Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI | Advanced Sensors and Instrumentation

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
October 24 – 27, 2022

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Idaho National Laboratory

Project Overview

Project Schedule

- October 1, 2018 – March 31, 2022 (including 12 month no cost extension)

Participants

- **Idaho National Laboratory**
  - Vivek Agarwal (PI)
  - Koushik A. Manjunatha
  - Cody M. Walker
  - Nancy J. Lybeck
  - Ronald L. Boring
- **Oak Ridge National Laboratory**
  - Pradeep Ramuhalli
- **Electric Power Research Institute**
  - Michael Taylor
- **Constellation (Utility Partner)**

- **Technical Point of Contact**
  - Richard B. Vilim (Argonne National Laboratory)

Project Overview

Implementation of digital monitoring in nuclear will require utilization of wireless sensors, online monitoring, and data visualization

Overview:

- A general methodology for techno-economic analysis of wireless sensor modalities.
- Application of data-based techniques for diagnostics and prognostics estimations.
- Identification of tools and visualization schema for getting the right information to the right person.
- Evaluation of cloud-based resources to enable additional cost savings.

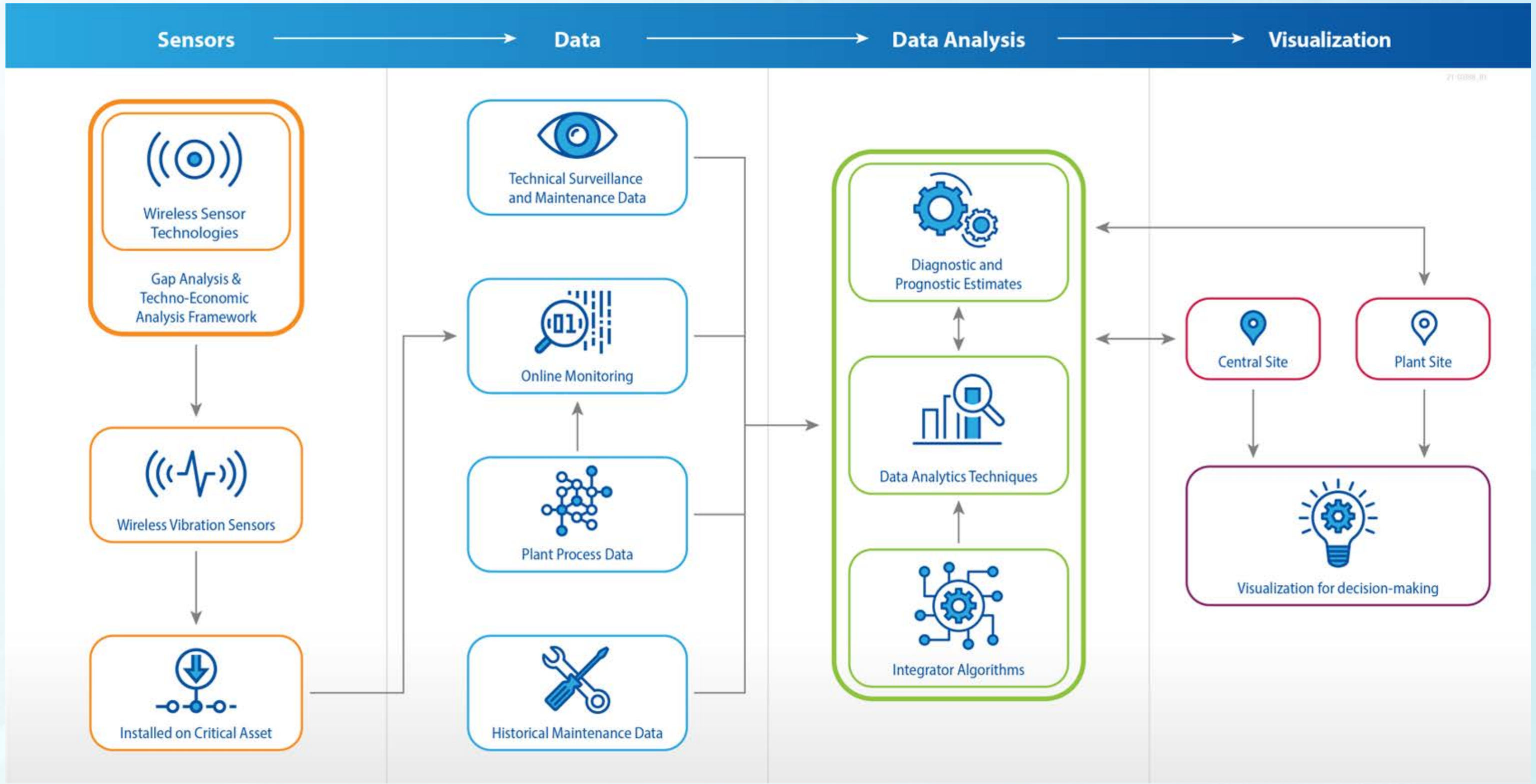

Figure 1. Steps for leveraging digital monitoring to enable cost-effective predictive maintenance for NPPs.

Technology Impact

Advances the state of the art for nuclear application

- Advances online monitoring at a nuclear plant site for different plant assets.
- Proposed a multi-band heterogeneous wireless architecture based on distributed antenna system.
- Provides machine learning approaches to integrate and analyze heterogeneous structured and unstructured data (i.e., analytics-at-scale).
- Visualization of information to make informed decision-making.

Supports the DOE-NE research mission

- Enable economical long-term operation of existing fleet of reactors.
- Research outcomes can be utilized to develop maintenance strategy for advanced reactors.
- Aligns with the DOE-NE mission to support application of artificial intelligence and machine learning to operation and maintenance of reactor technologies.

Impacts on the nuclear industry

- Enable industry to transition from preventive maintenance strategy to predictive maintenance strategy.
- Enhance reliability and economic operation of domestic existing fleet.
- Development of verified and validated tools to be adapted by advanced reactors.

Results and Accomplishments

Techno-Economic Analysis (TEA) allows the comparison of different network architectures to achieve desired capacity and coverage

- Wireless technologies differ in quality of service, latency, and bandwidth requirements.
- A one-size-fits-all solution may not be an option.
- A heterogenous network with diverse range of wireless technologies may be highly desired.
- TEA covers the operational and capital expenditures (OPEX and CAPEX) as well as the economic performance measures, total cost of ownership (TCO) and net present value (NPV).

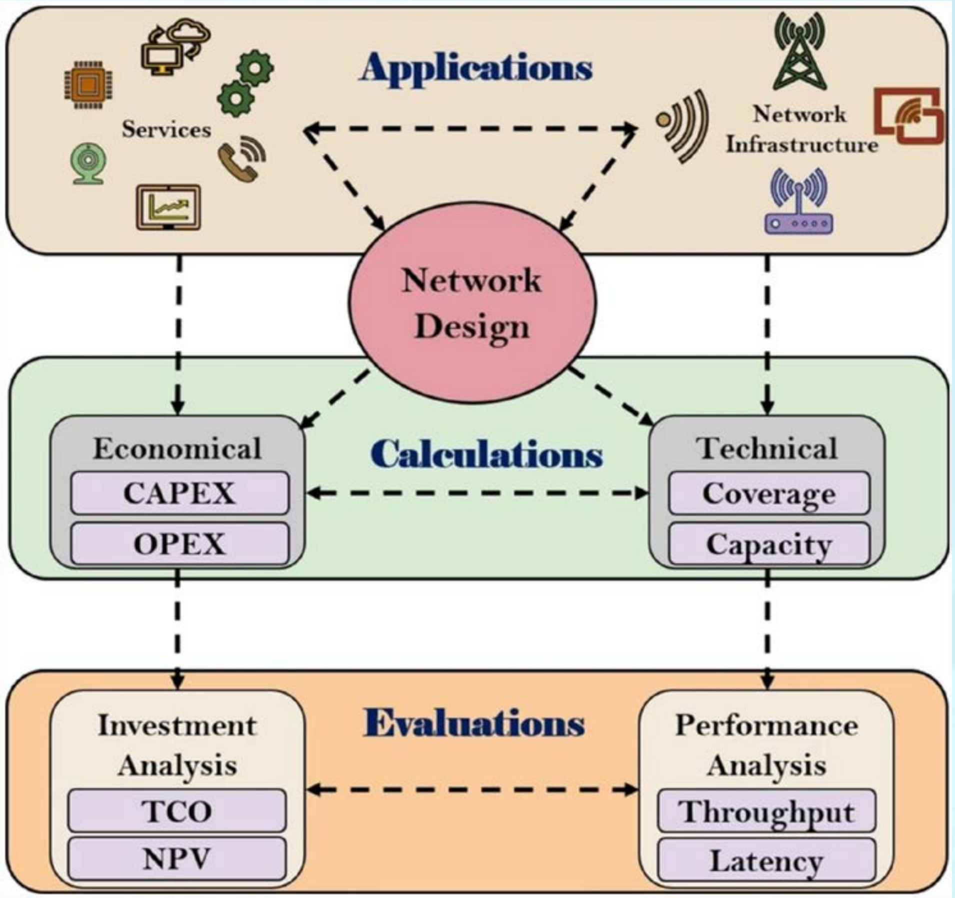

Figure 2. Flow diagram of TEA

Manjunatha, K. A., & Agarwal, V. Multi-band heterogeneous wireless network architecture for industrial automation: A techno-economic analysis. Wireless Personal Communications, 1–19, 2022.

Results and Accomplishments

The proposed system is predominantly Distributed Antenna System (DAS) or wireless local area network.

- High bandwidth and data transmission rates, with low latency
- Prioritized data transmission
- Provision for most of the wireless technologies to have either a Wi-Fi or DAS system as their back-end network
- Act as a bridge between end devices and the internet or an outside network
- Easy network maintenance by assimilating all the networking technologies into a single network architecture.

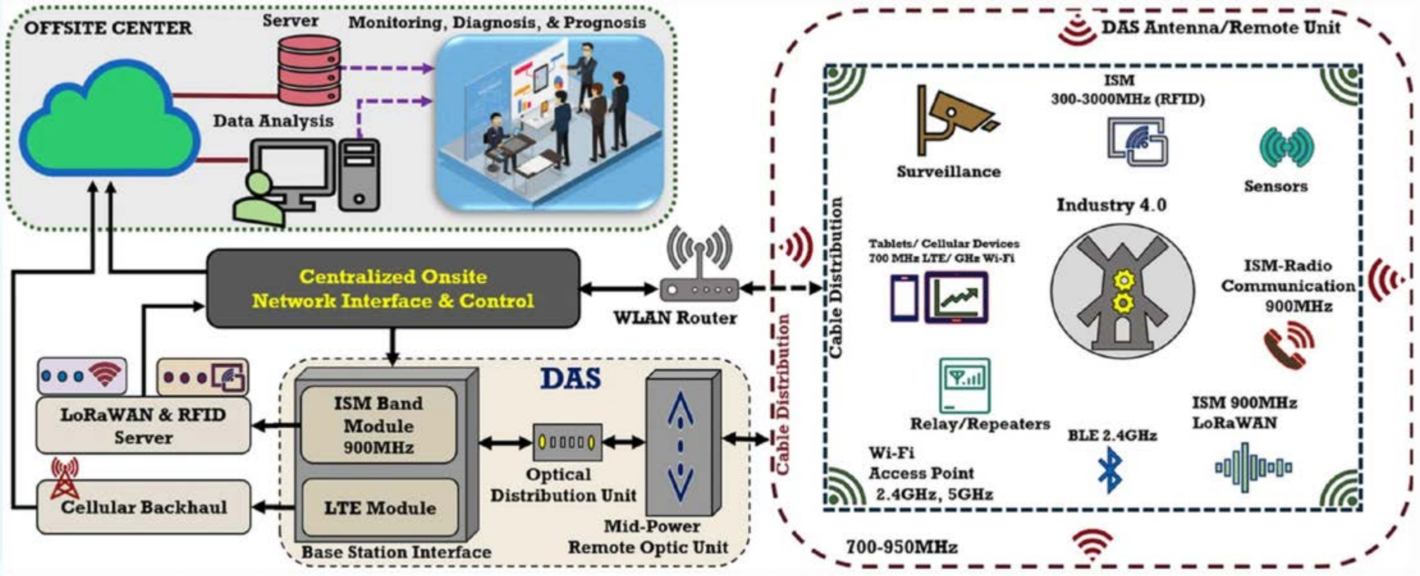

Figure 3. Proposed wireless network architecture.

Manjunatha, K. A., & Agarwal, V. Multi-band heterogeneous wireless network architecture for industrial automation: A techno-economic analysis. Wireless Personal Communications, 1–19, 2022.

Results and Accomplishments

Once the data have been collected, they must be analyzed to produce diagnostic and prognostic results.

- This research focused on a boiling water reactor's feedwater and condensate system.
- Feature selection included Shapley additive explanations.
- Three different ML methods (i.e., long short-term memory [LSTM] networks, support vector regression [SVR], and random forest [RF]) were employed to estimate two different forecast horizons (i.e., 1 hour and 1 day) for pump temperature.

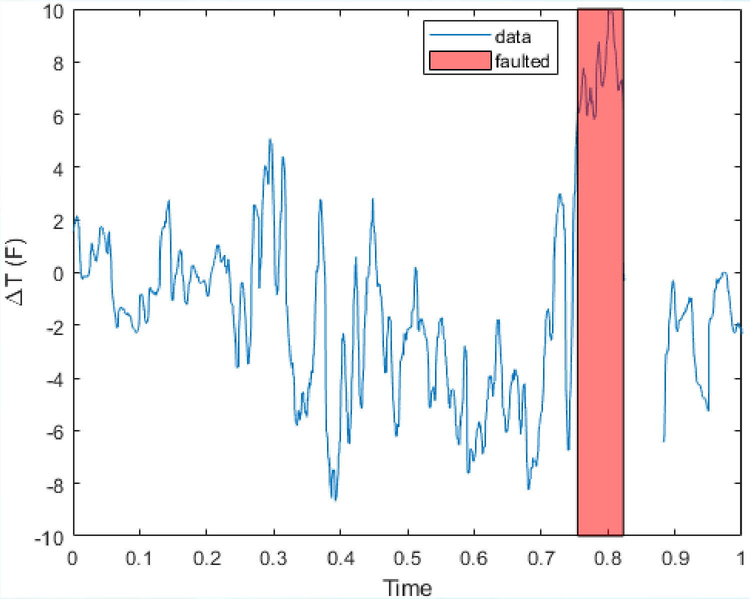

Figure 4. The average seasonal component temperature subtracted from the current component temperature.

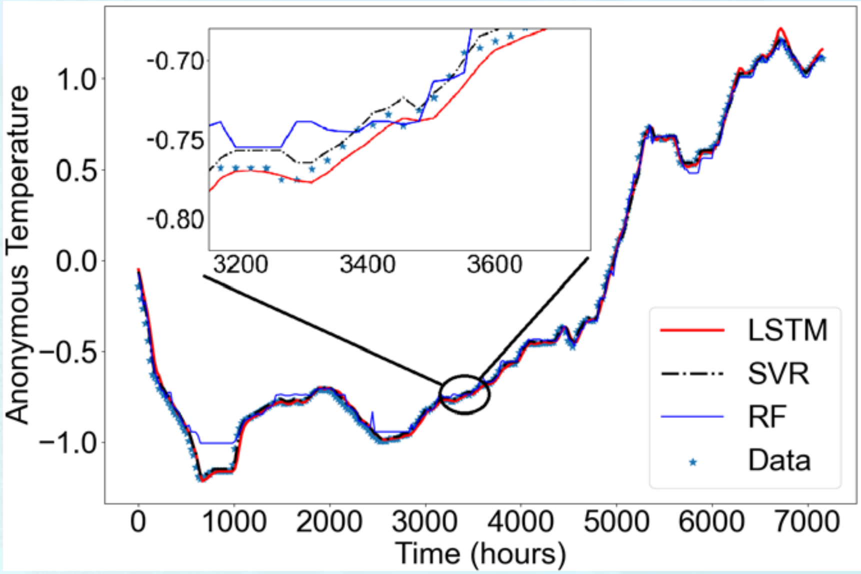

Figure 5. Predictions of pump temperature 1 day ahead, using the SHAP-determined input to LSTM, SVR, and RF models.

Walker, C., Ramuhalli, P., and Agarwal, V., Lybeck, N. L., and Taylor, M. Development of Short-Term Forecasting Models Using Plant Asset Data and Feature Selection, International Journal of Prognostics and Health Management, vol. 13, no. 1, June 8, 2022..

Results and Accomplishments

Data visualization should provide meaningful, actionable information to the human in the loop.

- Consequential information should clearly indicate if there is a significant deviation from an expected pattern.
- Interdependent information should be grouped meaning-fully.
- Dashboards displaying high-level information for monitoring plant conditions should also allow the ability to delve into additional lower-level information to provide context or specific historical data.
- There should be a clear distinction between measured and predicted information, since all predictive information entails some level of uncertainty.

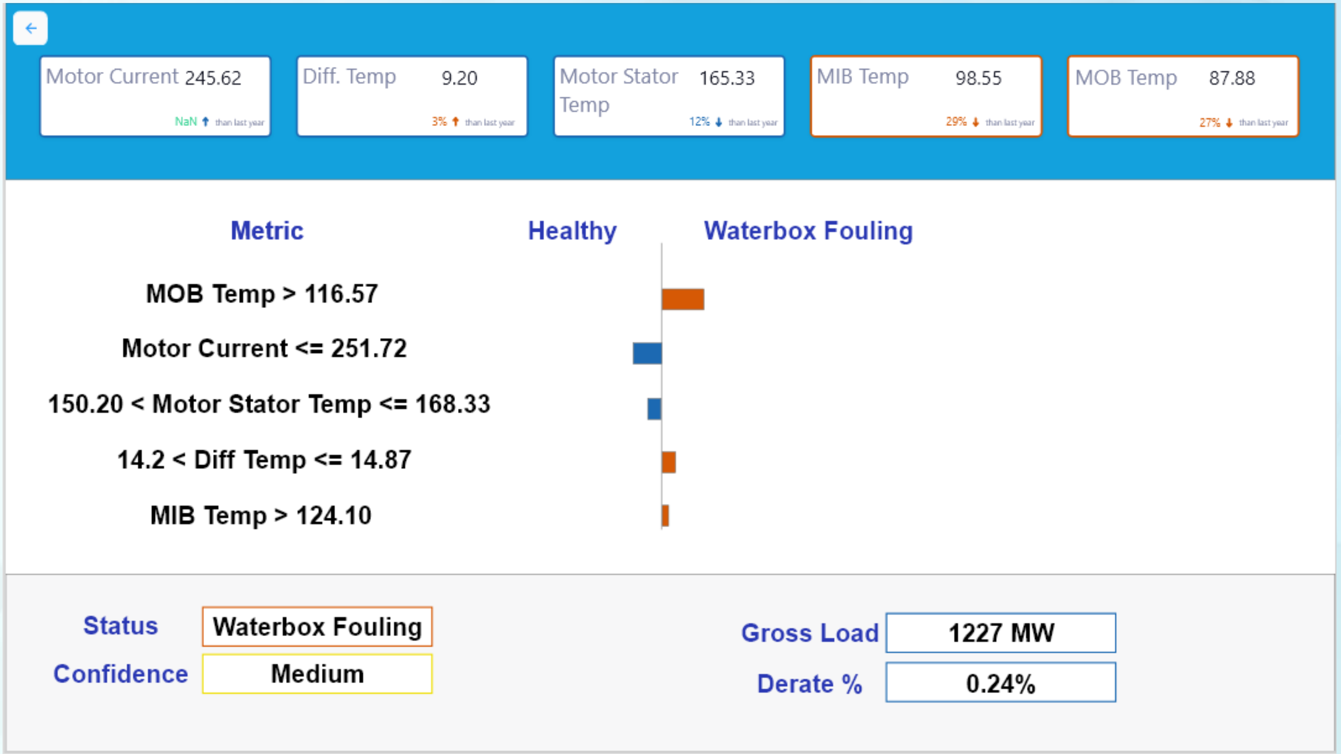

Figure 6. Prototype of machine learning output interface for quickly explaining model outcomes and feature importance.

Results and Accomplishments

Cloud computing may provide economic solutions for nuclear power operation through additional computing power and storage.

- Cloud-based services afford many new opportunities for transitioning to an offsite centralized maintenance and diagnostics (M&D) center.
- Cloud-based services offer things such as distributed denial of service protection, data storage, upgrading, patching, backups, monitoring, and monitoring.
- Cloud-based services also provide off-the-shelf AI tools for automated ML, anomaly detection, computer vision, and natural language processing.

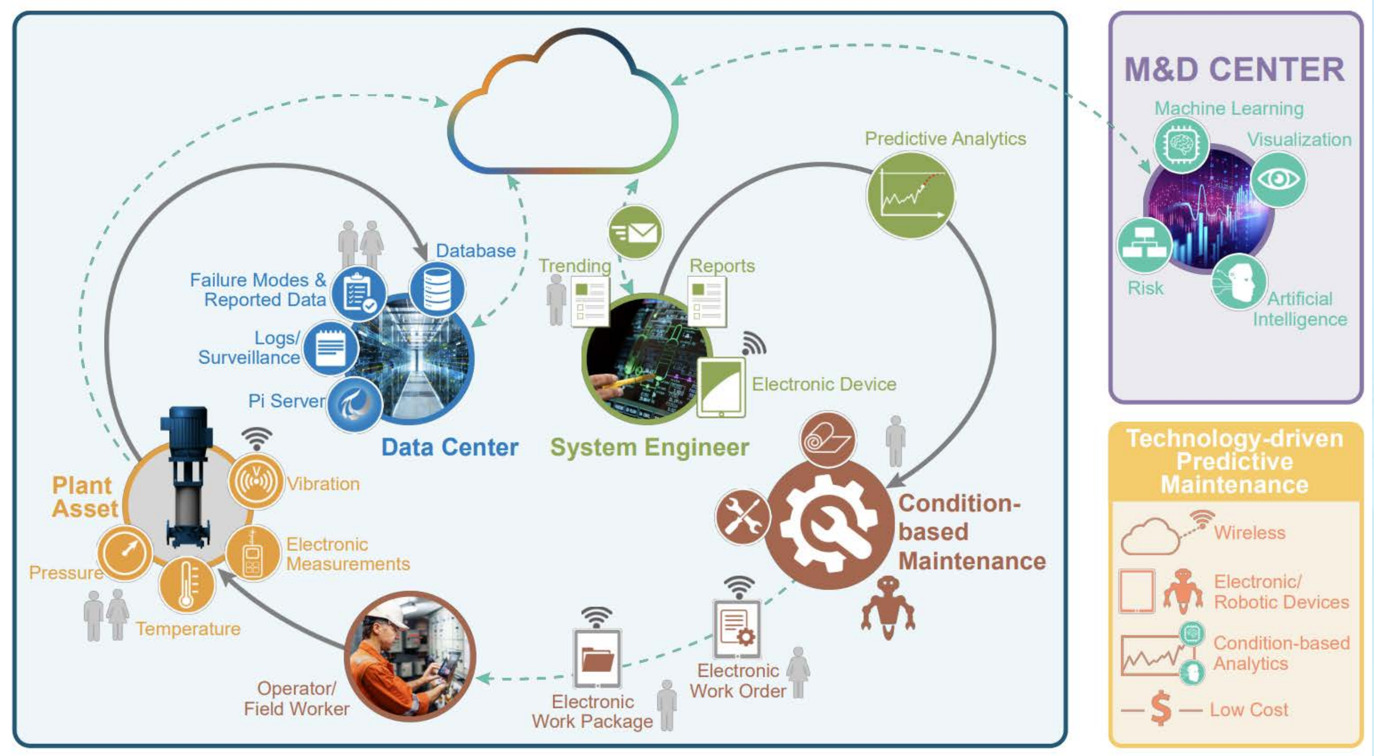

Figure 7. Example of how cloud computing services can be utilized to enable cost-efficient, predictive maintenance.

Walker C.M., P. Ramuhalli, V. Agarwal, N. Lybeck, M. Taylor. "Development of an end state vision to implement digital monitoring in nuclear plants. PHM Society Conference, Nashville, TN, November 1–4 2022.

Concluding Remarks

- Developed a techno-economic analysis framework to evaluate different wireless sensors.

- Developed diagnostic and prognostic models based on heterogeneous data sets from different plant sites:
  - Applied Shapley additive explanations (SHAP) values to understand importance of a feature
  - Applied Variance inflation factors (VIF) method to understand the level of multicollinearity among plant variables.

- Identified visualization gaps and standards to present information in right format to minimize information overload, enhancing informed decision-making.

- Complete end-to-end vision for conducting online monitoring as data are collected wirelessly, stored, preprocessed, modeled, and visualized using cloud computing services.

Open Challenges

- Challenges facing nuclear for implementing an online-based prognostic health management system:
  - Digitalization of infrastructure.
  - Communication and cybersecurity
  - Human in the loop.

- Explainability of artificial intelligence is also crucial for widespread industry adoption of emerging technologies.

Path Forward

- Cloud-based application to enable scalable predictive maintenance
  - INL, Blue Wave AI Labs, and Constellation.

- Development of a technical basis for explainability of artificial intelligence
  - INL and Public Services Enterprise Group, LLC.

- High Penetration Wireless Networking for Nuclear Power Plant Sensing
  - Operant Networks, INL, and Constellation.

- Development of multi-band wireless architecture to ensure coverage, connectivity, and co-existence among various communication technologies.

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Scientific Impacts

Publications

- Walker C.M., P. Ramuhalli, V. Agarwal, N. Lybeck, M. Taylor. “Development of an end state vision to implement digital monitoring in nuclear plants. PHM Society Conference, Nashville, TN, November 1–4 2022.
- Walker, C., Ramuhalli, P., and Agarwal, V., Lybeck, N. L., and Taylor, M. Development of Short-Term Forecasting Models Using Plant Asset Data and Feature Selection, International Journal of Prognostics and Health Management, vol. 13, no. 1, June 8, 2022.
- Manjunatha, K. A., & Agarwal, V. Multi-band heterogeneous wireless network architecture for industrial automation: A techno-economic analysis. Wireless Personal Communications, 1–19, 2022.
- Walker C.M., Ramuhalli, P., Agarwal, V., Lybeck, N., Taylor, M. Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization. 12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference. Providence, RI. June 13–17, 2021.
- Ramuhalli, P., Walker, C. M., Agarwal, V., Lybeck, N., Taylor, M. Nuclear Power Prognostic Model Assessment for Component Health Monitoring. 12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference. Providence, RI. June 13–17, 2021.
- Manjunatha, K. A., and Agarwal, V. ISM band Integrated Distributed Antenna Systems for Industry 4.0: A Techno-Economic Analysis. IEEE Global Communication Conference, December 2020.

Thank You

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