

Diagnostic Digital Twin for Nuclear Piping-Equipment Systems using Deep Learning Approaches

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Abstract

Advanced nuclear reactors offer pioneering applications due to their compact design, robustness, reliability, and high capacity factors. These reactors can be utilized in remote or disaster-affected regions, delivering dependable power where it is critically needed. Their high efficiency and reduced greenhouse gas emissions make them a viable choice for sustainable energy production. To promote their broader adoption, it is essential to minimize maintenance life-cycle costs while ensuring their structural integrity. Recent advancements in artificial intelligence (AI) and deep learning algorithms have made Digital Twin (DT) technology a practical solution for the autonomous operation of advanced nuclear reactors. Enhanced DT technology can provide a cost-effective method for improving system health monitoring. An important component of nuclear DT frameworks is the condition monitoring of safety-critical systems, such as piping and equipment systems, which involves the systematic collection and analysis of sensor data from the plant.

Coolant is transferred safely and efficiently between vessels in a nuclear facility using piping-equipment systems. These systems are susceptible to flow-accelerated corrosion and erosion, which can lead to the thinning of pipe walls. Unchecked degradation can cause cracks and failures in the piping infrastructure. Conventional non-destructive testing (NDT) methods are often labor-intensive and require plant shutdowns, resulting in substantial financial losses for electric utility companies. Implementing a digital twin, equipped with condition monitoring capabilities, allows for the analysis of real-time sensor data, providing maintenance personnel with alerts regarding any detected degradation. Specifically, machine

learning algorithms can identify minor damage in pipe structural integrity, thus eliminating the need for costly NDT equipment and reducing the frequency of plant outages for inspections.

This research proposes a diagnostic digital twin for nuclear piping systems, including their design, construction, and ongoing condition monitoring as they age. The design and construction phases involve developing digital tools to enhance the conversion between Building Information Modeling (BIM) software and structural design Finite Element (FE) software. These tools also enable virtual compatibility checks to ensure the correct installation fit. The condition monitoring framework employs an artificial intelligence (AI)-based approach to detect degradation, such as pipe wall thinning, caused by flow-accelerated corrosion (FAC) due to the transportation of high-temperature and high-pressure fluids in nuclear power plants.

A laboratory-based demonstration of a diagnostic “as-built” digital twin is conducted for a piping system, utilizing data from simulations and empirical systems to track aging and degradation progression. A case study is designed and installed in the laboratory, involving a piping system subjected to pipe-wall thinning, representative of realistic nuclear piping systems. The system undergoes on-site vibrations for analysis and workflow development. Simulation-trained deep learning algorithms, including Multi-Layer Perceptrons (MLPs) and Convolutional Neural Networks (CNNs), are compared for their diagnostic capabilities and computational efficiency. Advanced data processing techniques, such as domain randomization, are also demonstrated.