Adaptive Stochastic Reduced-Order Modeling for Autonomous Ocean Platforms

by

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Abstract

Onboard forecasting and data assimilation are challenging but essential for unmanned autonomous ocean platforms. Due to the numerous operational constraints for these platforms, efficient adaptive reduced-order models (ROMs) are needed. In this thesis, we first review existing approaches and then develop a new adaptive Dynamic Mode Decomposition (DMD)-based, data-driven, reduced-order model framework that provides onboard forecasting and data assimilation capabilities for bandwidth-disadvantaged autonomous ocean platforms. We refer to the new adaptive ROM as the incremental, stochastic Low-Rank Dynamic Mode Decomposition (iLRDMD) algorithm. Given a set of high-fidelity and high-dimensional stochastic forecasts computed in remote centers, this framework enables i) efficient and accurate send and receive of the high-fidelity forecasts, ii) incremental update of the onboard reduced-order model, iii) data-driven onboard forecasting, and iv) onboard ROM data assimilation and learning. We analyze the computational costs for the compression, communications, incremental updates, and onboard forecasts. We evaluate the adaptive ROM using a simple 2D flow behind an island, both as a test case to develop the method, and to investigate the parameter sensitivity and algorithmic design choices. We develop the extension of deterministic iLRDMD to stochastic applications with uncertain ocean forecasts. We then demonstrate the adaptive ROM on more complex ocean fields ranging from univariate 2D, univariate 3D, and multivariate 3D fields from multi-resolution, data-assimilative Multidisciplinary Simulation, Estimation, and Assimilation Systems (MSEAS) reanalyses, specifically from the real-time exercises in the Middle Atlantic Bight region. We also highlight our results using the Navy's Hybrid Coordinate Ocean Model (HYCOM) forecasts in the North Atlantic region. We then apply the adaptive ROM onboard forecasting algorithm to interdisciplinary applications, showcasing adaptive reduced-order forecasts for onboard underwater acoustics computations and forecasts, as well as for exact time-optimal path-planning with autonomous surface vehicles.

For stochastic forecasting and data assimilation onboard the unmanned autonomous ocean platforms, we combine the stochastic ensemble DMD method with the Gaussian Mixture Model - Dynamically Orthogonal equations (GMM-DO) filter. The autonomous platforms can then perform principled Bayesian data assimilation onboard and learn from the limited and gappy ocean observation data and improve onboard estimates. We extend the DMD with the GMM-DO filter further by incorporating incremental DMD algorithms so that the stochastic ensemble DMD model itself is updated with new measurements. To address some of the inefficiencies in the first combination of the stochastic ensemble DMD with the GMM-DO filter, we further introduce the GMM-DMD algorithm. This algorithm not only uses the stochastic ensemble DMD as a computationally efficient forward model, but also employs the existing decomposition to fit the GMM to and perform Bayesian updates on. We demonstrate this incremental stochastic ensemble DMD with GMM-DO and GMM-DMD using a real at-sea application in the Middle Atlantic Bight region. We employ a 300 member set of stochastic ensemble forecasts for the "Positioning System for Deep Ocean Navigation - Precision Ocean Interrogation, Navigation, and Timing" (POSYDON-POINT) sea experiment, and highlight the capabilities of reduced data assimilation using simulated twin experiments.

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