An Industrial IoT Approach to Enable Remote Asset Health Monitoring for Short Line Railroad Operators

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***Abstract*—This paper presents findings from a comprehensive two-part industrial case study focused on remote asset health monitoring and diagnostics in the railroad industry. The case study was carried out through a multiparty collaboration project between Ridgetop Group Inc. (Ridgetop), Reading and Blue Mountain Northern (RBMN) Railroad, and Innovative Operations Technology LLC in Port Clinton, PA. The first phase of the study, spanning March 2023 to August 2023, involved field testing Ridgetop's original Sentinel Motion Development Kit (SMDK). This kit comprises a wireless network of customized smart sensors that are mounted on Timken bearing end caps and transmit critical vibration and temperature data to a cellular-connected gateway system. The Linux-based gateway hosts Ridgetop's Sentinel MotionView software package for data acquisition, analysis, and sensor-gateway management. Results from this initial phase guided the research team in optimizing the custom sensor hardware design and it led to the development of new software analytics for near real-time monitoring and diagnosis of critical faults and anomalies associated with bearings, wheels, and track conditions. Encouraged by these results, Ridgetop undertook a redesign of the modular SMDK technology elements to align more closely with the IEEE 1856-2017 PHM Standard Framework for Prognostics and Health Management of Electronic Systems. The results from the second phase, spanning September 2023 to April 2024, details Ridgetop's completion of the hardware, firmware, and software redesign process as a means to realize the following eight functional blocks outlined in the IEEE 1856-2017 standard; 1) Sensors (S), 2) Data Acquisition (DA), 3) Data Manipulation (DM), 4) State Detection (SD), 5) Health Assessment (HA), 6) Prognostic Assessment (PA), 7) Advisory Generation (AG), and 8) Health Management (HM).**

Keywords—Railroad, Rolling Stock, Sensors, Internet-of-Things (IoT), Condition-based Maintenance (CBM), Prognostic Health Management (PHM), Near Real-time Monitoring, Vibration Analysis, Remote Asset/Fleet Health Management.

I. Introduction

The modernization of industrial operations through the integration of Internet of Things (IoT) technologies has revolutionized asset management practices across various sectors. As global reliance on rail infrastructure intensifies, need for advanced safety measures becomes paramount. Advanced monitoring systems, specifically those that capture vibration, temperature, and gyroscopic data play a crucial role in enhancing railroad safety and operational efficiency.

These systems are vital for maintaining reliable and safe rail transportation networks and represent a significant evolution from traditional reactive maintenance strategies to proactive, technology-driven approaches [1]. Real-time monitoring systems enable continuous surveillance of rail equipment and infrastructure conditions. Within such systems, vibration sensors detect anomalies indicative of mechanical wear or balance issues [2], temperature sensors monitor for overheating components that could lead to failures or fire hazards, and gyroscopes are essential for ensuring track geometry, integrity, and providing alerts for any deviations that might lead to derailments or other structural instabilities [3].

These technologies benefit railroad operations in two ways: (1) they enhance safety and reliability, and (2) they improve operations efficiency of railroad networks. By enabling condition-based maintenance (CBM)—where inspections and repairs are conducted based on the actual state of the equipment rather than predetermined schedules—rail companies can reduce downtime and maintenance costs.

This approach optimizes allocation of resources, extends the lifespan of rail components such as wheel bearings and the track itself, and supports better management of the rail system [5]. Integrating these data streams into a centralized monitoring system facilitates more informed decision-making for both passengers and freight rail entities. This proactive approach is becoming a cornerstone of modern rail management, pushing the industry towards safer and more efficient operations amid growing demands and the complexities of contemporary transportation networks [6].

Recent rail accidents such as the 2023 Odisha, India train collision and the East Palestine, OH, USA derailment underscore the critical need for such advanced monitoring systems. The Odisha collision in June 2023, one of the deadliest in recent history, resulted in over 290 fatalities and more than 1,000 injuries as a result of two trains colliding. Preliminary investigations suggested that signal failure and human error may have been the key errors in this situation. The enormity of this disaster underscores the potential benefits of CBM monitoring systems, which could provide immediate alerts regarding signal malfunctions or unauthorized track changes, potentially preventing such accidents. Similarly, in February 2023, a freight train carrying hazardous materials derailed in East Palestine, leading to a significant spill of toxic chemicals. This incident prompted evacuations and raised serious environmental as well as health concerns. The cause of the derailment was linked to a mechanical failure — an overheated wheel bearing or “hot box”. This incident highlights the importance of how temperature and vibration monitoring could detect and prevent overheating bearings before they lead to derailments. This type of mechanical failure is precisely what CBM aims to detect early on. Advanced sensor systems can continuously assess the condition of train components and track integrity, sending instant alerts if parameters deviate from their nominal values, thereby enabling preventative actions before a failure leads to an accident [7].

Adoption of these monitoring technologies not only mitigates risks but also provides environmental and societal benefits by enhancing system efficiencies, thereby supporting global sustainability efforts. However, the deployment of advanced monitoring technologies faces challenges, including high costs, complexities in data management, cybersecurity risks, and lack of standards that enable the adoption of new and emerging technology. Overcoming these challenges requires comprehensive strategies that incorporate technology integration, workforce training, and stringent regulatory compliance to safeguard sensitive data and ensure the effective use of these technologies [4].

This paper presents the culmination of a two-phase case study conducted in collaboration with Ridgetop Group Inc. (Ridgetop), the Reading and Blue Mountain Northern Railroad (RBMN), and Innovative Operations Technology, and discusses Ridgetop’s comprehensive framework for integrating advanced monitoring and analytics technologies into existing railroad operations – Sentinel Motion for Rail. The goal of the technology is to offer actionable insights and recommendations that can be adopted by rail operators worldwide to enhance safety and efficiency, ultimately contributing to the evolution of global rail infrastructure. The first phase of the study, conducted between March 2023 and August 2023, focused on the deployment and evaluation of Ridgetop's original Sentinel Motion Development Kit (SMDK) within the railroad environment. This phase entailed the installation of a wireless network of customized smart sensors on the end caps of Timken bearings (Figure 1), transmitting critical vibration and temperature data to a centralized gateway system. Leveraging the Linux-based Sentinel MotionView software package, the research team conducted comprehensive data acquisition, analysis, and sensor-gateway management, yielding valuable insights into asset health and performance.

Building upon the insights garnered from the initial phase, the study progressed to its second phase, spanning September 2023 to April 2024. In this phase, Ridgetop undertook a comprehensive redesign of the SMDK technology elements, aligning them with the IEEE 1856-2017 PHM Standard Framework for Prognostics and Health Management of Electronic Systems. This redesign process encompassed hardware, firmware, and software enhancements, aimed at optimizing the functionality of the monitoring system across the eight key functional blocks outlined in the IEEE standard.

By presenting the findings of this case study, this paper contributes to the growing body of knowledge on IoT-enabled asset monitoring in the railroad industry. Through a detailed examination of the technology background, technical approach, results, and summary of the study, insights are provided to inform future advancements in remote asset health monitoring and diagnostics within critical infrastructure sectors.

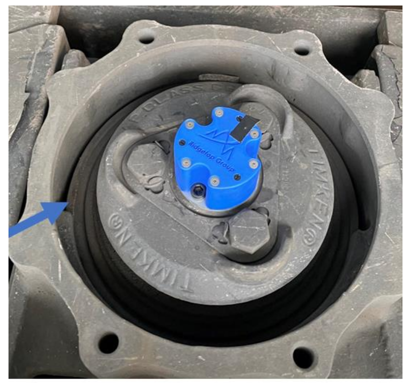

Figure 1: Mounting location of wireless smart sensor when installed on a Timken Bearing end cap.

II. Technology Background

The Sentinel Motion technology stack represents a significant advancement for remote asset health monitoring and analysis, particularly within industrial IoT applications such as the railroad industry. Ridgetop’s story with this technology was first published in 2015, where Ridgetop was awarded multiple Small Business Innovation Research (SBIR) contracts to explore the use of MEMS-based wireless accelerometer sensors to detect gear tooth faults in helicopter transmissions [9]. Recognizing the critical nature of transmission failure, which can lead to catastrophic outcomes, the research focused on the sensor’s capability to provide precise and reliable data under extreme operational conditions. The sensors had to be small enough to fit in the confined spaces of a helicopter gearbox yet robust enough to handle the high vibrations and variable temperatures of flight operating conditions. The successful implementation of these sensors demonstrated their potential to significantly enhance the safety and maintenance protocols in aviation by providing actionable intelligence on gear health when performing feature data extraction on different vibration analysis methods. In 2015, to advance the NASA prototype, Hofmeister et al. developed a wireless triaxial MEMS-based sensor that was tested at the Transportation Technology Center, Inc. (TTCI), which is now MxV Rail in Pueblo, Colorado [10]. This new sensor design targeted the measurement of vibration and speed on rotating shafts, critical for monitoring the health of industrial machinery. The integration of IoT enabled the sensors not only to collect data but also to communicate it instantly across networks, facilitating remote monitoring and diagnostics. That publication also detailed the development of advanced calibration techniques that allowed the sensor to be adjusted for dynamic conditions of industrial use, thereby enhancing the accuracy and reliability during the data collection process. In 2018, the research shifted towards tailoring the sensor design for even more challenging operating conditions within aerospace and railroad applications [11]. These settings demanded sensors that could endure not just extreme vibration, but also significant thermal fluctuations and mechanical shock as identified in the IEC-61373 Category 3 standard for axle mounted shock and vibration requirements in railway applications. This study highlighted how an updated hardware manufacturing process was implemented to enhance the durability of the sensor circuitry, including the use of specialized materials for thermal stability and vibration damping. Modifications also focused on miniaturization and power efficiency, essential for applications where Size, Weight, and Power (SWaP) are of critical importance. In 2019, Hofmeister et al. continued to concentrate on ruggedizing the MEMS-based sensors specifically for rolling stock applications [12]. This phase of development tackled the harsh conditions of rail transport, where sensors must withstand continuous vibration in addition to extreme shock, weather, and electromagnetic interference. This study highlights the use of composite materials for the sensor casings, which provided the necessary ruggedness while maintaining sensor sensitivity. It also highlighted the implementation of advanced signal processing algorithms to filter out the environmental noise, ensuring that the data remains accurate and reliable. This evolution of the RotoSense hardware design has been shown in Figure 2 below.

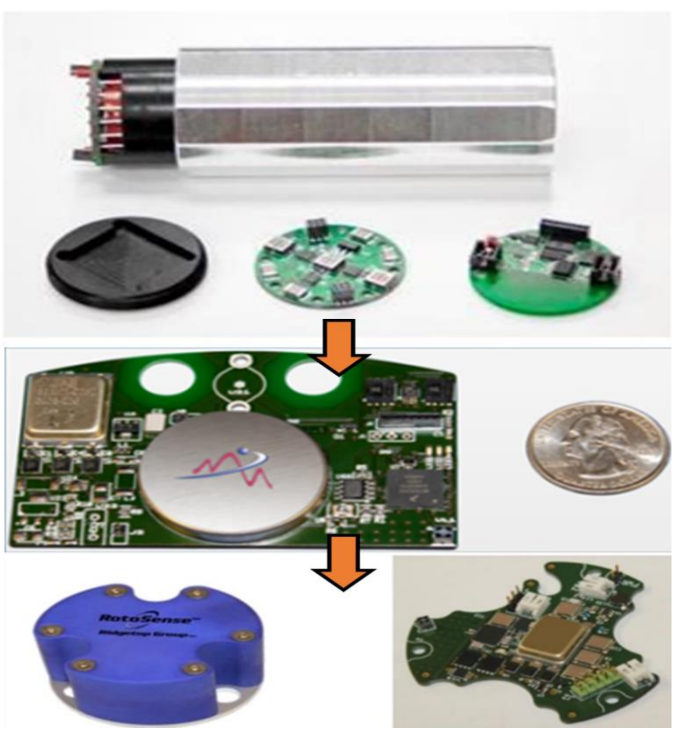

Figure 2: Evolution of Ridgetop's RotoSense module in the last decade – top panel shows the sensor design in 2010-2016, middle panel shows the sensor design in 2018, and the bottom panel shows the sensor design post 2018.

Today, RotoSense has continued to evolve into a network of different IoT-enabled smart sensors that are designed to monitor not only acceleration and vibration, but also temperature, gyroscope, GPS location, and other custom data signatures depending on the application. The various data streams are all controlled and acquired through a central data management and control hub – the Sentinel Gateway device utilizing various IoT communication protocols such as low-power WiFi [13] , Bluetooth Low Energy (BLE), Zigbee, and other commonly used IoT protocols supported by Linux operating systems. Furthermore, the Sentinel Gateway hosts the web-based Sentinel MotionView software package that allows wireless sensor communication and data acquisition (DA), management, and visualization of key data analytics and alerts for the monitored asset. When user defined thresholds for feature data are crossed, the Sentinel MotionView software generates alerts and notification for anomalies and cases of potential equipment failure. This three-part solution is visualized in Figure 3 and Figure 4.

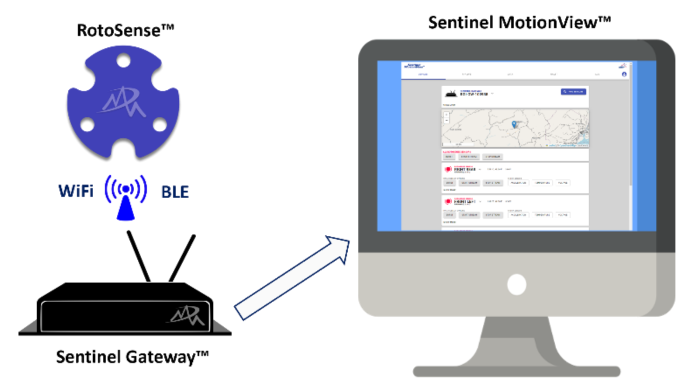

Figure 3: Ridgetop's Sentinel Motion Development Kit (SMDK) comprising RotoSense smart sensors, the Sentinel Gateway data management and control hub, and the Sentinel MotionView software platform on any machine for advanced analytics, visualization, and alerts.

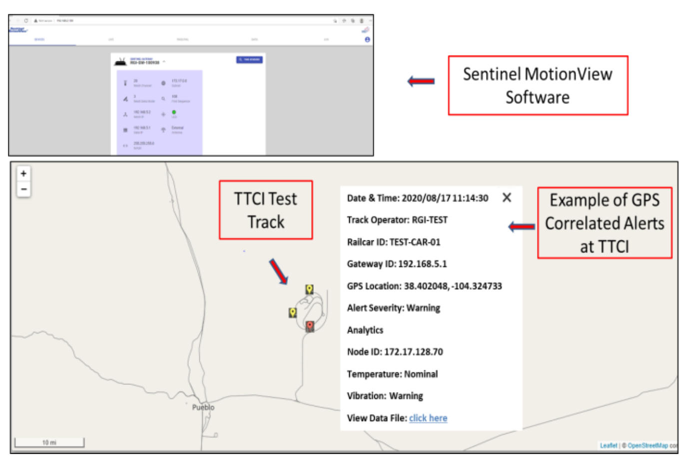

Figure 4: Example of GPS data and alert correlation at the high tonnage-loop at the Transportation Technology Center Inc. (TTCI) in Pueblo, Colorado.

III. Technical Approach

Figure 5 displays the framework for the IEEE 1856-2017 PHM Standard [8], which has significantly helped various industries and market segments conceptualize core operational processes and functional blocks that are required to develop a complete PHM solution. When designed and implemented correctly, this framework allows reliability engineering teams and practitioners to carefully assess the health of any given system, predict its future state, and recommend maintenance actions to ensure reliability and safety. The framework is divided into two main columns: (1) Core PHM Operational Processes and (2) PHM Functional Model, with the latter being subdivided into Functional Blocks corresponding to each operational process. At the base, sensors gather performance data, which is then acquired and manipulated into usable health state information. This data is analyzed to assess current health and predict future states. Advisories are generated to inform maintenance actions, culminating in actions to restore or maintain system health. This hierarchical model ensures continuous monitoring and proactive management of system reliability and safety.

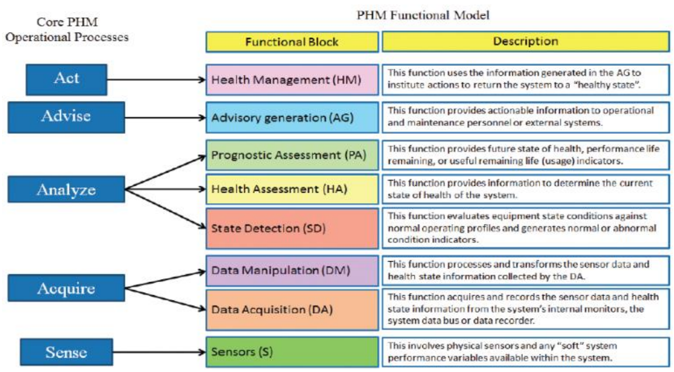

Figure 5: IEEE 1856-2017 Standard Framework for Prognostics and Health Management of Electronic Systems comprising five operational processes (Sense, Acquire, Analyze, Advise, Act) and their corresponding functional blocks [8].

As detailed throughout this paper, Ridgetop's Sentinel Motion technology has been redesigned to incorporate all essential functional blocks and core PHM operational processes in accordance with the IEEE 1856-2017 PHM Standard Framework [8]. This redesign targets a specific industrial IoT application focused on monitoring bearings, wheels, and track conditions within the railroad industry. This holistic approach ensures the maintenance of integrity and performance of crucial equipment in railroad settings. Implementing Sentinel Motion involves installing RotoSense smart sensors on the end caps of Timken or Hyatt wheel bearings to gather condition-based data (CBD) essential for daily railroad operations. This data is subsequently sent to the Sentinel Gateway for local storage, analysis, and visualization via the Sentinel MotionView software platform. The comprehensive technology stack shown in Figure 6 is designed to meet the specific needs of remote asset monitoring in challenging environments, and is further discussed in relation to the IEEE 1856-2017 standard.

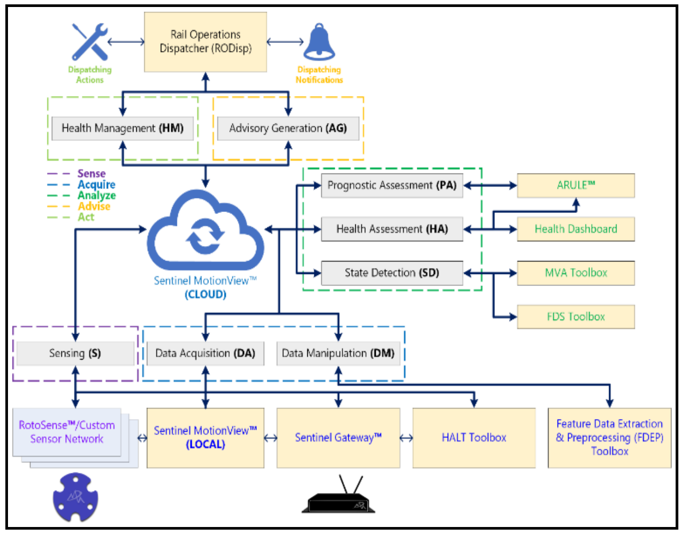

Figure 6: Ridgetop's Sentinel Motion technology comprising RotoSense smart sensors, the Sentinel Gateway data management and control hub, and the Sentinel MotionView software platform on any machine for advanced analytics, visualization, and alerts.

A. *Sentinel Motion Development Kit (SMDK)*

The Sentinel Motion Development Kit (SMDK) represents a sophisticated integration of hardware, firmware, and software components that aim to facilitate the deployment of RotoSense smart sensors, the Sentinel Gateway, and the Sentinel MotionView (SMV) software platform. The main goal of this technology stack is to assist with the 'Sense (S)' and 'Data Acquisition (DA)' functions essential for effective real-time data management in industrial settings. It enables the acquisition, control, and supervision of diverse data streams such as acceleration, gyroscope, temperature, and GPS coordinates, providing a comprehensive monitoring solution for critical assets and equipment. The system's user interface, showcased in Figure 7, offers an intuitive graphical user interface (GUI) that simplifies the interaction with these complex data streams, making it accessible and user-friendly.

The SMDK also incorporates advanced features for automated testing and analysis across various operational modes, enhancing flexibility and control for technology end users. It includes a low-power sleep mode to optimize battery usage, crucial for long-term, uninterrupted monitoring tasks. Within the GUI, operators can define thresholds for key parameters like acceleration and temperature, where the RotoSense smart sensors remain inactive during sleep mode but are triggered to send data and alerts when these parameters breach set thresholds. This intelligent power management illustrated in Figure 8 and ensures that the system is both energy-efficient and responsive to critical changes in the monitored system or subsystem.

In the context of industrial IoT applications for the railroad industry, the capabilities of the SMDK translate into substantial benefits. For instance, its ability to monitor temperature and acceleration data in real-time is vital for hot box detection, where overheating of axle bearings can lead to catastrophic failures or derailments as observed with the East Palestine Derailment. Similarly, the system's sensitive impact detection capabilities are crucial for identifying wheel impact load issues, which can signify uneven rail surfaces or wheel defects. Moreover, the integration of GPS and gyroscopic data helps in pinpointing and analyzing track geometry issues, ensuring timely maintenance and reducing the risk of derailments. Overall, the SMDK's robust data acquisition and management capabilities enhance safety, efficiency, and reliability in railroad operations, making it an invaluable tool in the maintenance and monitoring of critical railway infrastructure.

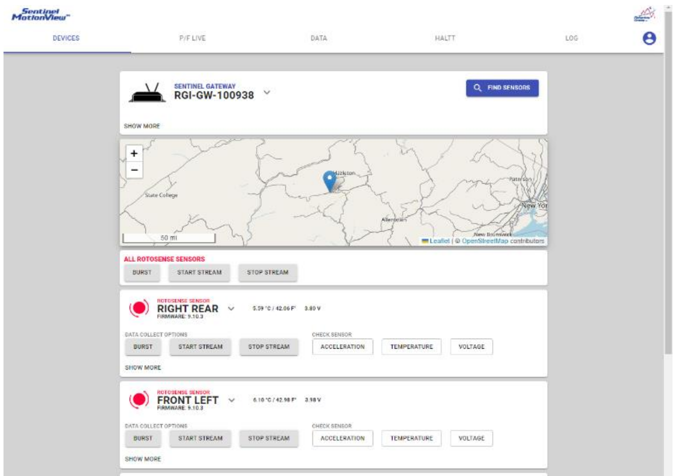

Figure 7: Sentinel MotionView (SMV) web-based Graphical User Interface (GUI) for storage, management, and control of data between RotoSense smart sensors and the Sentinel Gateway device.

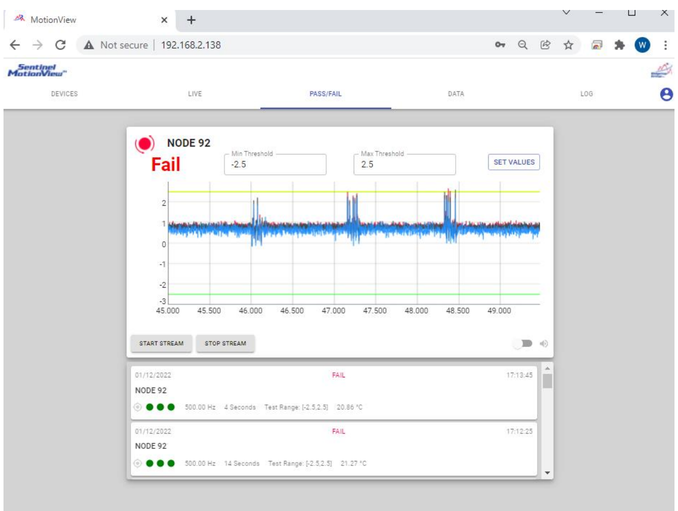

Figure 8: An example of using automated testing and analysis using data threshold in the SMV GUI.

B. *Highly-Accelerated Life Testing (HALT) Toolbox*

The HALTT (Highly-Accelerated Life Testing) Toolbox as shown in Figure 9, is a new GUI capability that was designed to expedite and simplify the process of scheduling and monitoring accelerated life tests. Its main function is to assist with the DA functional block. The HALTT Job Scheduler (HJS), is the central component of the toolbox, which offers a user-friendly and comprehensive scheduling system. The interface allows users to navigate easily through the process of setting up a test. It includes options to show an upcoming job, thus providing a clear overview of scheduled tests. Some other key elements of the HJS interface include: (1) Node Select: Dropdown menu to select the specific sensor node to be tested, (2) Data Collect Mode: Dropdown menu to select the preferred data collection mode for the sensor, (3) Start/End Time: Datetime fields for defining the test's duration, (4) Interval Type and Interval N: Inputs facilitating the definition of testing intervals, where the N value specifies the numerical frequency of the interval., and (5) Streaming Duration: Input to decide the duration of streaming data collection, provided in seconds. Beneath the scheduler, a status message indicates the upcoming jobs, thereby keeping the testing team informed and prepared. The simplicity of the HALTT interface belies its powerful functionality, providing a seamless integration into the workflow of reliability engineers and technicians.

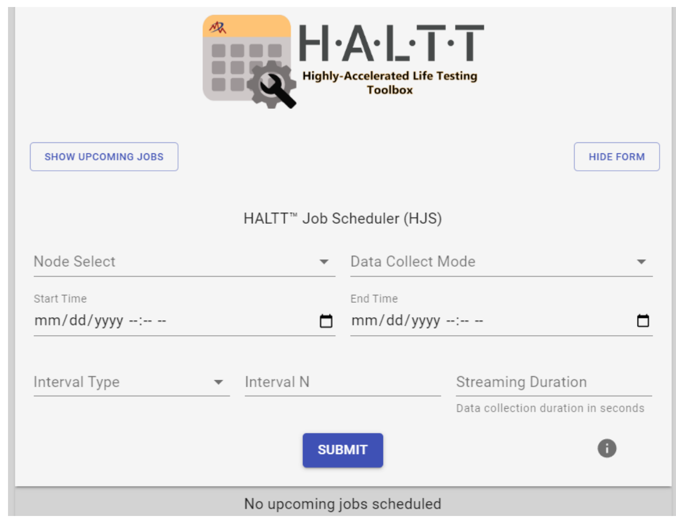

Figure 9: HALTT (Highly-Accelerated Life Testing) Toolbox Graphical User Interface (GUI).

C. *Feature Data Extraction & Preprocessing (FDEP) Toolbox*

The Feature Data Extraction & Preprocessing (FDEP) toolbox within the Sentinel MotionView software platform serves as a foundational suite of scripts tailored to refine and prepare data during its initial processing stages. This toolbox plays a pivotal role in the Data Manipulation (DM) functional block, transforming large amounts of raw sensor data into actionable insights. Through signal conditioning techniques such as filtering, isolation, and smoothing, the FDEP toolbox enhances data quality by removing noise and, where necessary, normalizing data to a common scale to facilitate analysis. Beyond basic statistical measures, the FDEP toolbox extracts an extensive range of domain-specific condition indicators from the cleaned data. These indicators span both time-domain features—like Mean, RMS, and Variance—and frequency-domain features, including Fast Fourier Transform (FFT) and Power Spectral Density (PSD), gained through detailed Fourier and wavelet analyses. This comprehensive approach to feature extraction ensures that nuanced characteristics of the gear and bearing signals are captured, providing a detailed overview of equipment condition.

Integrating vibration analysis methods, as demonstrated in the study on shaft-mounted accelerometers [16], significantly augments the diagnostic capabilities of Sentinel MotionView, especially in the local fault diagnosis of geared systems. These accelerometers capture enhanced vibration signals that are critical for the early detection and precise localization of mechanical irregularities, which are pivotal for maintaining operational reliability and efficiency in railroad settings. The early detection capabilities help avert costly breakdowns and enhance safety by identifying potential gear damages, such as broken teeth or other localized faults, before they lead to system failures.

Furthermore, Sentinel MotionView's advanced vibration analysis tools, will continue to be updated to include techniques like the Speed Based Resampling Scheme (SBRS) and Continuous Wavelet Transform (CWT), which are adept at handling the variable load and speed conditions typical in railroad environments. These methodologies allow for accurate fault diagnostics under non-stationary conditions, adapting to real-world operational variations and ensuring reliable monitoring. By leveraging these sophisticated vibration analysis techniques, Sentinel MotionView offers more accurate diagnostics, enhances anomaly detection, and supports effective maintenance strategies.

D. *State Detection with Feature Data Selection (FDS) Toolbox*

The Feature Data Selection (FDS) toolbox is another collection of software routines and Python scripts that assist with the State Detection (SD) functional block. Following the Feature Data Extraction & Preprocessing (FDEP) phase, the FDS toolbox specializes in isolating the most pertinent features from a preprocessed dataset. This refined selection is imperative for constructing high-fidelity predictive models, ensuring that only the most informative and discriminative features are employed, thereby reducing computational overhead and avoiding model overfitting. Utilizing a suite of algorithmic strategies, the FDS toolbox encompasses dimensionality reduction techniques to eliminate redundant information, ranking and filtering methods to prioritize features based on statistical significance, and embedded techniques that inherently consider feature relevance.

E. *State Detections with Multivariate Analysis (MVA) Toolbox:*

The Sentinel MotionView software package has also been redesigned to include a sophisticated state estimation toolbox that leverages Multivariate Analysis (MVA) algorithms, providing an advanced approach to anomaly detection and diagnostics for critical components such as bearings, wheels, and track features in railroad operations. As shown in Figure 10 this toolbox encompasses various MVA techniques as highlighted in multiple publications from Szidarovski et al. [14][15], each tailored to enhance the precision of health monitoring systems by evaluating multiple data streams simultaneously. The key algorithms employed include the Multivariate State Estimation Technique (MSET), Auto-Associative Kernel Regression (AAKR), and methods based on the Mahalanobis distance, all of which utilize specially defined distance measures to compare the current operational data against a baseline of healthy system data.

These MVA methods are instrumental in identifying deviations that indicate potential faults and degradation before they lead to failure, thus supporting proactive maintenance strategies. By employing techniques such as least squares for MSET, nonparametric Kernel estimation for AAKR, and covariance matrix analysis for Mahalanobis distance, the toolbox enables a comprehensive analysis of the multivariate data collected from sensors. This approach not only helps in pinpointing the exact nature and location of an anomaly but also enhances the diagnostic capabilities of the system by providing a more detailed assessment of the current state of the equipment when compared against a known healthy system.

The benefits of integrating these MVA algorithms into Sentinel MotionView are substantial. They allow for a holistic view of system health by considering the interrelations among various sensor measurements, thus avoiding the pitfalls of single-dimensional analysis which may overlook critical interactions that are indicators of potential issues. This multivariate approach enhances the accuracy of anomaly detection and diagnostics, leading to more reliable and timely interventions. Consequently, it aids in maintaining the operational readiness of railroad components, ensuring safer and more efficient rail operations.

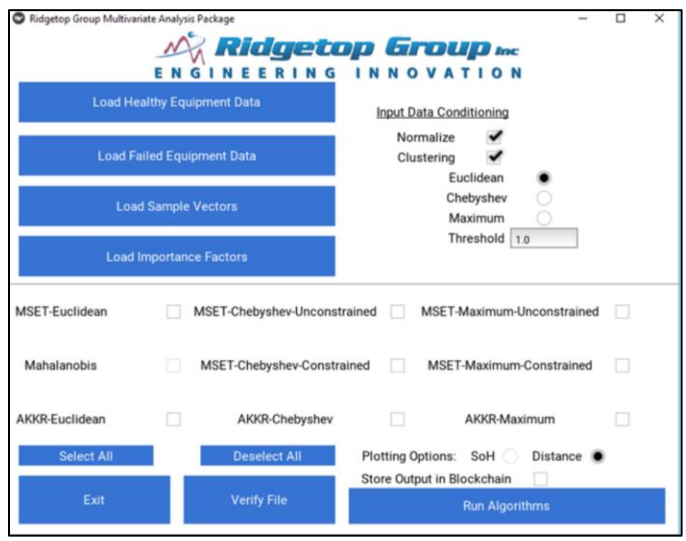

Figure 10: GUI View for Multivariate Analysis (MVA) Toolbox.

F. *Health Assessment and Prognostic Assessment with ARULE:*

ARULE, standing for Advanced Remaining Useful Life Estimation, is a key component of Ridgetop's Prognostic Health Management (PHM) solutions, designed to evaluate complex systems and predict their operational futures. It efficiently processes extracted feature data to showcase a clear Fault-to-Failure Progression (FFP) signature and key prognostic indicators such as Remaining Useful Life (RUL), State-of-Health (SoH), and Prognostic Horizon (PH). An example of its application is illustrated in Figure 11, where ARULE processes Time Synchronous Averaging (TSA) signals extracted from RotoSense data to forecast failures in helicopter gearbox systems. This predictive capability is vital for maintenance teams, enabling them to implement predictive maintenance schedules effectively and prevent catastrophic failures.

When fully integrated into the Sentinel MotionView software platform for specific IoT applications, ARULE enhances its functionality by aligning with the IEEE 1856-2017 standard for Prognostics and Health Management of Electronic Systems. This integration allows for continuous monitoring and accurate prediction of the lifespan and reliability of system components, which are essential for proactive maintenance planning. The system's adaptability to dynamically update predictions based on real-time data ensures the accuracy and relevance of its outputs, preventing unexpected downtime and extending equipment life.

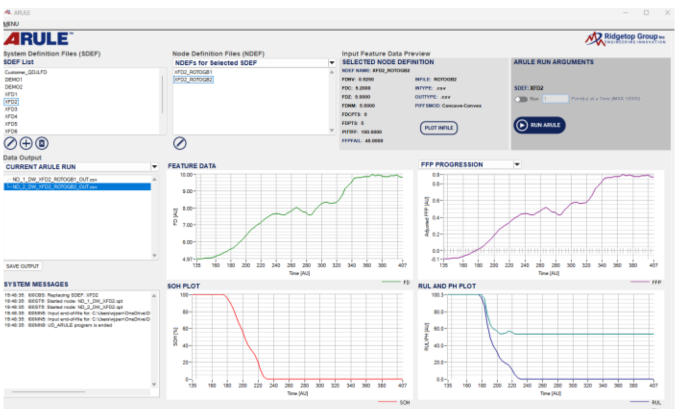

Figure 11: GUI View for Adaptive Remaining Useful Life Estimation (ARULE) software for determining SoH, RUL, and PH from feature data extracted from RotoSense.

G. Advisory Generation and Health Management:

As demonstrated throughout this paper, Ridgetop Group has implemented significant enhancements to the system architecture of Sentinel MotionView to integrate previously existing technology elements under a single collection of hardware, firmware, and software tools. Another key development that is still ongoing, is the integration of an advanced dashboard visualization which aggregates and displays data from Sentinel Motion Development Kits (SMDKs) deployed across a network of trains and locomotives. This dashboard facilitates the streamlined monitoring and management of a comprehensive array of gateways and sensors that are essential for assessing the health of railway systems.

The dashboard incorporates several essential features to enhance its technical utility including such as User Profile Management, which maintains and allows access to vital contact information, supports effective communication, and timely alerting of key personnel in case of system advisories or failures. Alert Threshold Settings can also be adjusted based on different data types and frequencies, enabling proactive responses to emerging issues through timely notifications. Additionally, an API that enables Data Export to third party software platforms extends the system's capabilities by allowing the export of critical data and alerts, such as GPS information, to SQL databases for further analysis and integration with other asset management systems used by the railroad. As shown in a previous software implementation in Figure 12, the AG and HM dashboard has been designed to be both functional and user-friendly, with intuitive navigation and clear displays that provide rapid insights into the health and operational status of connected devices.

To further improve the AG and HM functional blocks, the integration of predictive analytics and machine learning algorithms will be explored by the Ridgetop research team. Specific methods that are currently being explored include Random Forest Regression, clustering algorithms, predictive forecasting, and classification algorithms to create decision trees or neural networks. These technologies will help analyze both historical and real-time data to anticipate potential system failures, and could help establish a feedback loop that records and analyzes maintenance outcomes that enhance the accuracy of predictive models and the effectiveness of maintenance schedules.

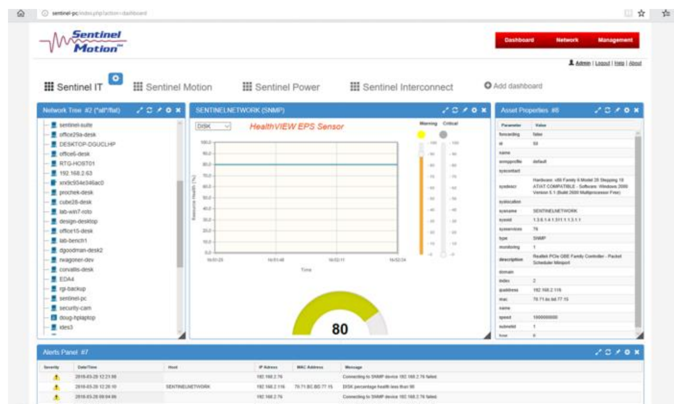

Figure 12: Dashboard Visual displaying network tree of monitored sensor nodes, alert log, and real time visualization of system or subsystem degradation.

IV. RESULTS

Throughout the pilot study conducted with Reading and Blue Mountain Northern (RBMN) Railroad and Innovative Operations Technology, Ridgetop Group has identified several key insights into monitoring bearings, wheels, and track conditions within the railroad industry. This multi-phase study began with deploying and field-testing Ridgetop's original Sentinel Motion Development Kit (SMDK). Initially designed primarily as a functional data acquisition system, the first phase involved rigorous testing of smart sensors mounted on Timken bearing end caps, critical for transmitting raw vibration and temperature data to a cellular-connected gateway.

The insights and lessons learned from this initial testing phase were crucial in optimizing the sensor hardware and spurred the development of new software analytics for near-real-time monitoring and diagnosis of critical faults. These enhancements addressed the operational challenges and environmental stresses identified during testing, providing a more comprehensive understanding of the mechanical stresses railway components endure. As a result, Ridgetop undertook a large scale system redesign of the SMDK's components to align closely with the IEEE 1856-2017 PHM Standard Framework.

The second phase of the study, running from September 2023 to April 2024, demonstrated successful integration for many of these components into a unified system as shown in Figure 13 and Figure 14. It is important to note that the collaboration with RBMN and Innovative Operations Technology is still an ongoing engineering effort that continues to refine and customize the different aspects of the PHM solution. This ongoing development is aimed at tailoring the technology blocks to further meet the evolving needs of the railroad industry while also adhering to the core PHM operational processes in the IEEE 1856-2017 PHM standard.

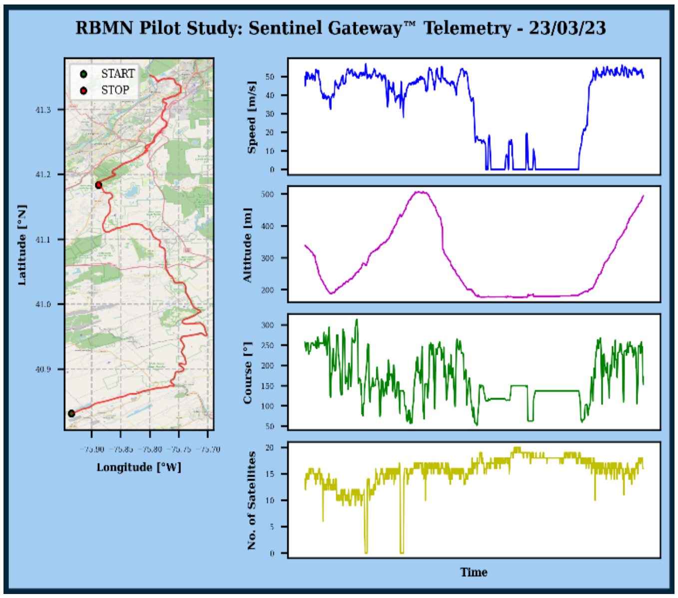

Figure 13: Example GPS Telemetry Data from a Sentinel Motion Development Kit (SMDK) installed at the Reading and Blue Mountain Northern Railroad (RBMN).

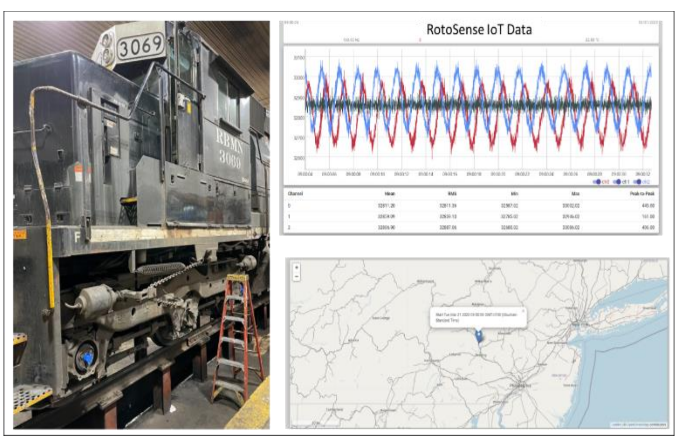

Figure 14: Example SMDK data for accelerometer, temperature, GPS, and automated vibration analysis calculations.

V. SUMMARY AND CONCLUSIONS

This paper provides a detailed examination of a two-part industrial IoT case study focused on the integration of advanced monitoring technologies for remote asset health monitoring and diagnostics within the railroad industry. Conducted by Ridgetop Group Inc., in collaboration with Reading Blue Mountain and Northern Railroad (RBMN) and Innovative Operations Technology, the study showcases significant advancements in real-time asset monitoring and management. The first phase, spanning from March to August 2023, involved deploying Ridgetop's original Sentinel Motion Development Kit (SMDK). This kit featured a network of customized smart sensors mounted on Timken bearing end caps, which transmitted critical vibration and temperature data to a Linux-based gateway equipped with Ridgetop's Sentinel MotionView software for data acquisition and analysis. The insights gained from this phase were pivotal in refining the sensor hardware and developing new software analytics for near-real-time monitoring and diagnostics of critical faults in bearings, wheels, and track conditions.

Encouraged by the initial findings, the second phase of the study, from September 2023 to April 2024, focused on a comprehensive redesign of the SMDK to align more closely with the IEEE 1856-2017 PHM Standard Framework. This framework delineates eight functional blocks for PHM system level solutions, including Sensors, Data Acquisition, and Health Management, among others. The redesign involved substantial modifications to hardware, firmware, and software components of the system, enhancing its capability to execute advanced diagnostics and health management in line with industry standards.

In summary, this case study contributes significantly to the growing body of knowledge on the benefits of integrating IoT-enabled technologies in critical infrastructure sectors. It not only demonstrates the practical applications of such technologies in enhancing asset health monitoring and diagnostics but also aligns with global efforts to improve the safety, efficiency, and sustainability of transportation networks.

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