Health-Aware Control for Optimized Production and Maintenance: A Unified Framework

Abstract

In the contemporary manufacturing sector, operational efficiency is sought alongside the preservation of machinery longevity, presenting a significant challenge. Traditionally, production and maintenance have been handled as separate entities, often leading to inefficiencies due to their interconnected nature. A pioneering approach—termed a **health-aware control framework**—is introduced in this research, whereby machine health awareness is integrated into both production and maintenance planning. Through this integration, system performance, encompassing production quality, output rate, energy consumption, and equipment lifespan, is optimized cohesively and proactively.

Research Question

How can a unified control framework be developed that incorporates machine health awareness into production and maintenance planning to simultaneously enhance system performance and extend equipment longevity?

This inquiry tackles the shortcomings of conventional approaches, where production and maintenance are treated as distinct domains, overlooking their reciprocal effects. A solution is pursued that bridges this divide, facilitating informed decision-making across all operational tiers.

Solution Overview

A **health-aware control framework** is proposed, wherein machine health—specifically the **state of health (SOH)**—is embedded as a fundamental parameter within production systems. By establishing SOH as a measurable and controllable variable, machine degradation is proactively managed while production targets are met. A bidirectional linkage between high-level strategic planning and low-level operational execution is fostered, ensuring that decisions at every level contribute to both immediate performance and sustained equipment health. The framework is realized through a structured, five-step implementation process, outlined below.

Step-by-Step Implementation

1. Establishing Controllability of Machine Lifespan

The framework's foundation is built upon the demonstration that machine degradation can be controlled, even within complex systems. A rolling mill was utilized as a case study, where simulations were conducted to illustrate that wear rates can be regulated by adjusting operational parameters such as speed or load. This step establishes that machine lifespan is a manageable variable rather than a predetermined outcome, paving the way for health-aware control integration.
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2. Cost-Effective Degradation Identification

For practical implementation, machine degradation identification is required to be both precise and economical. Techniques employing **Sparse Bayesian Learning** were developed, utilizing historical data to detect wear patterns without dependence on expensive physical models. Physically interpretable insights into the SOH are provided, rendering the framework scalable and adaptable across various industrial settings, from small workshops to expansive factories.
Processes

3. Advanced Control Strategies for Degradation Management

Degradation is actively managed through the application of **model predictive control (MPC)** and **linear quadratic regulators (LQR)** at both high and low operational levels. A novel **state-action cost estimation** approach is introduced, whereby the impact of control actions—such as modifying machine speed—on degradation is quantified. Simulations, including those involving autonomous mining carts, confirmed that these controllers optimize production metrics while minimizing wear, striking an effective balance between performance and health.
Mathematics

4. Bidirectional Integration of High- and Low-Level Control

A distinctive feature of the framework is the bidirectional connection established between strategic planning and operational execution. Degradation costs are incorporated into high-level production planning, ensuring that low-level actions—such as machine settings—are aligned with overarching objectives like quality or energy efficiency. The framework's adaptability was demonstrated through simulations, showing adjustments to shifting priorities while wear is mitigated, creating a seamless integration between planning and execution.
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5. Joint Optimization of Production and Maintenance

Production and maintenance are unified through a comprehensive optimization process in the final step. A cost function balancing production quality, output rate, energy consumption, and degradation costs is optimized using the **SARSA algorithm**. Dynamic adaptation to changing conditions is ensured, harmonizing both systems. Simulations involving autonomous mining carts validated the framework's capacity to achieve diverse objectives—such as high output or reduced energy use—while maintaining machine health, delivering a fully integrated solution.
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Conclusion

A transformative perspective for manufacturing is presented through the integration of health-aware control into production systems. Resilience and efficiency are enhanced, equipping industries with practical tools to lower costs and elevate performance. By connecting high-level strategies with low-level operations, machine health and production goals are aligned synergistically rather than in opposition. Future refinements are anticipated to broaden industrial applicability, with advanced optimization techniques explored to further enhance longevity and outcomes. The foundation is laid for smarter, more sustainable manufacturing, where operational excellence is driven by health-aware control.