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Latent Dynamics Graph Convolutional Networks for Model Order Reduction

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Graph Neural Networks (GNNs) have emerged as powerful tools for nonlinear Model Order Reduction (MOR) of time-dependent parameterized Partial Differential Equations (PDEs) [1].
However, existing methodologies struggle to combine geometric inductive biases with interpretable latent dynamics, overlooking dynamics-driven features or disregarding geometric information, respectively.

In this work, we address this gap by introducing Latent Dynamics Graph Convolutional Networks (LD-GCNs) [3], a purely data-driven, encoder-free architecture that learns a global, low-dimensional representation of dynamical systems conditioned on external inputs and/or parameters [2].
The temporal evolution is modeled in the latent space and advanced through time-stepping, allowing for time-extrapolation, and the resulting trajectories are consistently decoded onto geometrically parametrized domains using a GNN.
Our framework enhances interpretability by enabling the analysis of latent trajectories and supports zero-shot prediction through interpolation in the latent space.

The methodology is mathematically validated via a universal approximation theorem for encoder-free architectures, and numerically tested on complex computational mechanics problems involving physical and geometrical parameters, including the detection of bifurcating phenomena for Navier-Stokes equations.

References:

[1] Federico Pichi, Beatriz Moya, and Jan S. Hesthaven. "A graph convolutional autoencoder approach to model order reduction for parametrized PDEs". In: *Journal of Computational Physics* 501 (Mar. 2024), p. 112762. ISSN: 0021-9991. DOI: 10.1016/j.jcp.2024.112762.
[2] Francesco Regazzoni et al. "Learning the intrinsic dynamics of spatio-temporal processes through Latent Dynamics Networks". en. In: *Nature Communications* 15.1 (Feb. 2024), p. 1834. ISSN: 2041-1723. DOI: 10.1038/s41467-024-45323-x
[3] Lorenzo Tomada, Federico Pichi, and Gianluigi Rozza. *Latent Dynamics Graph Convolutional Networks for Model Order Reduction.* In preparation.

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