Event-Driven Foundations of Autonomy: Laboratories and Digital Twins

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Abstract

Autonomous laboratories and executable digital twin environments demand more than automation—they require connected, intelligent cyberinfrastructure built on bidirectional data flow, semantic integration, and knowledge-based reasoning. In such complex environments, event-driven architecture serves as the foundational design principle. Event-driven approaches enable next-generation platforms with orchestration of complex, distributed workflows across instruments, computational models, and decision-making agents.

In this presentation, we detail our mission-driven development of an event-based approach within the AIMD-L (Artificial Intelligence for Materials Design Laboratory) and IMQCAM (Institute for Model-based Qualification and Certification of Additive Manufacturing) projects. This includes novel uses of our OpenMSIStream streaming framework**,** workflow orchestration through data portals**,** and emerging strategies for globally unique, persistent identifiers (PIDs) for physical samples**.** These tools enable real-time coordination of heterogeneous scientific components, paving the way for agile, model-centric experimentation.

Beyond infrastructure, a central challenge in achieving autonomy is representing knowledge in a form that supports both scientific discovery and intelligent decision-making. We address this by adopting the graphical expression of materials data (GEMD) as a canonical, machine-readable structure to represent material histories, synthesis and processing steps, and characterization events. GEMD captures causal relationships across workflows, enabling provenance-aware, AI-ready experimentation.

As we move forward, we are exploring the integration of GEMD with semantic technologies and traditional RDF-based knowledge graphs**,** enabling hybrid reasoning systems that support adaptive decision-making, explainability, and closed-loop optimization. Together, these developments form a flexible, event-driven foundation for autonomous science platforms and certifiable digital twins in materials science.