



# ME – PhD Thesis Colloquium



## Continual Koopman Learning for Data-Driven Control of Nonlinear Systems

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### ABSTRACT

Precise control of nonlinear dynamical systems remains a fundamental challenge across science and engineering, as a unifying mathematical framework for such systems remains elusive. While linear control theory offers a powerful and well-established toolbox, its applicability to nonlinear systems is limited, motivating the search for globally valid linear representations. Koopman operator-theoretic methods provide a promising data-driven approach by enabling linear embeddings of nonlinear dynamics. However, in practice, learned Koopman models often lack predictive accuracy and resort to bilinear state-input representations, making tractable controller synthesis difficult. Moreover, they struggle to generalize beyond training data and lack robustness to changes in system dynamics arising from intrinsic or environmental factors.

To address these challenges, we propose a sequence of contributions that combine structured representations, adaptation, and safety within a learning-enabled control framework. First, we introduce a physics-informed Koopman representation based on generalized momenta, yielding a linear control-affine model in lifted coordinates with known input structure. This formulation avoids the bilinear state-input coupling inherent in standard Koopman approaches, enabling improved prediction accuracy and tractable controller synthesis. To overcome the lack of robustness under distribution shifts, we develop an adaptive Koopman learning architecture that combines offline model learning with online neural adaptation. An autoencoder-based network learns the Koopman embedding from nominal data, while the system dynamics are continuously updated in real time using prediction errors in the lifted space. Furthermore, we extend this framework to context-dependent Koopman operators that generalize across parameterized families of dynamical systems, enabling rapid adaptation, transfer, and scalable deployment across system configurations.

To further enhance performance and data efficiency, we introduce an active learning strategy that leverages information-theoretic metrics to guide excitation toward the most informative regions of the state-input space, coupled with a contractive adaptation mechanism that ensures stability and convergence during online updates. Finally, to ensure safe operation, these methods are integrated within a model predictive control (MPC) framework augmented with control barrier functions (CBFs) and uncertainty-aware constraint tightening. Together, these contributions establish a principled approach for combining structured representations, continual adaptation, active exploration, and safety-critical control. The proposed methods are validated through extensive simulations and real-world robotic experiments, demonstrating improved prediction accuracy, robustness, and reliable constraint satisfaction compared to existing approaches.

### ABOUT THE SPEAKER

Rajpal Singh received his bachelor's degree in mechanical engineering from the National Institute of Technology, Srinagar, in 2020. He is currently pursuing a Ph.D. degree in the Indian Institute of Science (IISc), Bengaluru, in the DACAS lab under the supervision of Prof. Jishnu Keshavan. His current research interests are broadly in the areas of nonlinear dynamics and control, data-driven control, continual learning, and control-oriented learning.

