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Digital Twins in Mechatronics: A Symmetry-Based Approach to System Modeling and Analysis

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This paper explores the integration of symmetry principles into digital twin models for complex mechatronic systems, highlighting their potential to enhance modeling efficiency, anomaly detection, and system scalability. By leveraging structural and functional symmetries, the proposed approach supports modular system design, reduces computational overhead, and improves predictive maintenance capabilities. A comprehensive case study is presented, featuring a modular automated production line composed of a conveyor with 90 FIFO buffer positions, multiple CNC machining centers, and two 7-axis robots controlled via Siemens Sinumerik RunMyRobot/Direct Control. The simulation framework combines Software-in-the-Loop (SiL) and Model-in-the-Loop (MiL) methodologies, employing a CMVM digital twin of the CNC controller, Simit for communication simulation, and Mechatronic Concept Designer (MCD) for behavior modeling. Hierarchical physical and functional decomposition, aligned with Weiss and Qiao's methodology, is applied to facilitate the development of a Component Mapping Matrix and to ensure simulation fidelity. The proposed approach demonstrates how incorporating symmetry and modularity in digital twins can accelerate deployment, enhance robustness, and improve decision-making in cyber-physical manufacturing environments.

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