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DIGITAL TWINS FOR CIVIL INFRASTRUCTURES – FROM DATA AND MODELS TOWARDS INTEGRATION AND DECISION SUPPORT

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ABSTRACT

Digital twins are continuously updated virtual representations of physical objects, processes or systems that support simulation-based decision-making by establishing a two-way link between physics-driven models and real-world observational data. Although they first gained prominence in the manufacturing industry under the Industry 4.0 paradigm, digital twins have since found application in a wide range of domains among others in critical civil infrastructure such as road networks, bridges, wastewater treatment facilities, and energy grids: systems characterized by high cost, long service lives, and stringent safety requirements. Thereby, the predictive capability and operational utility of digital twins depend fundamentally on sophisticated computational mechanics, the ability to run simulations in real time, and seamless integration between data and models.

Building dependable digital twins for civil infrastructure systems requires deep interdisciplinary collaboration, integrating domain-specific modeling, numerical simulation, data assimilation, and machine learning to construct, validate, and interconnect the necessary sub-models, datasets, and interfaces. In contrast to conventional simulation workflows, digital twins face the added challenges of satisfying real-time performance requirements, incorporating streaming data, and continuously updating their underlying models – tasks that become especially demanding in high-

dimensional, multi-physics, or nonlinear problem settings. In safety-critical applications, achieving the levels of robustness and interpretability demanded by stakeholders places further constraints on numerical stability, uncertainty quantification methods, and the design of model hierarchies.

Topics of interest include, but are not limited to:

- Computationally efficient numerical modeling strategies (e.g., FEM, ROMs) and scientific machine learning techniques (e.g., PINNs, Neural Operators) for representing the behavior of complex physical assets,
- Collection, management, processing, and integration of sensor data from physical objects and laboratory experiments to support model calibration and continuous real-time updating,
- Fusion of heterogeneous models and multi-source data into a coherent digital representation (e.g., via model hierarchies or hybrid physics-informed data-driven frameworks),
- Geometric, topological, and semantically rich information modeling, together with concepts for spatial and semantic interlinking of data and models,
- Synchronization and twinning strategies for maintaining consistency between a physical asset and its digital counterpart over time,
- System architectures for digital twin platforms, strategies for deployment at scale, and application-specific use cases,
- Methods for quantifying and propagating uncertainties throughout digital twin frameworks.