Data-informed physics-based modeling of complex dynamical systems

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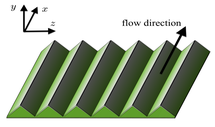
Motivation

Modeling and control of complex systems

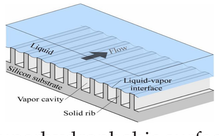
- **Challenges**
  - large number of degrees of freedom
  - complex dynamics
  - uncertainties
  - small-data issues: unreliable or insufficient measurements, ...
- **Objective**
  - control-oriented modeling
  - model-based control design
  - estimation
  - sensor/actuator placement
- **Economic impact**
  - prevent/suppress turbulence
  - reduce skin-friction drag
  - informed data acquisition
  - stable power grid operation

Flow control

passive



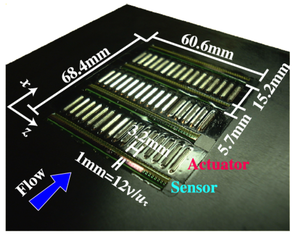
riblets



superhydrophobic surface

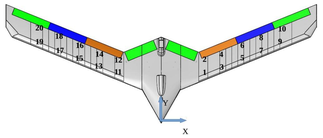
chevrons

active

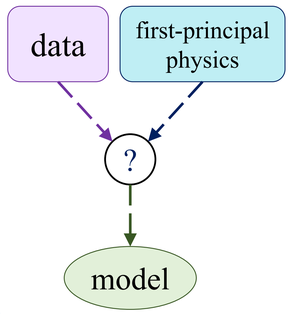


hot-film sensors and wall-deformation actuators

(Yoshino *et al.* 2008)



Data-driven vs physics-based modeling



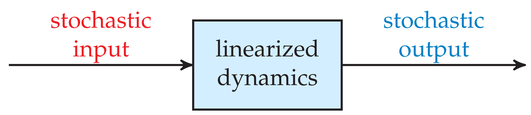
Data-driven: flexible but not robust
small-data issues

Physics-based: robustness
trade-off (complexity vs accuracy)
modeling uncertainties

⋆ How can data be used to refine the predictive capability of physics-based models?

Approach

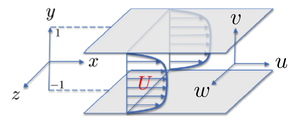
Stochastically forced linearized equations



- view second-order statistics as data for **inverse problems**
- identify forcing statistics to account for available velocity statistics

Completion of turbulent flow statistics

Turbulent channel flow

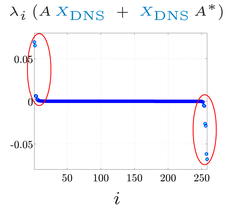


Linearized Navier-Stokes Eqs.

$$\dot{\psi} = A\psi + B\,\mathbf{d}$$
$$\mathbf{v} = C\psi$$

Lyapunov equation: $A\,X + X\,A^* = -B\,\Omega B^*$

white-in-time excitation too restrictive!

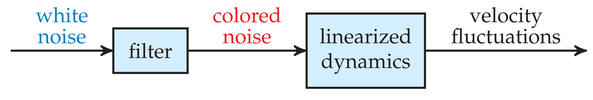


- **Convex optimization problem**

$$\begin{aligned} \underset{X,\,Z}{\text{minimize}} \quad & -\log\det(X) + \gamma\,\|Z\|_\star \\ \text{subject to} \quad & AX + XA^* + Z = 0 \\ & (CXC^*)_{ij} = \Phi_{ij} \qquad (i,j) \in \mathcal{I} \end{aligned}$$

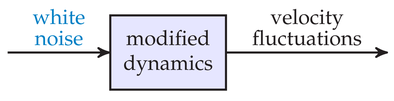
- **Dynamics of colored-in-time forcing**

$\dot{\psi} = A\psi + B\,\mathbf{d}$



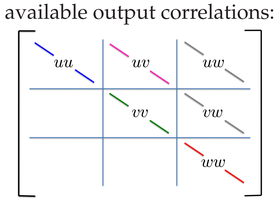
low-rank modification

$\dot{\psi} = (A + B\,C_f)\,\psi + B\,\mathbf{w}$

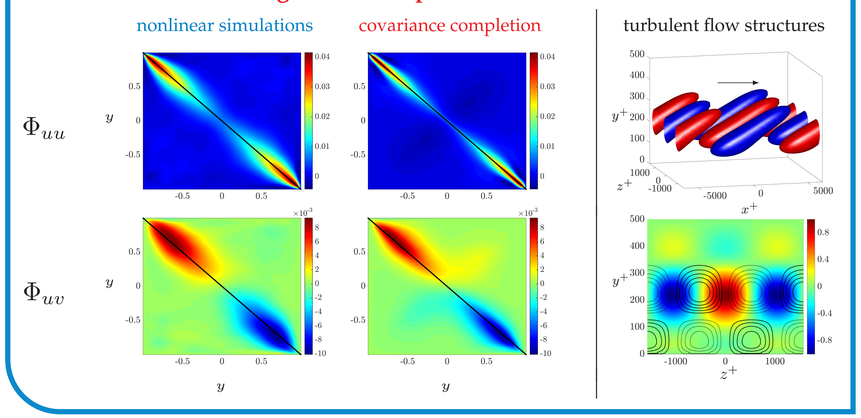


Structured covariance completion

available output correlations:



- **Recovered off-diagonals - two-point correlations**



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Sample publications

[1] A. Zare, Y. Chen, M. R. Jovanović, and T. T. Georgiou, "Low-complexity modeling of partially available second-order statistics: theory and an efficient matrix completion algorithm", *IEEE Trans. Automat. Control*, vol. 62, no. 3, pp. 1368-1383, March 2017.

[2] A. Zare, M. R. Jovanović, and T. T. Georgiou, "Colour of turbulence", *J. Fluid Mech.*, , vol. 812, pp. 636-680, February 2017.

[3] W. Ran, A. Zare, M. J. P. Hack, and M. R. Jovanović, "Modeling mode interactions in boundary layer flows via Parabolized Floquet Equations", *Phys. Rev. Fluids*, 2017, Note: Submitted, also arXiv:1712.02024.

[4] A. Zare, H. Mohammadi, N. K. Dhingra, M. R. Jovanović, and T. T. Georgiou, "Proximal algorithms for large-scale statistical modeling and sensor/actuator selection", *IEEE Trans. Automat. Control*, 2018, Note: Submitted, also arXiv:1807.01739.

[5] W. Ran, A. Zare, M. J. P. Hack, and M. R. Jovanović, "Stochastic receptivity analysis of boundary layer flow", *Phys. Rev. Fluids*, 2018, Note: Submitted, also arXiv:1807.07759.