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Machine Learning Framework for Anomaly Detection and Maintenance Optimization in Large-Scale Cryogenic Systems

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Abstract:

CERN, home of the 27 km long LHC (Large Hadron Collider) particle accelerator, operates and maintains the world's largest cryogenic infrastructure. This complex system is essential to the LHC's functionality, reliability, and availability. Big data analytics and machine learning are promising techniques to extract descriptive and predictive models in complex systems for operation support, early identification of failures, and prescriptive maintenance.

We propose a machine learning framework for the anomaly detection and prescriptive maintenance of the LHC helium compression system. The initial proof of concept has been based on data acquired from 20 motor-compressor systems (12 low-pressure and 8 high-pressure) custom-made by Aerzen™ to meet CERN's cryogenic system requirements. Since their commissioning, all the principal operational parameters have been tracked and saved in a proprietary database owned by CERN. Furthermore, since 2016, these compressors have been subject to close monitoring via periodic analysis of vibrational data obtained using specific triaxial accelerometers. Measurements are manually taken at four points: two on the female rotor and two on the male rotor, and subsequently stored in a dedicated database. By using all those data, the proposed framework is designed with the aim of automatically detecting anomalies and estimating the RUL (Remaining Useful Life) of the compressor systems and their components. The objective is to ensure a longer lifespan for all the compressors, leading to savings in maintenance and operational costs.

The initial version of the framework, leveraging autoencoder (AE) architecture, renowned for its capacity to learn condensed representations of signals and subsequently reconstruct them, has been trained using data representing typical operational conditions. By learning to reconstruct the normal signal, any disparity between the AE's reconstruction and the actual collected signal in the test phase served as an indicator for measuring signal abnormalities. This approach has showcased encouraging results in systematically and consistently identifying anomalies and their underlying causes. Furthermore, the integration of a system capable of identifying and tracking potential issues with the aim of safely extending the service life becomes crucial as the motor-compressor systems will approach the 40,000 hours recommended maximal usage window before the next long shutdown and the planned major overhauling in manufacturer's premises.
Considering future applications, the algorithm has been engineered to be computationally efficient. This effort seeks to facilitate the integration of the developed model into compact, energy efficient IoT devices that can be used directly on-site to acquire and process data in real-time. Furthermore, this design paves the way for the integration of federated learning, an innovative privacy-preserving approach to machine learning that, through the aggregation of on-site generated models, allows for the continuous improvement of anomaly detection accuracy and reliability.
The proposed framework can potentially be extended to other cryogenic facilities given the large amount of data available and the secure and privacy-preserving federated learning platform available at CERN, to allow several IoT devices to share the model parameters to improve the global model robustness and accuracy for the use of all participating facilities.

Submitters Country

Switzerland

Author: CACACE, Paolo (Sapienza Universita e INFN, Roma I (IT))

Co-authors: REIS SANTOS, Diogo (CERN); GIUSTI, Lorenzo; SERIO, Luigi (CERN)

Presenter: CACACE, Paolo (Sapienza Universita e INFN, Roma I (IT))

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