ValveGuard-Net: A VAE-LSTM Architecture for Early Fault Signatures, Time-to-Failure Projection, and Root Cause Pathway Analysis

Muhammad Usama, Mahnoor

Abstract

Industrial valve failures in process control systems can lead to catastrophic consequences including production losses, safety hazards, and environmental damage. This paper presents a novel predictive maintenance framework combining Variational Autoencoder-Long Short-Term Memory (VAE-LSTM) networks for real-time anomaly detection with advanced time-to-failure (TTF) prediction capabilities. Our approach leverages multivariate time series data from temperature indicator controllers (TIC) to detect subtle degradation patterns before critical failures occur. The VAE component learns a probabilistic latent representation of normal valve behavior, while LSTM layers capture temporal dependencies in sequential operational data. We introduce a cubic polynomial degradation model that tracks reconstruction error evolution to predict remaining useful life with 95% confidence intervals. The framework achieves 98.7% anomaly detection accuracy with a false positive rate below 5%, detecting anomalies on average 47.3 minutes before failure events. Additionally, we implement feature-wise reconstruction error analysis for root cause identification, revealing that process variable (PV) deviations contribute 62% to detected anomalies. Experimental validation on industrial valve datasets containing 7,023 normal operation sequences and 1,782 test sequences with known failures demonstrates the framework's superiority over traditional threshold-based methods, reducing unplanned downtime by an estimated 73% and maintenance costs by 45%. The proposed system provides interpretable diagnostics through contribution analysis, enabling operators to take targeted corrective actions. This work advances the state-of-the-art in industrial predictive maintenance by integrating probabilistic deep learning, temporal modeling, and prognostic analytics into a unified framework suitable for real-time deployment in Industry 4.0 environments.

Index Terms—Predictive Maintenance, Variational Autoencoder, LSTM, Anomaly Detection, Time-to-Failure, Industrial Valves, Deep Learning, Reconstruction Error, Root Cause Analysis, Industry 4.0