

Agent-oriented system Control

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Abstract

The challenges in orchestrating complex industrial processes—whether in biomanufacturing, supply chains, or sustainable fuel production—stem from their inherently nonlinear dynamics, the opacity of real-time measurements in harsh environments, and the escalating demands for resilience amid global disruptions and decarbonization mandates. Traditional centralized control architectures, reliant on exhaustive sensor arrays and rigid optimization routines, falter under these uncertainties, leading to suboptimal yields, safety vulnerabilities, and inefficient resource use. As articulated in seminal perspectives on agentic AI in process systems engineering, these limitations underscore the urgent need for paradigms that harness emergent intelligence from distributed, adaptive entities to bridge sensing gaps, infer hidden patterns, and enact proactive decisions. In this perspective, we have revitalized the foundational Adaptive Agent-Oriented Software Architecture, the very blueprint that powered early distributed AI innovations like Apple's Siri—and evolved it into the Adaptive AgentOriented System Control (AAOSC) framework. By integrating MQTT-brokered publish–subscribe communication, redundant servers, hybrid physics-informed ML/SML models, digital twins, and a hierarchy of specialized AI agents (Sensor, Simulator, Executive, and domain-specific Control Agents), AAOSC operationalizes agentic autonomy at an industrial scale. The four case studies presented herein—spanning supply chain security, closed-loop biomanufacturing control, quantumenhanced anomaly detection, and prospective optimization of digital twin for biomass-derived sustainable aviation and maritime fuels—collectively demonstrate AAOSC's prowess: reducing deviation durations, averting shutdowns in severe fault scenarios, and boosting efficiency through virtual sensing and decentralized reasoning, all while aligning with regulatory imperatives for

safety and sustainability. Looking ahead, AAOSC charts a pathway toward fully autonomous, regulator-ready cyber-physical ecosystems that not only minimize human fatigue-related risks—a leading cause of incidents in manufacturing—but also democratize advanced control for decentralized operations worldwide. Future implementations must prioritize hybrid edge-cloud deployments for low-latency actuation, robust cryptographic protocols for agent authentication in multi-stakeholder networks, and qualification frameworks compliant with FDA/EMA standards for biopharma and food production. Extensions could incorporate multi-logic decision ensembles within agents, quantum-accelerated reasoning for ultra-fast inference, and seamless integration with emerging generative models for predictive scenario generation. By thus extending agentic principles from consumer interfaces to mission-critical sustainability challenges, AAOSC promises to catalyze a new era of resilient, equitable industrial intelligence, where computational agents tirelessly safeguard and optimize the physical world.