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.