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ADVANCED COMPUTATIONAL AND MACHINE-LEARNING TOOLS TO ENABLE PREDICTIVE DIGITAL TWINS FOR ELECTRIC PROPULSION

Abstract

Digital twins (DTs) for Electric Propulsion (EP) are revolutionary technologies that offer strategic value and game-changing potentials in view of the evolving needs of the space industry as well as the cost-efficiency, reliability, and upscaling challenges it is facing today.

In this paper, we will delve into the specific technical efforts ongoing at Imperial Plasma Propulsion Laboratory (IPPL) to enable a world-first predictive and versatile DT for the Hall thruster technology, and other EP devices by the extension of our methodologies and building block capabilities.

The discussions will revolve around our latest achievements and the ongoing research on two principal software building blocks of Hall thrusters' (EP's) DT. These building blocks are: (i) a cost-effective full-kinetic particle-in-cell (PIC) model for detailed physics/engineering analysis and to generate extensive high-fidelity data for machine learning (ML), and (ii) ML-based, low-computational-cost reduced-order models (ROMs) to predict the thrusters' performance and operational behaviour.

Regarding building block (i), we will report the progress achieved on further advancement of the reduced-order PIC scheme. The novel reduced-order PIC, conceptualized and developed at IPPL, is a well-received powerful kinetic modelling approach that drastically reduces the computational cost of conventional kinetic simulations while maintaining the fidelity of results.

The reported progress on reduced-order PIC pertains to its enhancement using machine-learning techniques so that the code can provide highly accurate results at three orders of magnitude reduced computational cost compared to the state-of-the-art PIC codes. This effectively paves the way to computationally affordable and practical kinetic models of full-size plasma propulsion technologies.

Concerning building block (ii), we present our latest results on the data-driven/machine-learning-based reduced-order plasma modeling. The data-driven ROMs allow fast and reliable predictions of the thrusters' performance, thus, enabling simulation-based design optimizations. Moreover, as the underpinning data-driven architectures can seamlessly work with numerical and experimental data, the derived ROMs can be used for thrusters' autonomous control. The main data-driven algorithms whose results we will present are the Sparse Identification of Non-linear Dynamics (SINDy) and a recent in-house-developed breakthrough algorithm, the "Phi Method".

We will conclude by discussing how the described physics-based and machine-learning-enabled building blocks can be integrated into the DT's architecture, hence, yielding a highly flexible predictive asset for revamped design and development of EP technologies.