Physics Aware Machine Learning Surrogates for Real-Time Digital Twin in Additive Manufacturing

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Overview: The primary goal of this Dornfeld Manufacturing Vision Concept is to develop a Cyber Adaptive Manufacturing Intelligent System (CyAMIS, pronounced Siamese) that integrates concepts from the emerging area of physics-aware machine learning (ML) to formulate, develop, and deploy a near-real-time Siamese (digital) twin to reliably and efficiently achieve the best part quality and desired material microstructure in additive manufacturing processes.

Rationale: Traditional manufacturing of designed components relies on streamlined process planning, with part tolerances and specifications provided on a part-by-part basis before fabrication. The manufacturing process is optimized during pre-processing rather than on-the-fly, mainly because no control techniques are available for tailoring material properties in real-time. Closed-loop control will support on-the-fly modification of the process plan to autonomously correct variations in the manufacturing environment and stochastic effects. However, to support rapid feedback to the machine tool in real-time, the manufacturing process’s current material state needs to be tracked. Such real-time tracking could be achieved using the CyAMIS framework consisting of a computational digital twin of the manufacturing process and material state of the workpiece. However, manufacturing simulations are compute-intensive and too slow to be deployed in an interactive environment. This bottleneck could be overcome by leveraging recent advances in physics-aware ML to improve process control, complexity, and confidence. This general framework applies to both additive and conventional methods and other future manufacturing approaches (i.e., formative) spanning length scales and materials classes.

Challenges: One of the main challenges in developing a digital twin is accelerating the computations to perform them in real-time. There currently does not exist an interactive digital twin framework that can be used in real-time to enable interactive performance monitoring and control of manufacturing systems. ML algorithms, with their generalizing capability, are an ideal substitute for compute-intensive manufacturing simulations. Recent advances in physics-aware ML can be employed to assess the material state and properties of the manufactured component much faster than traditional simulations. ML for design and real-time control is novel and has not been explored in existing manufacturing systems.

This concept would require collaboration between experts in machine-learning, manufacturing, and control systems. Some of the critical ingredients of the concept include: (1) the development of advanced computational strategies for creating high-fidelity physics simulators of layered manufacturing processes, including fluid-structure interaction and material microstructure modeling; (2) hybrid ML-physics emulators for real-time predictions, prognosis, and diagnosis, using AI/ML that is explicitly physics aware, accounts for uncertainty, and can continuously assimilate multi-scale, multimodal, and multi-fidelity manufacturing data; (3) holistic design of cyber-physical manufacturing, using a digital twin to enhance closed-loop system design with multimodal sensing and actuator systems for real-time performance monitoring and control of additive manufacturing and the optimization of product design rather than just part specifications. Further, the CyAMIS framework can be used as a data record to validate the part quality and provide supply-chain assurance. We believe such a digital twin framework to be the future of modern manufacturing systems, ultimately leading to Manufacturing 5.0 systems.