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MACHINE LEARNING METHODS FOR UNCERTAINTY QUANTIFICATION, RISK ASSESSMENT, AND RELIABILITY ANALYSIS IN DIGITAL TWINS

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ABSTRACT

Digital twin models enable continuous, near real-time assessment of the risk of damage and failure in complex engineering systems by tightly coupling high-fidelity simulations with live sensor data. However, high-fidelity digital twin models are often computationally expensive, making quick-turnaround risk evaluation, control, and many-query reliability analysis prohibitively costly. Machine learning (ML) has emerged as a key enabling technology to bridge this gap by accelerating uncertainty propagation, learning surrogate dynamics from heterogeneous data, and quantifying both aleatoric and epistemic uncertainties under realistic operating conditions.

This Minisymposium aims to bring together recent advances in ML-driven uncertainty quantification, risk assessment, and reliability analysis for digital twin applications. We invite contributions on, but not limited to: (i) physics-informed and data-driven surrogates, reduced-order models, polynomial chaos, Gaussian process, and operator-learning approaches for stochastic dynamical systems; (ii) multifidelity methods for estimating tail-risk measures such as conditional value-at-risk, probability of failure, and other rare-event statistics for nonlinear systems with dependent and high-dimensional inputs; (iii) deep quantile, Bayesian, ensemble, and generative models for uncertainty-aware prediction and decision-making; (iv) active learning, adaptive sampling, and optimal experimental design for rare events and reliability-based design optimization; (v) sensor fusion, data assimilation, and online model updating for time-evolving twins; (vi) uncertainty-aware control, prognostics and health management, and predictive maintenance; and (vii) cross-disciplinary applications in structural and mechanical systems, energy and combustion plants, additive manufacturing, aerospace, and civil infrastructure.

By bridging methodological developments with engineering practice, this session aims to foster a community discussion on trustworthy, computationally efficient digital twins capable of robust, risk-informed decision-making across a broad spectrum of disciplines.