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Digital Twins and Surrogate Modeling in Computational Fluid Dynamics

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ABSTRACT

Digital Twins (DTs) are advanced virtual representations of physical systems that dynamically integrate real-time data, physics-based first principles, and numerical predictive models to enhance decision-making, optimize performance, and improve reliability. The impact of Digital Twins in CFD spans a wide range of applications, including aerospace, energy systems, and biomedical engineering. They enable predictive maintenance, flow control, and design optimization, as well as real-time monitoring of complex systems.

In the context of Computational Fluid Dynamics (CFD), the development of DTs is motivated by many engineering and industrial applications, and requires a tight coupling between high-fidelity numerical simulations and data-driven methodologies. The elevated computational cost of performing such analysis is commonly dealt with Surrogate or Reduced-Order models (ROMs), often exploiting Scientific Machine Learning strategies to accurately capture complex flow phenomena while ensuring computational efficiency.

This minisymposium aims to explore recent advancements of Digital Twins in CFD, focusing on key challenges such as model accuracy, real-time data assimilation, and scalability. A central theme is the seamless integration of high-fidelity numerical simulations with data-driven and machine learning-based surrogate models, enabling a new generation of hybrid Digital Twin frameworks.

In complex, turbulent, and multi-scale flows, high-fidelity CFD is essential to capture the underlying physics, while surrogate models enable fast and adaptable predictions for real-time applications. Their integration balances accuracy and efficiency, supporting practical Digital Twin deployment. High-performance computing and advanced numerical methods generate reliable data to build and calibrate reduced-order and machine learning models. Data assimilation continuously incorporates experimental and sensor data, improving predictions, while uncertainty quantification ensures robust assessment of reliability under modeling and data uncertainties.

By bridging advanced CFD methodologies, applied mathematics, and data-driven approaches, this minisymposium seeks to foster interdisciplinary exchange on state-of-the-art developments and practical implementations of Digital Twins in fluid dynamics.