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1. Cost-Aware Fault Diagnosis in Industrial Systems

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Abstract

Within the domain of prognostics and health management (PHM) for industrial systems, data-driven predictive maintenance strategies aim to optimize maintenance decisions by leveraging sensor data, thereby reducing operational costs. While machine learning techniques have achieved significant progress in tasks such as remaining useful life (RUL) prediction, the widespread industrial application of these methods is critically limited by uncertainties arising from model misspecification - a scenario where the selected model cannot perfectly capture the true data-generating process. Prevailing methodologies predominantly pursue the ultimate accuracy of diagnostic models, typically achieved by increasing model complexity and expanding data volume. This resource-intensive strategy often leads to diminishing marginal returns and, more importantly, fails to adequately incorporate the economic impact of downstream maintenance activities. To address this fundamental issue, this study proposes a novel paradigm for intelligent fault diagnosis oriented towards maintenance cost optimization. By deeply embedding economic performance indicators into the training process of diagnostic models, this research aims to fundamentally resolve the misalignment between prediction and decision-making objectives. The current dominant research paradigm adheres to a sequential “Estimate-then-Optimize” (ETO) workflow. First, a probabilistic predictive model is trained on historical data with the objective of maximizing predictive accuracy (e.g.,



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minimizing mean squared error or cross-entropy). Subsequently, the outputs of this predictive model are used as inputs for a downstream maintenance optimization model. This paradigm implicitly operates under the assumption that higher predictive accuracy invariably leads to superior decision quality. However, this paper posits that this assumption is frequently invalid in real-world settings characterized by model misspecification and imperfection.

2. Physics-Guided Conditional Diffusion Model for Cross-Condition SOH Degradation Data Generation of Lithium-Ion Batteries

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Abstract

Prediction for lithium-ion batteries is essential for safety and economic efficiency, but obtaining enough data is difficult because full-lifecycle aging tests are slow and expensive. While deep generative models can synthesize degradation data to expand training datasets, existing generative approaches rarely support predictive generation and often lack physical consistency. To address these limitations, this study proposes a physics-guided conditional diffusion model that generates high-fidelity degradation data relying on operating conditions. The proposed framework first trains a surrogate model based on a pseudo-two-dimensional mechanism to establish a physical baseline for the degradation trend. Subtracting this baseline from real data simplifies the modeling task into residual distribution learning. A conditional diffusion model then employs FiLM to map operating conditions to the residual space. Experiments reveal that the proposed approach outperforms existing baselines in both distribution similarity and predictive generation accuracy. Furthermore, adding these generated data to limited training datasets significantly reduces the estimation errors of downstream prognostics models. This provides a practical and effective solution for battery health management under data constraints.

3. Hierarchical Multi-LLM Agent Framework for Intelligent Fault Diagnosis of High-Speed Train Braking System

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Abstract

Fault detection and diagnosis (FDD) of high-speed train (HST) braking systems is critical for ensuring operational safety and reliability. With the rapid development of smart sensors, large volumes of multi-dimensional monitoring data have been collected, providing opportunities for data-driven FDD approaches.

However, existing methods generally suffer from limited interpretability and poor adaptability to evolving operational conditions. Moreover, conventional diagnostic workflows still heavily rely on domain experts for data preprocessing, model construction, and result interpretation, imposing significant burdens on maintenance personnel. Recent advances in large language models (LLMs) and multi-agent systems (MAS) offer promising avenues for automating and enhancing these diagnostic processes. This study proposes a hierarchical multi-LLM agent framework for intelligent fault diagnosis of HST braking systems. The proposed framework employs LLM-based cognitive agents organized in a layered architecture comprising four functional modules: (1) a data preprocessing module with specialized agents for missing data imputation and feature engineering; (2) a modeling module for adaptive fault classification model construction; (3) a diagnosis module for fault identification with natural language-based reasoning; and (4) a system optimization module implementing iterative performance enhancement through sample-aware reweighting strategies. By leveraging the natural language understanding and code generation capabilities of LLMs, each agent autonomously executes its designated sub-task while collaborating with other agents through structured communication protocols, thereby automating the end-to-end diagnostic pipeline. The framework is validated using real operational monitoring data collected from the braking system of a high-speed train, comprising over 40 monitoring variables. Experimental results demonstrate that the proposed approach achieves satisfactory fault detection performance while providing enhanced interpretability through the natural language reasoning chains generated by the agents.

4. A Drilling Instability Prediction Method for Outburst-Prevention Drilling Robots Based on Mechanism-data Fusion

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Abstract

To address the challenge of drilling instability (including sticking, blowout, and suction) in geological mutation zones of highly outburst-prone coal seams, this paper proposes a drilling instability prediction method for outburst-prevention drilling robots based on mechanism-data fusion. Firstly, time-series features characterizing coal hardness mutations and gas pressure fluctuations are extracted from multi-source drilling signals using signal processing techniques. Key features sensitive to different instability modes are selected through causal analysis methods, establishing a mapping between instability modes and sensitive features. Secondly, based on the coupling dynamics of the drill tool and gas-bearing coal, the state phase space is reconstructed and a time-varying ellipsoid model is introduced to describe the dynamic stability boundary. The generalized ellipsoid norm is defined as a dynamic early-warning indicator of the drilling stability margin. Finally, stability boundary constraints are incorporated into a neural network to simultaneously predict the drilling state trajectory and stability region evolution. This method integrates mechanistic knowledge with real-time data, enabling early identification of instability risks and providing decision support for safe drilling of outburst-prevention drilling robots in complex geological conditions.

5. A Causality-Guided Framework for Compound Fault Data Generation

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Abstract

The scarcity of compound fault data severely limits the generalization capability of data-driven models for system-level fault diagnosis in nuclear power plants. Existing generative approaches synthesize fault samples based solely on statistical correlations, lacking interpretability and failing to preserve the physical fault propagation mechanisms inherent in complex systems. To address these limitations, this paper proposes a temporal causal variational autoencoder (TimeCausalVAE) that integrates a structural causal model into the variational autoencoder framework to generate causally consistent compound fault samples. Specifically, a window-based temporal causal graph is first learned from multivariate time-series monitoring data to characterize both instantaneous and time-lagged causal dependencies among system variables. The encoder incorporates a causal layer that transforms independent exogenous latent variables into structured causal endogenous variables aligned with the temporal causal graph. A concept-level intervention strategy is then employed by modifying the causal concept nodes associated with target fault types, enabling controllable generation of compound fault data without requiring real compound fault samples. Structural causal consistency is enforced through a dedicated loss term that penalizes deviations between the generative process and the causal graph. Consequently, the generated data not only reproduce the statistical characteristics of monitoring signals through variational inference but also preserve causal dependencies and fault propagation mechanisms through structural causal constraints. Experimental validation on a nuclear power plant simulation system demonstrates that the proposed method effectively alleviates compound fault data scarcity and significantly enhances diagnostic accuracy, confirming the feasibility and superiority of causality-constrained generative modeling for safety-critical industrial applications.

6. NuHF-Claw: A Risk-Constrained Cognitive Agent Framework for Human-Centered Procedure Support in Digital Nuclear Control Rooms

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Abstract

The rapid digitization of nuclear power plant main control rooms has fundamentally reshaped operator interaction patterns, introducing complex soft-control behaviors and elevated cognitive risks that are not adequately addressed by existing human reliability analysis approaches. Although recent advances in large language models and autonomous agents offer new opportunities for intelligent decision support, their deployment in safety-critical environments remains constrained by risks of hallucinated reasoning and weakened human authority. This study proposes NuHF-Claw, a persistent cognitive-risk agent framework that enables risk-governed human-centered autonomy for digital nuclear operations. The core methodological innovation lies in the introduction of a risk-constrained agent runtime, which tightly couples cognitive state inference with probabilistic safety assessment to regulate autonomous system behavior in real time. By integrating cognitively grounded workload and situational awareness estimation with dynamic human error probability prediction, the framework transforms conventional offline reliability analysis into a proactive intervention mechanism embedded directly within operational workflows. Experimental validation on a high-fidelity digital control room simulator demonstrates that NuHF-Claw can anticipate interface-induced cognitive degradation, dynamically constrain unsafe autonomous recommendations, and provide risk-aware navigational guidance while preserving human decision authority. The results highlight a fundamental shift from automation-driven operation toward cognition-aware autonomy, offering a principled pathway for the safe integration of intelligent agents into next-generation nuclear control environments.

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Authors' contributions

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