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Data, Dynamics, and Manifolds: Machine Learning Approaches for Modeling and Controlling Complex Flows

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Abstract

Fluid flows often exhibit chaotic or turbulent dynamics and require a large number of degrees of freedom for accurate simulation. Nevertheless, because of the fast damping of small scales by viscosity, these flows can in principle be characterized with a much smaller number of dimensions, as their long-time dynamics relax in state space to a finite-dimensional invariant manifold. Classical data-driven methods for dimension reduction approximate this manifold as a flat surface, but for complex systems, this approach is severely limited. We describe a data-driven reduced order modeling method, "Data-driven Manifold Dynamics" (DManD), that finds a nonlinear coordinate representation of the manifold using a machine-learning architecture called an autoencoder, then learns an ordinary differential equation for the dynamics on the manifold. Exploitation of symmetries substantially improves performance. We apply DManD to a range of systems including transitional turbulence, where we accurately represent the dynamics with 25 degrees of freedom, as compared to the 105 degrees of freedom of the direct simulation. We then use the model to efficiently train a reinforcement learning control policy that is highly effective in laminarizing the flow. We also introduce an autoencoder architecture that yields an explicit estimate of manifold dimension. DManD can be combined with a clustering algorithm to generate overlapping local representations that are particularly useful for intermittent dynamics.

Bio

Michael D. Graham is the Steenbock Professor of Engineering and Harvey D. Spangler Professor of Chemical and Biological Engineering at the University of Wisconsin-Madison, and is also a Professor of Mechanical Engineering. He received his B.S. in Chemical Engineering from the University of Dayton in 1986 and his PhD. from Cornell University in 1992. After postdoctoral appointments at Houston and Princeton, he joined the faculty at Madison in 1994.

Professor Graham's research interests include the dynamics of complex fluids, blood flow, swimming microorganisms; and nonlinear dynamics in Newtonian and complex fluids. He is author of two textbooks: *Microhydrodynamics, Brownian Motion, and Complex Fluids* and *Modeling and Analysis Principles for Chemical and Biological Engineers* (with James B. Rawlings).

Among Professor Graham's professional distinctions are the François Frenkiel Award (2004) and Stanley Corrsin Award (2015) from the American Physical Society Division of Fluid Dynamics, and a 2018 Vannevar Bush Faculty Fellowship from the US Department of Defense.

Professor Graham has served as an Associate Editor of the Journal of Fluid Mechanics and as Editor-in- Chief of the Journal of Non-Newtonian Fluid Mechanics. He is Past President of the Society of Rheology.

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