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Digital Twin–AI Convergence for Predictive Modeling and Lifecycle Asset Management in Engineering Systems

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Abstract

The integration of Artificial Intelligence (AI) with Digital Twin (DT) technology has redefined the engineering landscape by enabling real-time, data-driven decision-making across the entire lifecycle of assets. This book chapter presents an in-depth exploration of AI-driven Digital Twin systems as transformative enablers of predictive modeling, intelligent control, and sustainable asset management. It addresses the evolution, architecture, and functional frameworks of Digital Twins while emphasizing the convergence of AI methodologies, including machine learning, deep learning, and reinforcement learning, in achieving adaptive and autonomous operations. The discussion extends to predictive maintenance, fault diagnosis, and Remaining Useful Life (RUL) estimation models that enhance operational reliability and performance resilience. Security, privacy, and trust mechanisms within interconnected Digital Twin ecosystems are analyzed to ensure data integrity and safe information exchange. The chapter also highlights standardization and interoperability protocols that support seamless integration across heterogeneous industrial platforms. A comprehensive focus is placed on the application of Digital Twins throughout the engineering asset lifecycle from conceptual design and development to operational optimization and end-of-life management. AI-enhanced simulations enable real-time optimization, while data-driven prescriptive analytics facilitate intelligent decision-making for resource utilization and performance enhancement. The fusion of Digital Twin systems with circular economy principles advances environmental sustainability by promoting closed-loop material flows, energy efficiency, and reduced carbon footprints. Emerging challenges in large-scale implementation, such as computational scalability, data governance, and ethical AI adoption, are also discussed to provide a holistic understanding of this evolving domain. The chapter concludes that AI-enabled Digital Twins represent a paradigm shift toward intelligent, self-adaptive, and sustainable engineering systems. By bridging the gap between physical and digital domains, these systems are establishing the foundation for next-generation industrial transformation that aligns innovation with sustainability, resilience, and operational excellence.

Keywords: Digital Twin, Artificial Intelligence, Predictive Maintenance, Reinforcement Learning, Interoperability, Sustainability

Introduction

The evolution of engineering systems in the era of Industry 4.0 has been profoundly influenced by the integration of advanced computational intelligence and virtual modeling technologies [1]. Among these, the convergence of Artificial Intelligence (AI) and Digital Twin (DT) frameworks represents a defining milestone in the transformation of asset management and engineering decision-making [2]. Digital Twin technology establishes a real-time digital replica of a physical asset or process, enabling seamless monitoring, simulation, and optimization throughout its lifecycle [3]. The addition of AI augments this digital ecosystem with the ability to learn from operational data, recognize complex behavioral patterns, and predict future states of assets under dynamic conditions [4]. This combination is reshaping industrial operations by enhancing system reliability, enabling adaptive performance control, and fostering a more intelligent and responsive engineering environment [5].

The development of Digital Twin technology can be traced through successive phases of digital innovation from basic computer-aided design and product modeling to the creation of interconnected, data-driven virtual environments [6]. In modern engineering contexts, Digital Twins serve as an intelligent bridge between the physical and virtual domains, continuously assimilating data from sensors, IoT networks, and control systems [7]. AI algorithms empower this synchronization process by interpreting vast quantities of real-time information, transforming raw data into actionable knowledge [8]. Through this interplay, Digital Twins are capable of mirroring complex system behaviors, identifying deviations from expected performance, and supporting predictive interventions before operational disruptions occur [9]. Such capabilities are redefining maintenance paradigms and setting new standards for operational excellence [10].