04-20..4

Friends / core team

Complex systems

M. Abel
M. Segond
Ambrosys

Closed-loop turbulence control — theory



L. Cordier, T. Duriez, E. Kaiser, B. Noack, K. von Krbek, C. Pivot, M. Schlegel, et al.

Statistical physics

Robert Niven
UNSW
Australia

Control theory

S. Brunton
U Washington

Closed-loop turbulence control — experimental demonstrators

D. Barros
J.-P. Bonnet
J. Borée
R. Li
V. Parezanovic
P'

R. Semaan
R. Radespiel
Braunschweig

R. King
TU Berlin

CFD + Stab.anal.

M. Morzyński
TU Poznań

More friends (experiments)

- **A. Spohn, V. Parezanovic, E. Kaiser** . . . . (PPRIME, Poitiers)
  . . . . soon: MLC in separation control over a smooth ramp
- **J. Borée, D. Barros, C. Li, Y. Cao** . . . . (PPRIME, Poitiers)
  . . . . MLC in drag reduction of an Ahmed body
  . . . . machine learning modelling in combustion engine
- **F. Harambat, T. Ruiz** . . . . (PSA, Peugeot-Citroën, Velizy)
  . . . . soon: MLC in drag reduction of a realistic car model
- **N. Gautier, N., J.-L. Aider, ...** . . . . (PMMH Paris)
  . . . . MLC for mixing enhancement of backward facing step
- **M. Stanislas, C. Raibaudo, C. Cuvier, ...** . . . . (LML Lille)
  . . . . MLC for separation mitigation of a turbulent boundary layer
- **A. Kourta, A. Debien & N. Mazellier** . . . . (PRISM, Orléans)
  . . . . MLC for separation mitigation of a turbulent boundary layer
- **C.O. Paschereit, K. Oberleithner, J. Moeck** . . . . (TU Berlin)
  . . . . . combustion-related experiments, soon: MLC in wind-turbine, cars
- **R. Radespiel, R. Semaan, P. Scholz, ...** . . . . (TU Braunschweig)
  . . . . MLC in drag reduction of a d-shaped body
  . . . . MLC in highlift airfoil with $\sim$100 actuators and $\sim$ 500 sensors

Overview

1. An eldorado of engineering applications
. . . . The need for closed-loop turbulence control

2. Weapons of choice
. . . . A review of turbulence control strategies

3. Machine learning control (MLC) as magic bullet
. . . . . Introduction to a fool-proof method

4. Recent MLC applications
. . . . Demonstrations in shear turbulence experiments

5. Turbulence control strategies revisited
. . . . . MLC as paradigm shift

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Turbulence control $\mapsto$ transport vehicles

Control goals

- lift increase
- drag reduction
- acoustic noise reduction
- mixing/combustion control

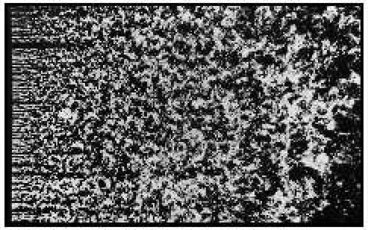
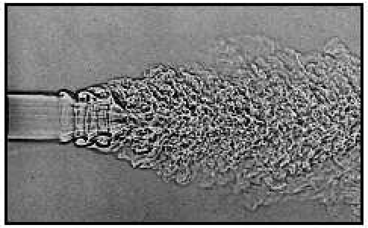
Control strategies

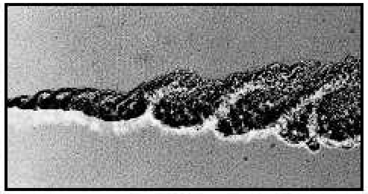
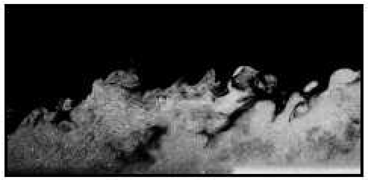
- aerodynamic design
- passive (e.g. riblets)
- active, open-loop
  (e.g. periodic blowing)
- active, closed-loop
  (largest opportunities!)

Turbulence control $\mapsto$ other applications

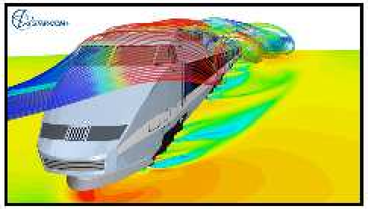
Turbulence control $\mapsto$ even more applications

Simple prototype flows

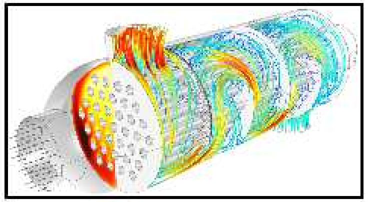
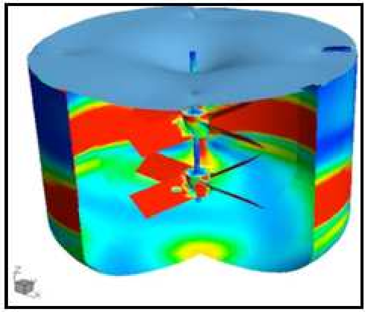
Transport vehicles

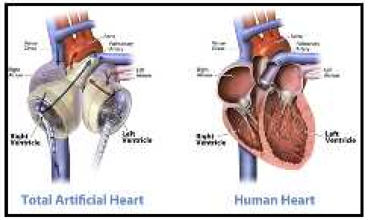




Energy systems




Production etc.

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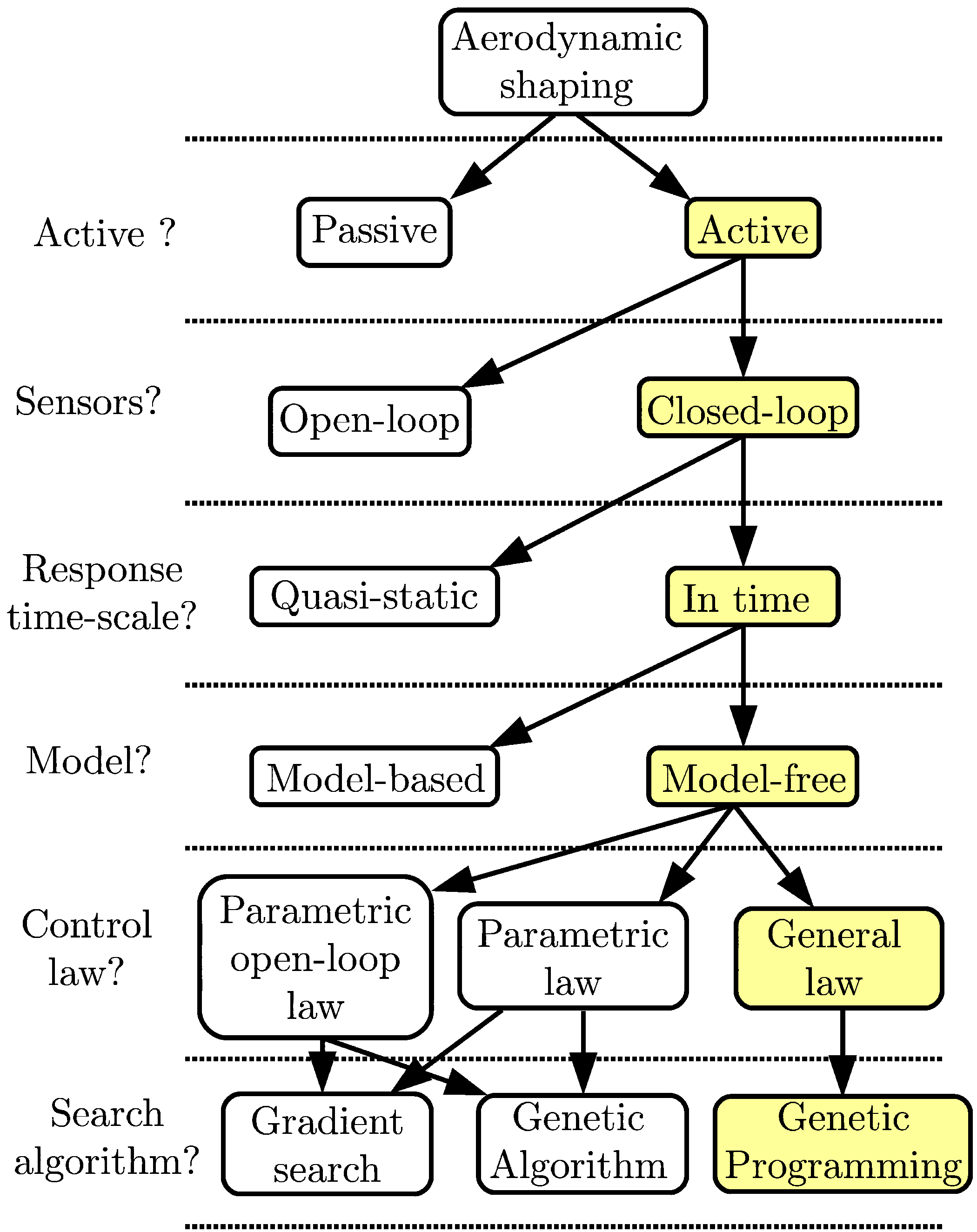
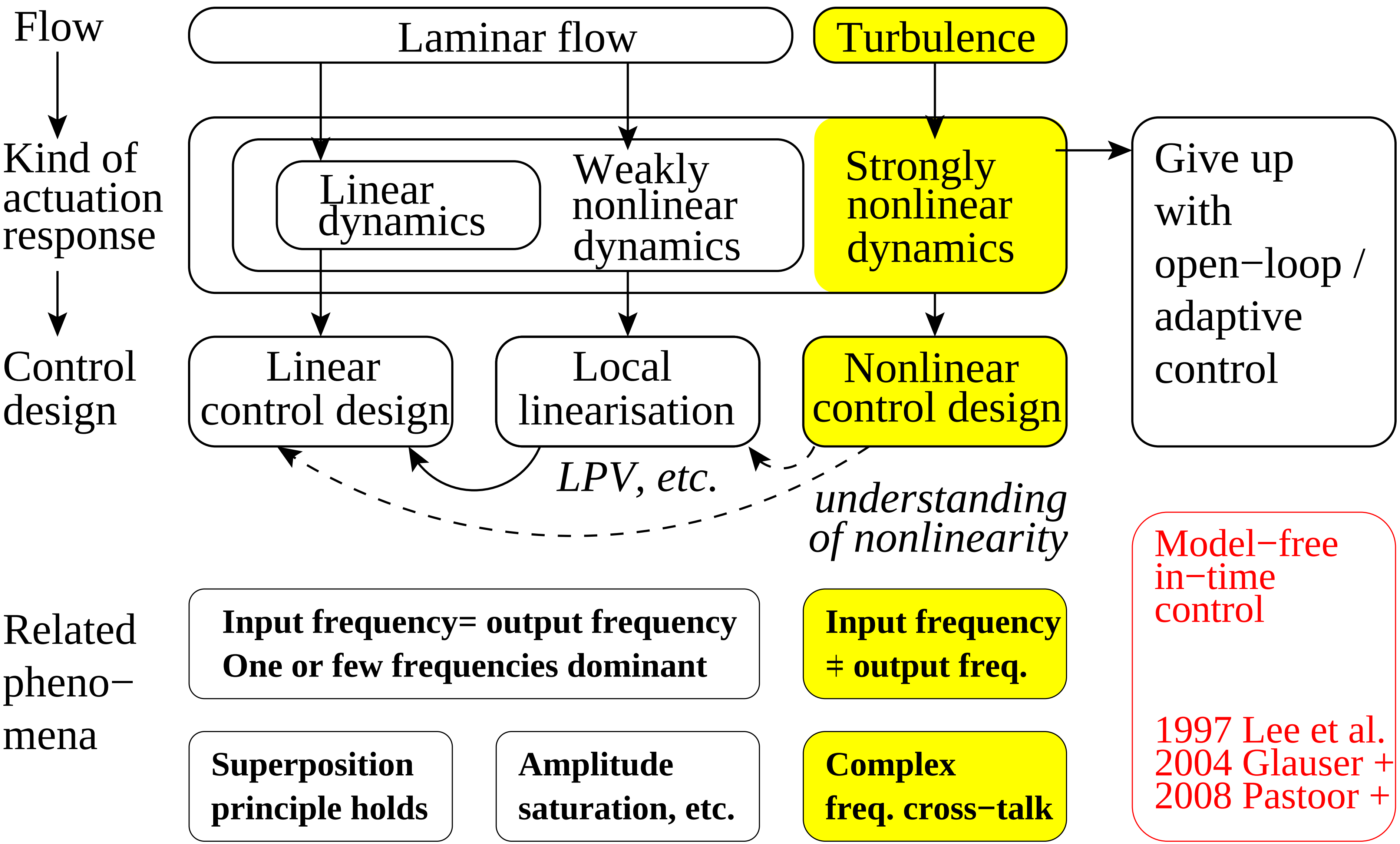
Turbulence control → decision tree



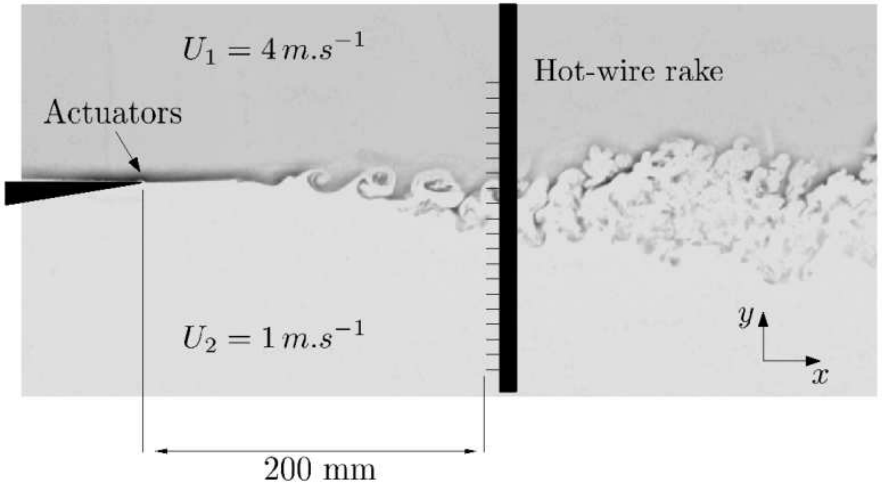
Turbulence control → nonlinearity challenge

Duriez et al. 2014 AIAA



Frequency cross-talk
= show stopper for model-based control

- **Reynolds stress**
  at any frequency
  changes mean flow
  ≡ Reynolds + Hussain 1972 JFMs



- **Normal turbulence cascade**
  Dominant ↦ high frequencies
- **Inverse turbulence cascade**
  Dominant ↦ lower frequencies
- **High frequency forcing**
  can mitigate the dominant frequency
  ≡ Glezer+ 2005 AIAA-J, ≡ Luchtenburg+ 2009 JFM, ...
- **Low-frequency forcing** too
  ≡ Aider+ 2014, ≡ Pastoor+ 2008 JFM, ...

Prototypic model of frequency cross-talk

Luchtenburg et al. 2009 JFM & Aleksić et al. 2010 AIAA

Simplified generalized mean-field model:

$$\frac{d}{dt}\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} \sigma_1 & -1 & 0 & 0 \\ 1 & \sigma_1 & 0 & 0 \\ 0 & 0 & -0.1 & -10 \\ 0 & 0 & 10 & -0.1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b \end{bmatrix}$$

$$\sigma_1 = 0.1 - a_1^2 - a_2^2 - a_3^2 - a_4^2$$

Goal = mitigate instability $J = \overline{a_1^2 + a_2^2} + 0.01\overline{b^2} \stackrel{!}{=} \min$

Linear control $\Rightarrow$ first oscillator uncontrollable!

- **Fixed point** . . . . $a_1 = a_2 = a_3 = a_4 = 0$
- **Linearized system around fixed point** . . . . $\sigma_1 = 0.1$

Nonlinear control: Excite 2nd osc. $a_3^2 + a_4^2 > 0.1 \Rightarrow \sigma_1 < 0$

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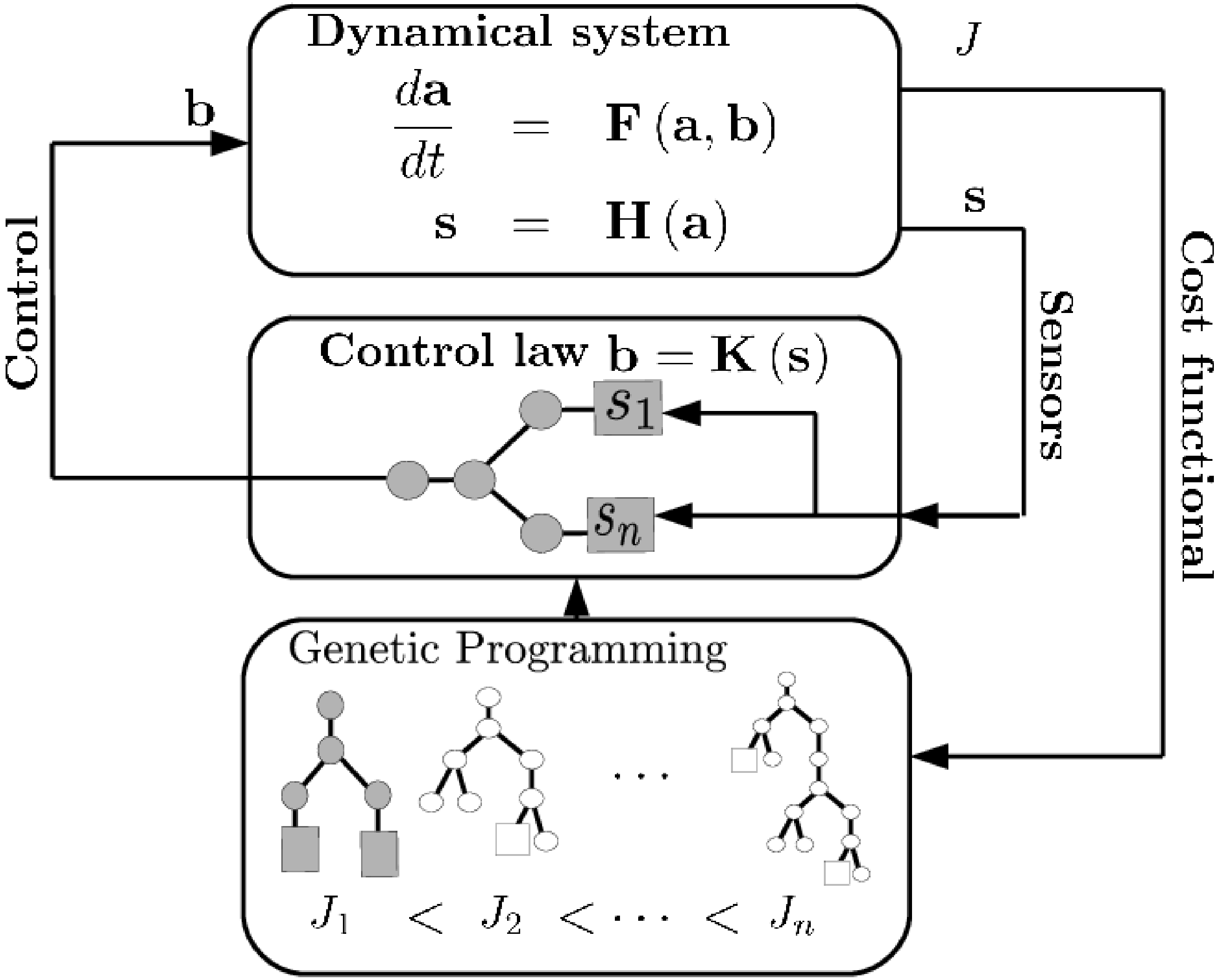
Machine learning control I

Duriez et al. 2014 AIAA, Wahde 2008



MLC = model-free optimization of control laws

Similar approaches exist for robotic missions, etc.

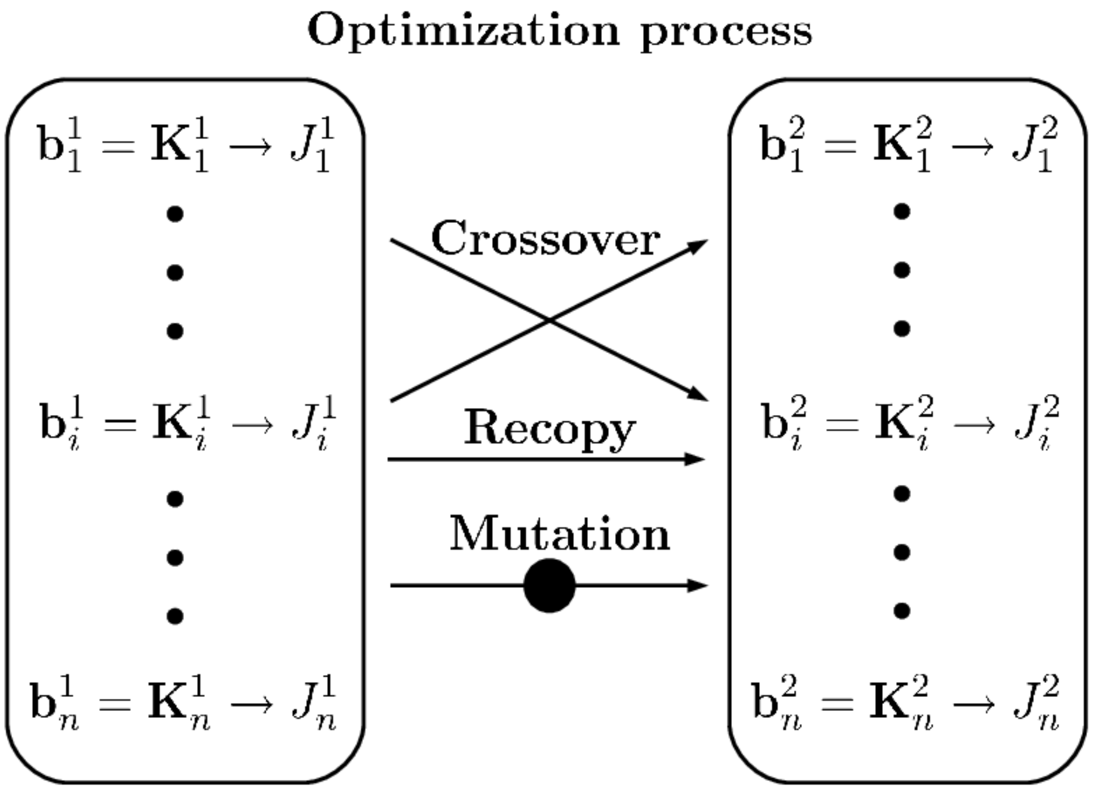
Machine learning control II

Duriez et al. 2014 AIAA

Step 1: 1st generation with random nonlinear control laws

$b_m^1 = K_m^1(s), m = 1, ..., 100$

Step 2–50:



Biologically inspired optimization of the control laws based on the 'fitness grades'

$J\left[b = K(s)\right]$

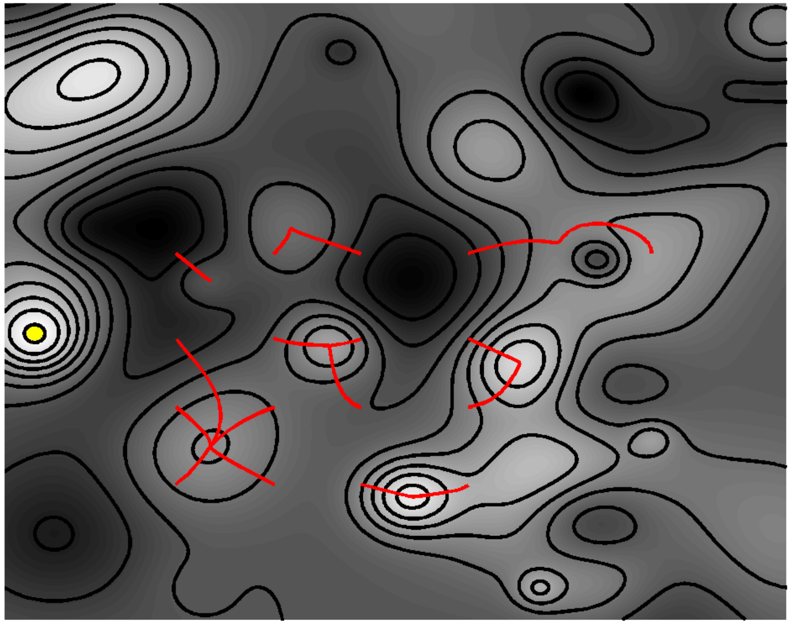
J.R. Koza 1992 Genetic Programming, The MIT Press

Machine learning control III

≡ *Duriez et al. 2014 AIAA*, ≡ *Gautier et al. 2015 JFM*

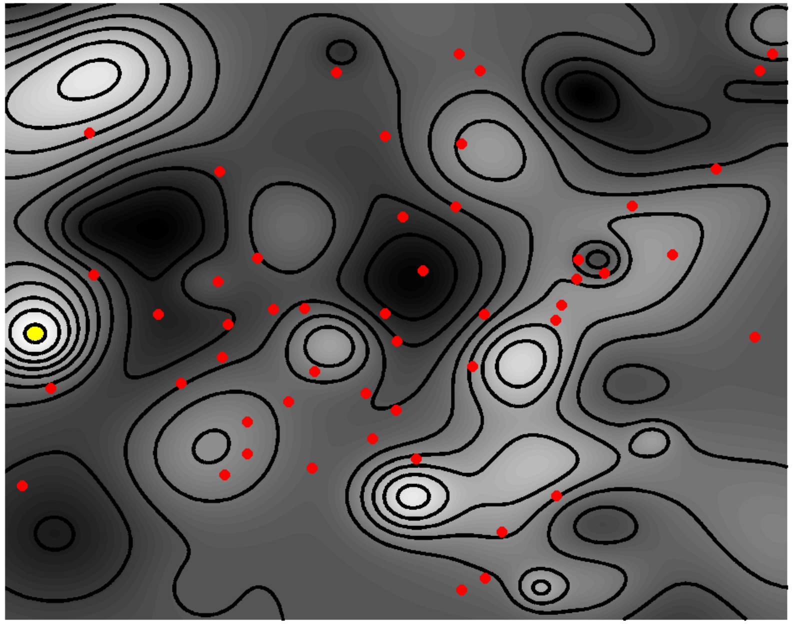
Gradient search

requires structure identification of the control law and parameter identification based on local minimization



Genetic programming

= evolutionary algorithm for regression with structure identification of control law

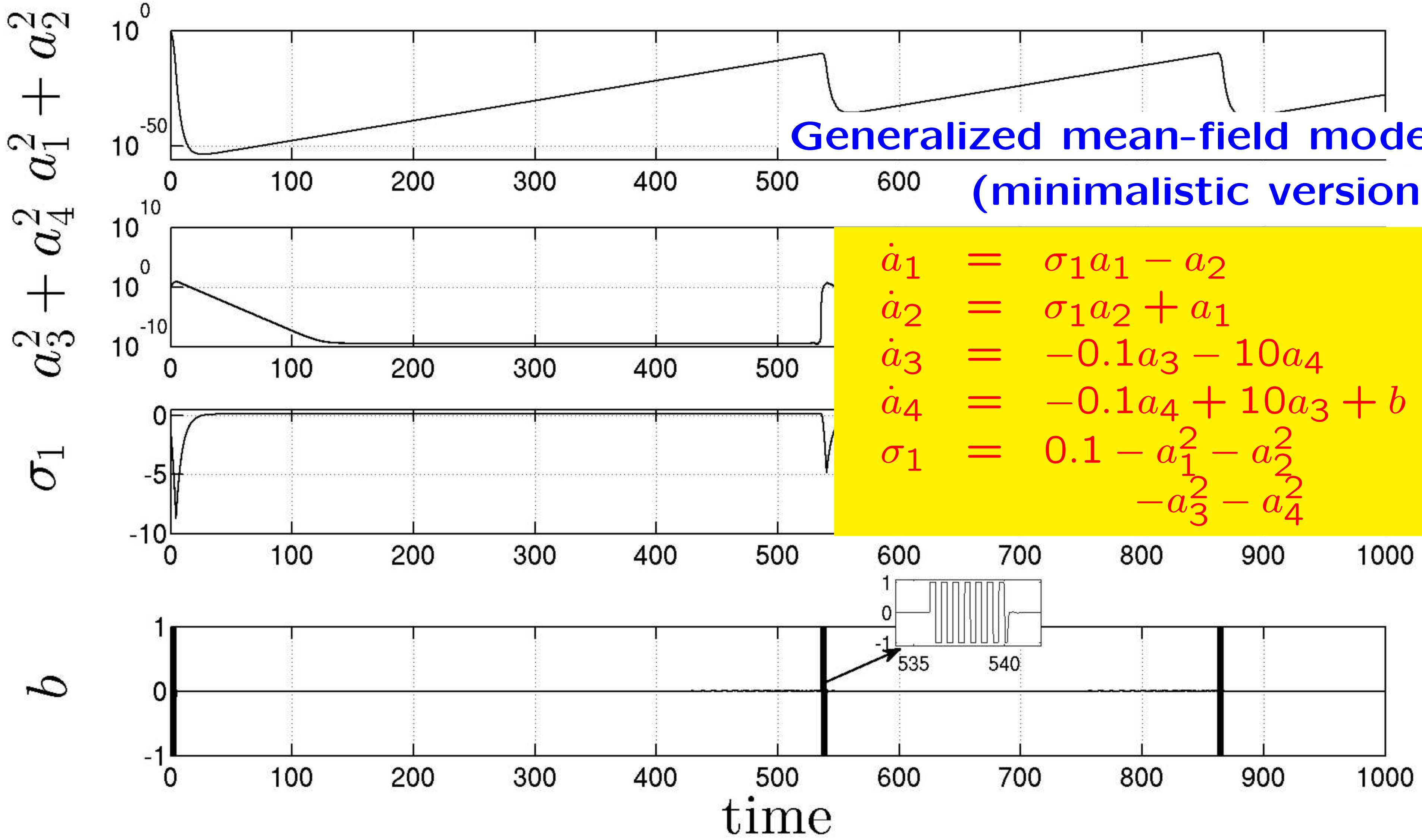


Example of an evolutionary minimization.

MLC $\mapsto$ generalized mean-field model

Luchtenburg, Günther, Noack, King & Tadmor 2009 JFM & Duriez et al. 2014 AIAA

MLC goal: $b(\boldsymbol{a})$ with $J = \frac{1}{T}\int_0^T dt\,\left[a_1^2 + a_2^2 + 0.01 b^2\right] = min$



Generalized mean-field model (minimalistic version)

$$
\begin{aligned}
\dot a_1 &= \sigma_1 a_1 - a_2\\
\dot a_2 &= \sigma_1 a_2 + a_1\\
\dot a_3 &= -0.1 a_3 - 10 a_4\\
\dot a_4 &= -0.1 a_4 + 10 a_3 + b\\
\sigma_1 &= 0.1 - a_1^2 - a_2^2\\
&\quad - a_3^2 - a_4^2
\end{aligned}
$$

MLC $\mapsto$ Lorenz equation

Duriez et al. 2014 AIAA

Forced Lorenz system

$$\frac{da_1}{dt} = \sigma\left(a_2 - a_1\right),$$
$$\frac{da_2}{dt} = a_1\left(\rho - a_3\right) - a_2,$$
$$\frac{da_3}{dt} = a_1 a_2 - \beta a_3 + b,$$
$$\sigma = 10,\ \beta = 8/3 \text{ and } \rho = 20$$

MLC goal:

Find a control law $b(\boldsymbol{a})$ with mimimizes the max. Lyapunov exponent

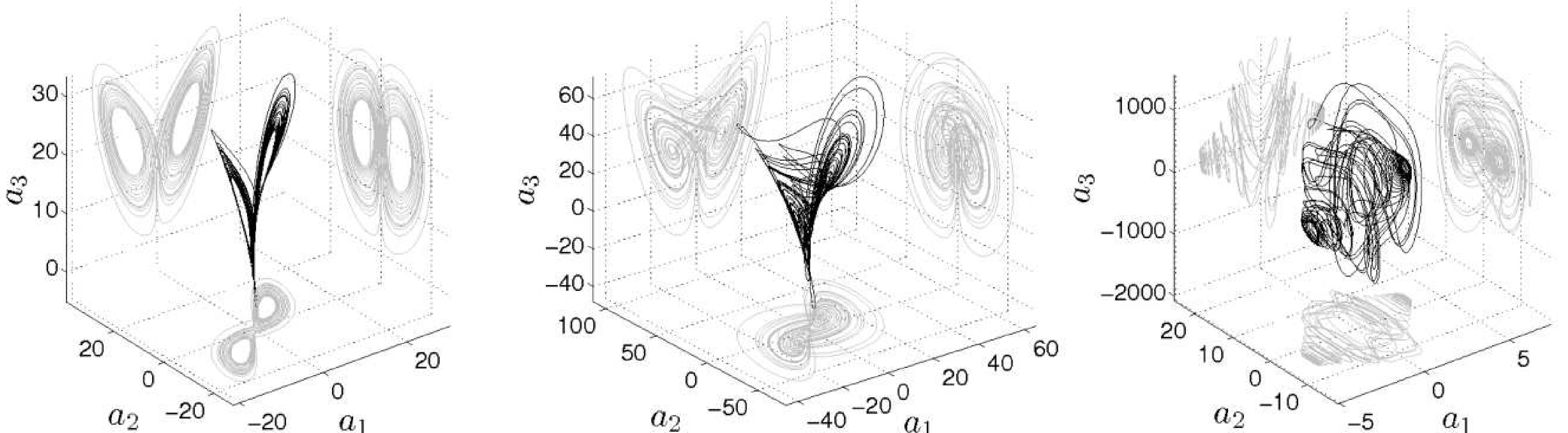
$$J = \exp(-\lambda_1) + \frac{\gamma}{T}\int_0^T dt\, b^2$$

Controlled Lorenz attractors

$\gamma = 1$ — $\lambda_1 = 0.715$,

$\gamma = 0.01$ — $\lambda_1 = 2.072$,

$\gamma = 0$ — $\lambda_1 = 17.613$



Overview

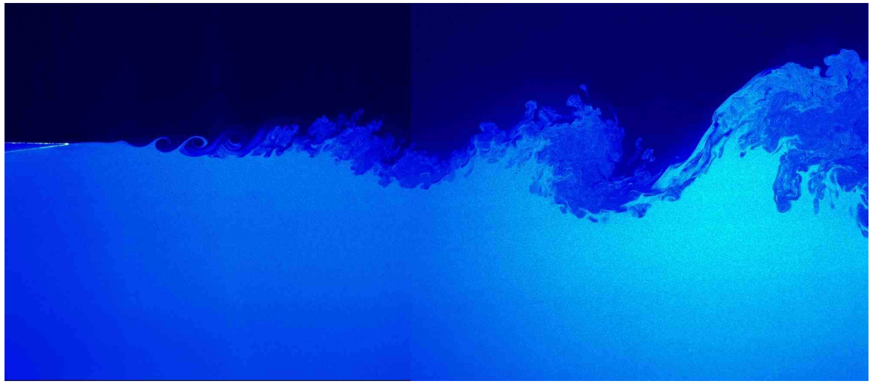
TUCOROM wind-tunnel

≡ Parezanović et al. 2014 FTC & ≡ Duriez et al. 2014 AIAA

New
turbulence control
wind-tunnel at P' →

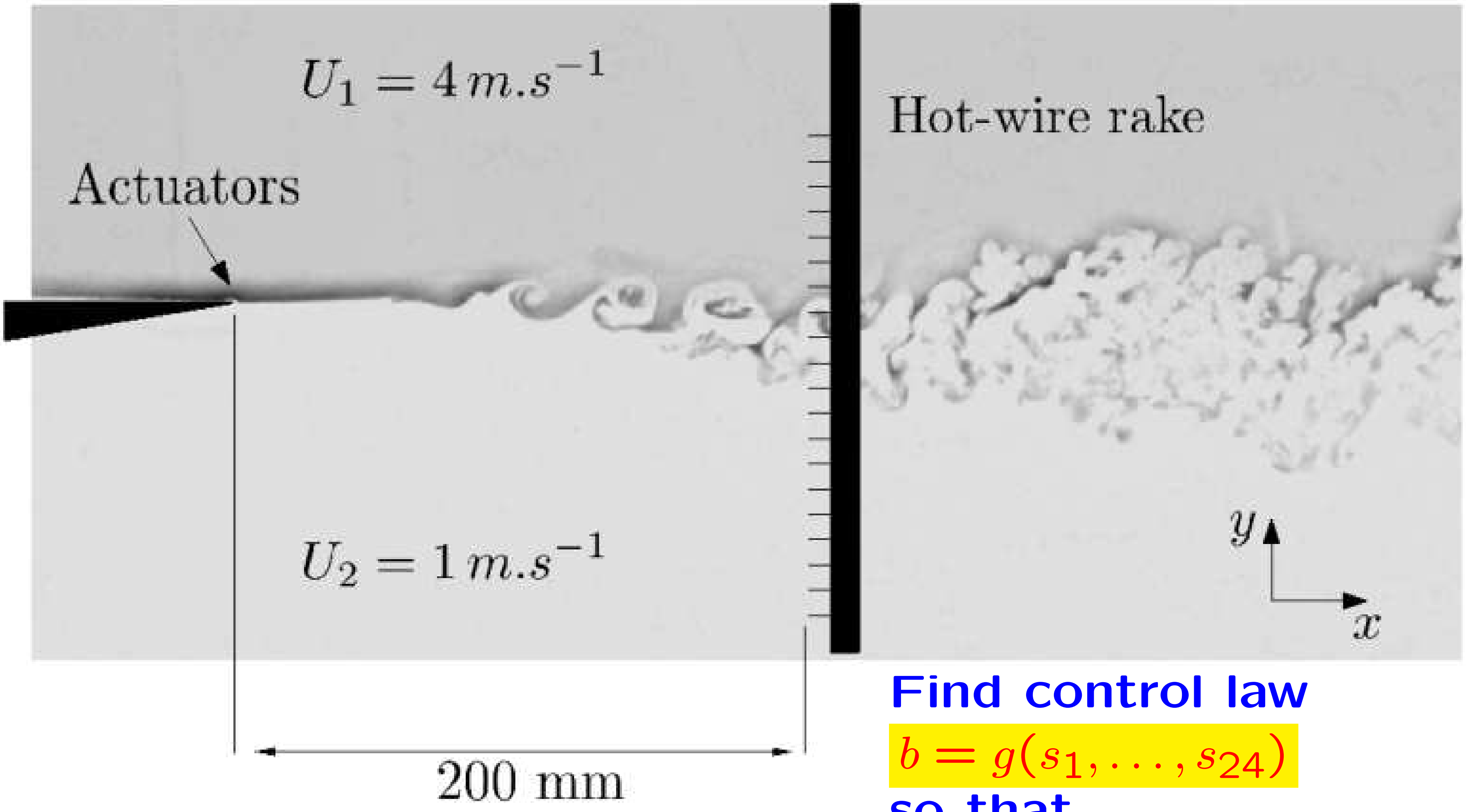
Control team
at control desk
↓

Flow visualization



TUCOROM mixing layer demonstrator

Parezanović et al. 2014 FTC



Find control law

$b = g(s_1, \ldots, s_{24})$

so that

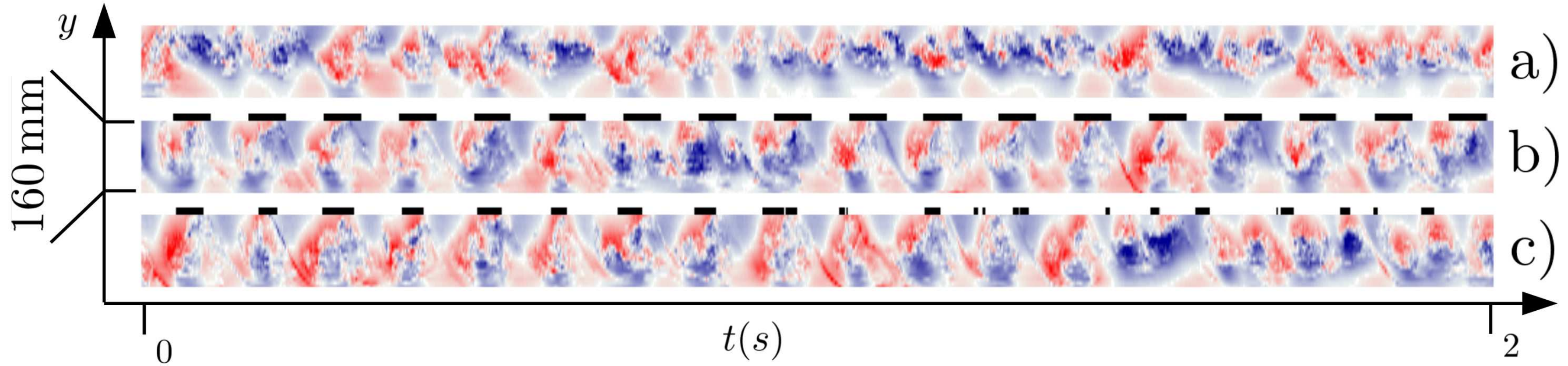
$J = \sum_{i=1}^{24} \overline{\left(s_i'\right)^2} = max$

TUCOROM mixing layer control experiment

Duriez et al. 2014 AIAA & Parezanović et al. 2014 FTC

set-up	actuation Q	width W
a) unactuated flow	0%	100%
b) best periodic forcing	100%	155%
c) MLC closed loop forcing	54%	167%
MLC vs open-loop	-46%	+12%

Pseudo visualizations from 24 hot-wire sensors



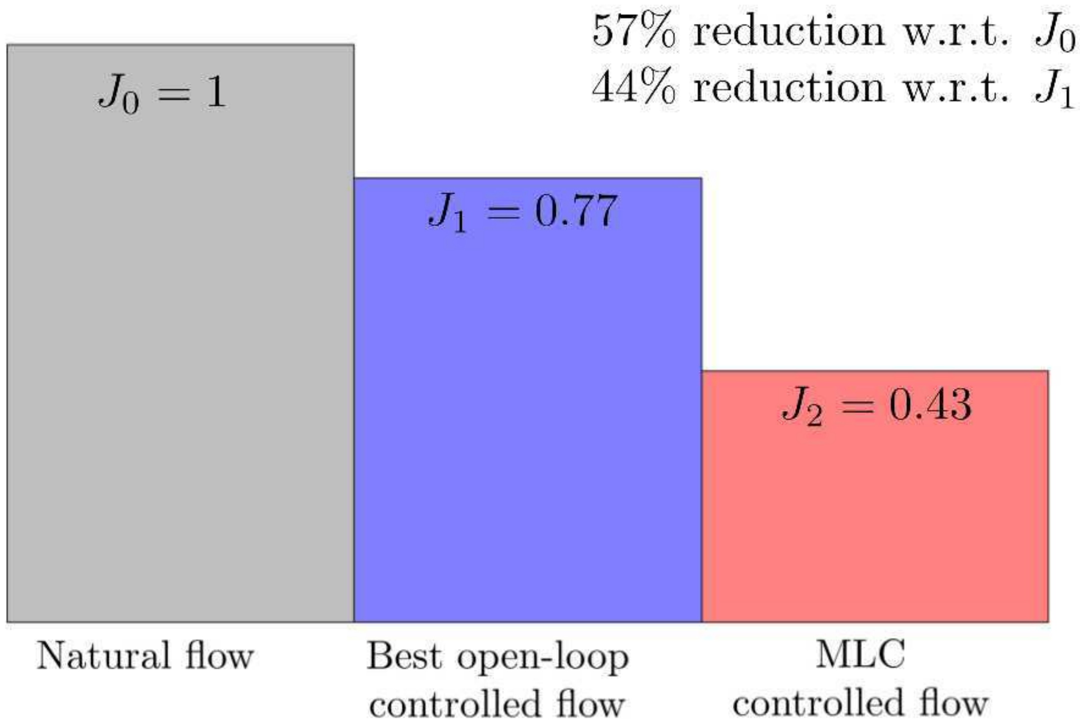
MLC has found a very effective nonlinear low-frequency resonance mechanism!

MLC in water tunnel experiment (PMMH)

Gautier, Aider, Duriez, Noack, Segond & Abel 2015 JFM (accepted)

Mixing enhancement (BFS) $J = \overline{s} + \frac{3}{2}\overline{|b|}^2 = \text{min!}$

s: normalized recirculation zone; b: normalized actuator velocity



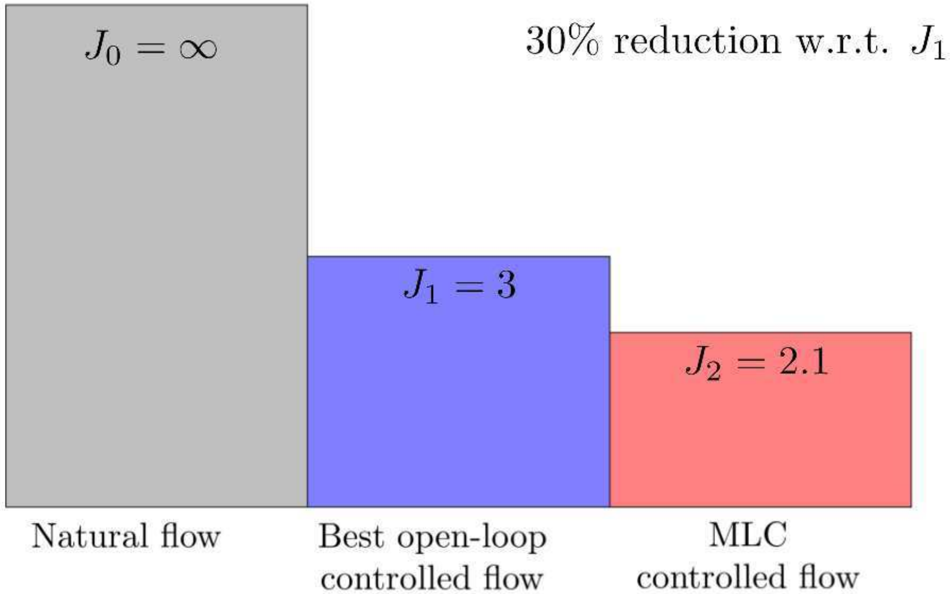
MLC has found a very effecting flapping mode mechanism for decreasing the recirculation zone!

MLC in a boundary layer experiment (LML)

≡ Duriez, Parezanović, Laurentie, Fourment, Delville, Bonnet, Cordier, Noack, Segond, Abel, Gautier, Aider, Raibaudo, Cuvier, Stanislas & Brunton 2014 AIAA

Separation control of a turb. boundary layer over a ramp

$J =$ measure of attachment $+$ actuation penality $=$ min!



MLC outperformed the best open-loop forcing

by finding periods where blowing is not efficient!

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Conclusions

≡ *Noack+ 2011 Springer (↦ROM); Kaiser+ 2014 JFM (↦CROM); Gautier+ 2015 JFM (↦MLC)*

- **Turbulence control = attractor control**

  Physics mechanisms are strongly nonlinear.

- **Model-based control design**

  → one or two frequencies

- **Model-free machine learning control design**

  → broadband turbulence

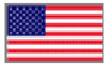
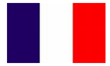
  - shear turbulence control, drag reduction, ...
  - MLC consistently outperformed best open-loop forcing
  - Even when a linear dynamics was invalidated.

- **In Progress: Cluster-based control (CROM, RL, ...)**

  → model-based alternative for MLC

More information or any ideas

Call 24h/7d

 	 	 	 	 
+61-2-62688330	+1-206-543-7124	+49-17682001688	+48-61-6652778	+33-549-366015

... or read

Kaiser+ 2014 JFM .... *CROM*	**Gautier+ 2015 JFM** ... *machine learning control*
Pastoor+ 2008 JFM .... *bluff-body control*	**Luchtenburg+ 2009 JFM** .... *airfoil control*

... or ask now!!!

In any case, stay tuned in for news + publications:

- http://MachineLearningControl.com
- http://ClusterModelling.com