Contribution ID: **79** Type: **Poster**

C2Po3D-05: Federated Learning Framework to support AI-Driven Prescriptive Maintenance in Large-Scale Cryogenic Infrastructures at CERN

Tuesday 20 May 2025 14:00 (2 hours)

CERN, home of the 27 km long LHC (Large Hadron Collider) particle accelerator, operates and maintains the world's largest helium cryogenic infrastructure. This complex system is essential to the LHC's functionality, reliability, and availability.
Big data analytics and machine learning have been successfully applied to CERN's cryogenic helium screw technology compressors. This approach tested the field, has proven to be a consistent way of extracting prescriptive maintenance models and estimating the Remaining Useful Life (RUL) of critical systems to identify anomalies and their underlying causes with the aim of avoiding costly operational disruptions.

Building on this foundation, we propose a decentralized framework based on Federated Learning (FL). Leveraging a client-server architecture, FL ensures data privacy by aggregating locally trained machine learning models, enabling collaborative model improvement without the need to share sensitive data between participants. CERN provides an optimal testing ground for the solution described, supported by the availability of CAFEIN, a FL platform independently developed at CERN, which will serve as the platform for model aggregation. Moreover, the LHC helium compression infrastructure offers a unique and distributed testbed composed by 20 motor-compressor units organized into five stations around the 27 km accelerator ring. The stations are further divided into low-pressure (Booster) and high-pressure (High Stage) compressor groups, each featuring distinct compressor models, providing a realistic environment to validate the developed solution.

In this setup, each compressor acts as a data source, streaming data into an edge device working as a local client. These edge devices train machine learning algorithms locally, which are then aggregated into global models based on the physical characteristics of the compressor analysed. This results in two distinct predictive models: one for the low-pressure compressors and another for the high-pressure ones. RUL estimation is then performed locally using a hybrid approach leveraging the compressor's reports and the proven autoencoder (AE) architecture combined with new solutions to take advantage of not only vibration data but also real-time operational data. The newly designed system is optimized to run on low computation edge device to perform analysis on-site and reduce model training power consumption with the aim of creating a ready to use distributed infrastructure that can be adapted to monitor other cryogenic facilities by leveraging the large amount of available data.

The application of CAFEIN FL and the developed algorithms offer a transformative approach to resource optimization, significantly enhancing the quality and robustness of RUL and prescriptive maintenance models as the number of participants involved increase, thanks to the proposed federated infrastructure. By enabling secure, privacy-preserving model training, this solution is an ideal candidate to be used across several international organizations and research centres operating with similar equipment. Paving the way to decentralize model development this infrastructure can incorporate a global range of data inputs without the need for data exchange, streamlining collaboration agreements and protecting sensitive information. The resulting models can be directly employed to optimize the maintenance and operational efficiency of facilities, leading to tangible benefits such as reduced downtime, extended equipment lifespans, CAPEX and OPEX cost optimization and minimized environmental impact. Ultimately, the developed solution powered by CAFEIN FL exemplifies how collaborative AI-driven strategies can foster innovation, sustainability, and economic efficiency in the industrial and research landscapes.

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))

Session Classification: C2Po3D - New Devices, Novel Concepts, and Miscellaneous II