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Developing Digital Twins from High Fidelity Simulations

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ABSTRACT:

Digital Twins (DTs) are receiving considerable attention from multiple disciplines. Originally conceived for aerospace applications, the focus of DTs was on structural health modeling for improving maintenance, operation, and performance on aircrafts. However, as a part of Industry 4.0 vision, it became recognized that the value proposition of DTs was much wider ranging; potentially improving healthcare, transportation, manufacturing, and infrastructure. At this time, capabilities for constructing and deploying DTs are still in their infancy. Much of the current literature is dedicated to the conceptualization of digital twins and identifying associated enabling technologies and challenges.

Most concepts of DTs consist of two essential parts: the physical asset and the digital asset. The physical asset is instrumented with sensors that measure information about the state of the system, and digital asset is an ensemble of computational models and methods that calculate the state of the physical system to some desired accuracy. These two parts are coupled such that physical asset uses information from the digital asset, and the digital asset uses information measured on the physical asset. The DT operates measuring, calculating, and exchanging information in real-time.

The objective of this project is to develop the fundamental methods and techniques that would leverage the significant investments in advanced modeling and simulation to create efficient, accurate, and secure DTs. The goal of these DTs is to enhance the safety, reliability, and economic viability of nuclear energy systems.

To achieve this objective, we start with the view that DT development should rely first on mechanistic model-based methods to leverage our community's extensive experience and understanding. Then model-free, data-driven, or machine learning (ML) techniques can be adopted to selectively, and correctively, augment limitations in the physics-based approaches. These integrated or "hybrid" models are advantageous because they are physics based, and therefore easier to verify and validate. Incorporation of data-driven components enables increased accuracy. An example would be solving the linear form of a complex nonlinear dynamics system and using ML to represent the nonlinear aspects of the problem that were intentionally neglected in the linearization. For these "hybrid" models to be real-time, the physics-based components must be represented by reduced order models. A fundamental challenge we plan to address is how to best construct the reduced order models (ROMs) from known physics for use in a hybrid model. Similarly, another contribution from this work will be explanations and guidance on which ML and data-driven methods best represent certain physics that are necessarily neglected in a ROM. Finally, we plan to integrate uncertainty quantification into the hybrid models to enable optimal performance of the physical asset in an uncertain environment.

From this research, we also define educational and service goals to create a curriculum for teaching and learning concepts and methods that underly DTs. This will include a reference text, instructional material, and training material to be provided with an open access license. This material would be accessible for virtual self-guided learning, training workshops, or adaptable to college courses at the undergraduate or graduate level. Ultimately, this facilitates current and future generations to develop the skills necessary to deploy DTs.

The overall significance of the proposed work will be to address fundamental knowledge gaps for the practical development and deployment of digital twins. In focusing on the application of nuclear energy systems the proposed work will help to address several challenges including secure and reliable remote and autonomous operation of reactors. Finally, on the development of educational materials, it ensures there will be knowledge transfer of the technical insights gained in the project to various communities including those in higher education, industry, and national laboratories.