

Intelligent multi-agent digital twin architecture for modeling and monitoring catastrophic events

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Abstract

This paper proposes a formally grounded intelligent multi-agent Digital Twin framework for the modeling, monitoring, and coordinated management of catastrophic events in distributed cyber-physical environments. The proposed architecture integrates distributed sensing devices, real-time data assimilation, Digital Twin-based state estimation, predictive modeling, inter-agent communication, and hierarchical decision support within a closed-loop adaptive control structure. The dynamics of catastrophic processes are described through stochastic spatial-temporal models, while system-level coordination, synchronization, and concurrency are represented using timed Petri nets. In addition, a global stochastic optimal control formulation is introduced to minimize expected risk and intervention costs under uncertainty. To illustrate the applicability of the framework, a flood-monitoring scenario in the Dniester River Delta is considered, involving 20 Digital Twin devices and 4 cooperative decision-making agents. The resulting model provides a structured basis for distributed monitoring, risk assessment, scalable coordination, and adaptive response in real time. The proposed framework offers a rigorous formal and architectural foundation for future simulation, formal verification, experimental validation, and deployment-oriented implementations in resilient disaster-management systems.

Keywords: *cyber-physical systems; digital twin; distributed intelligence; edge computing; multi-agent systems; optimal control; petri nets; risk assessment*

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