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REAL-TIME MONITORING AND VIBRO-MECHANICAL ANALYSIS: ENSURING THE INTEGRITY OF VENTILATION DUCT SYSTEMS IN HIGH-RISK ENVIRONMENTS

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Abstract: *This study presents a comprehensive framework for monitoring ventilation ducts in harsh environments, addressing operational challenges. Leveraging Industry 4.0 technologies, it employs advanced sensors, data processing, and Ethernet communication for enhanced reliability and flexibility. The system monitors vibration, temperature, and pressure to detect faults early, using frequency analysis and vibration envelopes to assess machine health. It features a multi-processor system for real-time data analysis and web-based diagnostic tools. Experimental validation shows comparable performance to traditional methods, with improved safety, durability, and reduced downtime, advancing predictive maintenance for industrial ventilation systems.*

Keywords: *real time analytics, vibration analysis; ventilation ducting, high risk environment, axial fan, predictive maintenance.*

1. INTRODUCTION

Industrial revolutions mark pivotal shifts in human progress, each driven by groundbreaking inventions. Currently, the fourth, known as Industry 4.0, merges physical and cyber systems through innovations like the Industrial Internet of Things (IIoT), real-time analytics, AI, and cloud computing, replacing traditional methods with highly integrated solutions. While some debate labeling this as the fourth revolution, ongoing technological integration is undeniable. These developments foster effective industry operations, emphasizing predictive maintenance (PdM). Ventilation ducts in high-risk areas—such as tunnels and industrial zones—are vital for safety and air quality but face harsh environments like vibration, temperature fluctuations, and contamination. Ensuring their integrity prevents failures that threaten safety and cause shutdowns. Real-time vibro-mechanical monitoring offers a comprehensive approach to assess system health and predict faults.

As a core enabler of Industry 4.0, PdM shifts away from traditional preventive or reactive maintenance. Instead, it relies on sensor data and advanced analytics to detect deviations early, allowing continuous operation and extending equipment lifespan. This is especially critical for ventilation ducts in contamination-sensitive zones, where repairs are costly, and access is restricted. Central to PdM are Prognostics and Health Management (PHM) systems, which utilize sensor data—vibration, temperature, pressure—to monitor and forecast equipment conditions. Nonetheless, implementing PdM in such environments faces challenges like high-stress conditions, remote sensing, and real-time data processing.

High-risk environments also pose operational issues. Mechanical degradation often results from vibrations caused by rotating parts like fans, leading to bearing failures and misalignments if unaddressed. Temperature swings, particle buildup, and electromagnetic interference further complicate monitoring. Traditional methods, such as periodic physical inspections using portable diagnostic tools, are limited—they cannot detect transient faults or progressive deterioration effectively, risking system failure. Therefore, real-time monitoring with integrated sensor networks and sophisticated data analysis becomes essential, enabling immediate fault detection and proactive maintenance plans.

Vibration analysis is vital for diagnosing mechanical issues, such as misalignment, unbalance, or bearing defects. Frequency domain analysis—using algorithms like FFT—transforms time-series vibration signals into spectrograms, revealing fault-related frequencies. Monitoring these frequencies over time helps assess deterioration and predict failures. Historically, vibration condition monitoring relied on portable tools and manual data review, which is impractical in high-risk zones. Integrating continuous vibration analysis into monitoring systems overcomes these limitations, providing real-time insights.

Effective real-time monitoring depends on robust communication networks. Traditional protocols like Modbus RTU over RS-485 suffer from electromagnetic interference, low data rates, and high costs. Ethernet-based protocols, such as Modbus TCP, offer higher throughput, reliability, and flexibility—supporting remote diagnostics and configuration from central control rooms. These networks are scalable, allowing easy addition of sensors and system upgrades.

This research aims to develop a holistic, real-time monitoring framework for duct systems in hazardous environments. Its objectives include:

1. Continuous parameter monitoring (vibration, temperature, pressure).
2. Advanced frequency-domain vibration analysis for fault detection.
3. Remote system access via web interfaces with secure connections.
4. Scalability to adapt to various system configurations.
5. Robust design resistant to environmental factors like dust, temperature changes, and electromagnetic interference.

2. MATERIALS AND METHODS

The designed system enables continuous online monitoring capability and vibro-mechanical assessment of the ventilation duct systems in high-risk areas with a direct build into the structure of the ventilation fans. It consists of a central core accommodated within a shielding enclosure fixed to the outer shell of the fan and various pressure-sensing elements arranged inside the fan duct. These modules acquire important data regarding air pressure conditions; they convert analog differential pressures and interface the data to the core through a two-wire RS485 bus proprietary to GE. It combines high modularity and scalability – the system suits short and long fan dimensions and different duct configurations well. In the presented prototype, two modules are used, and three sensing points of the pressure field are used.

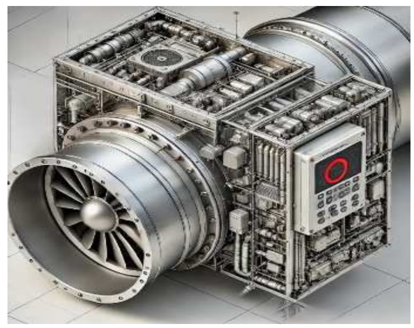

Fig. 1. Housing Box for the Monitoring system

Figure 1 presents the central housing, as the housing design specified in this application note is solid and adequately protected against environmental factors that can be problematic in areas at risk, such as tunnels: temperature changes, humidity, and even the presence of hydrocarbon particles. It is also capable of sustaining high vibration levels owing to its location on the fan casing to capture data from operational conditions.

2.1. Magnitudes and Sensors

The system continuously measures several magnitudes which are crucial for the reliability and efficiency of the ventilation duct system. These include the following:

- Analog temperature measurements at critical points such as motor windings, bearings, and external air. These values show the thermal status of the components and give an early warning of possible insulation deterioration or mechanical problems.
- Digital set points that show whether the critical temperature is higher than some defined values of safety.

- Fan tilt angles (pitch and roll) to monitor displacement resulting from impacts, or when unintentionally shaken off.
- The motor's speed of rotation and its direction by using the data obtained from the enclosed incremental encoder to evaluate the stability of the motor.
- Dynamic response or vibration velocity by a single-axis accelerometer to study dynamic characteristics and identify mechanical failures.
- More analog inputs channels for the possibility of the examination of other conditions, for example, of gas, humidity or/and other conditions.

The choice of these parameters guarantees full control over the working conditions of the fan, and the identification of faults in time. This type of maintenance is less costly and dangerous because it eliminates the chance of breakdown maintenance, hence reducing downtimes.

Temperature probes are also installed in the duct to measure airflow and see if it meets the requirements of the pressure sensor [5]. Defects in the electric motor are among the most essential problems in ventilation systems, and they comprise insulation faults as well as mechanical faults. Faults with insulation can cause short circuits because insulation abnormalities – particularly an increase in motor windings' temperature – pose additional risks. Bearing damages in the form of wear or breakages, oblique or mislocated rotor, and eccentricity are typical with vibrations and temperature oscillations of bearings. These problems are detected early through temperature and vibration, thus allowing a system to prevent massive failure from occurring [6].

The system also encompasses an AC heating resistor to reduce condensation within the fan at intervals of inactivity. The operation of the resistor is checked through a digital input to assess the functionality of the unit with accuracy, especially concerning the environmental conditions of the ventilation ducts.

An important aspect of the system is the analysis capability of the vibration signals in real time. Vibratory acceleration is measured and quantized with high accuracy for frequency domain information at limited areas of interest. With a unidirectional accelerometer mounted radially to the fan's axis, acceleration data are obtained in 2048-point packets and refreshed constantly for FFT calculation. This makes it possible to obtain a frequency spectrum of vibration movements up to 3 kHz necessary to identify mechanical disorders inclusive of rotor imbalance, misalignment or bearing failure. A sampling frequency of 6kHz is adopted and this enhances the application of the Nyquist-Shannon theorem hence enabling accurate vibration reconstruction [7]. However, other analog variables with a low rate of change are sampled at a lower rate to enhance the operation of the system. This integrated monitoring system is not just a data-transmission system but an extensive program, it can process data locally and diagnose in real-time. Through the constant monitoring of vibrations and other parameters, the system provides effective means for predictive maintenance practices and helps pressure duct and vent systems to be reliable, energy-efficient, and safe in high-risk environments.

2.2. External communications

The external communication component of the monitoring system is essential for the execution of analysis and data management in areas of high risk. From a physical standpoint, the system uses a 1000BASE-T Ethernet with an RJ45 connector for strong network compatibility. Currently, it serves as a web server that is accessible through the browser and the specific IP address. At the same time, it functions also as a slave device into Modbus TCP/IP architecture, used to manage several ventilation systems equipped with the monitoring device, providing a principal system with a complete view in large spaces like tunnels.

The system can also be employed for real-time observation of awareness-related processes and is also a data logger. It does not record events only when the monitored variables go beyond or are outside set thresholds or when instantaneous data logging has been called by the central control. Operating system control of time and date events is complemented by a real-time clock module for time synchronization when that control fails because of power loss [8]. The logged data is easily stored in the non-volatile flash memory and can be recalled and manipulated at a later time without having to send it to the main system. However, the system is programmed to provide an alert to the operator during crucial activities, thus fast response is observed.

The Gigabit Ethernet interface improves real-time operation and availability to perform hardware diagnostics, downloads, vibration spectrum analysis, and software updates remotely through SSH/SFTP links. Such strong communication equipment and systems are critical for sustaining the health of building ventilation systems in such heightened risks.

3. SYSTEM ARCHITECTURE

3.1 Multiprocessor System and Internal Communications

The system architecture is established on a multiprocessor platform designed for real-time surveillance and vibro-mechanical assessment. Tasks within the system are distributed between processors, leveraging their strengths:

- Single Board Computer Module (SBCM): 64-bit quad-core module, SDRAM and eMMC Flash memory fit into a low-cost tiny board (55mm x 40mm) via small mezzanine connectors. This module provides improvements in GPIOs, and interface capabilities (I, I2C, SPI, UART, Ethernet) compared to other Raspberry Pi systems. It includes operation statistics, data processing and storage, and data transfer; all of which are performed at high speeds.
- Digital Signal Controllers (DSCs): These are scattered throughout the system to complete various real-time activities such as digitizing, timing and data acquisition key in vibration analyzing together with other analog features.

One of the major difficulties of this architecture is in performing the vibration acceleration analysis in real time triggering data acquisition at a sampling rate of 6 kHz. Unlike most of the analog parameters, vibration acceleration requires higher levels of quantization to enable effective digitization and analysis. These 12-lited ADCs of the DSC are enough for general signals, but for the vibration data 16-lited resolution has to be implemented. Thus, it is integrated into the system the MCP33131-10, 16-bit single channel external ADC, for converting the vibration signals into digital format. This ADC uses an SPI interface and in this mode of operation DSC continuously sends pulses to trigger conversions and it also serves as the master's in data acquisition.

Despite the advantages of flexibility in real-time operations, SBCM faces some challenges. It cannot produce accurate periodic timing signals or continuously maintain the high-speed SPI serial as used in data such as vibration. To overcome these limitations in the design, a DSC is used for handling real-time operations such as sampling and temporary buffer storage [9]. After obtaining the above values, the processed data is sent to the SBCM through another SPI communication port in which the SBCM is the master while the DSC is the slave. Such division of labor helps SBCM to engage in highly processed concepts while not being pressured by the real-time acquisition of data.

The onboard DSC also controls other analog signals like temperature the vibration of the motor's rotational speed excluding pressure which is maintained by other DSCs connected through RS485. It provides shaft rotation measurements using encoder PULSES and supports the SBCM through its ADCs, Timers, counters and communication modules for smooth and light real-time operation.

The two processors—SBCM and DSC—communicate through dual channels: Both a full-duplex asynchronous serial port and a half-duplex SPI synchronous serial connection are integrated into the device. The SPI channel is solely used to transmit digitized vibration data while the asynchronous port is used for commanding back and forth using a proprietary protocol. From this protocol, the SBCM can ask for data and alter the levels of the encoder parameters as well as the thresholds for the magnitude of alarms [10]. Therefore, other electronic blocks that make up the complete system functionality are incorporated which incorporate signal conversion circuits, power miser circuits and communication interfacing circuits. Real-time data acquisition, processing and storage can therefore be performed within the network, making it easier to monitor and predict system anomalies.

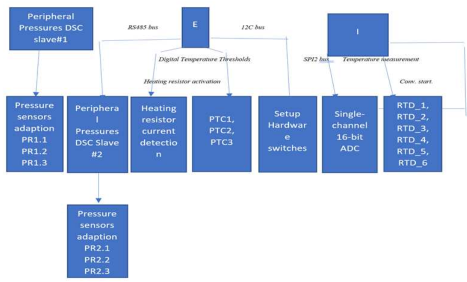

Fig. 1. System architecture block diagram

As shown in Fig. 2 the arrows referring to the analog inputs, the other arrows refer to the digital inputs, and the digital output and the remaining point towards internal interaction. This design enables the use of the real-time monitor and the vibro-mechanical analysis that acts as the guarantee of ventilation duct systems' integrity in high-risk security sub-sectors.

` 3.2. Signal adaptation circuits

Signal adaptation circuits were developed to synchronize sensors around ventilation ducts for real-time vibro-mechanical analysis. A single board computer (SBCM) manages digital inputs/outputs (0-3.3V), monitors fan bearing temperatures via comparators, controls heating relays, and interfaces with IMU and RTC via I2C for tilt detection and event timestamping.

Fig.3. Assembly of the accelerometer

Analog signals (0–5V) are processed via a DSC and external ADC. Six RTDs measure temperature, pressure sensors monitor differential air pressure, and a ±25g accelerometer captures motor vibration. The DSC controls fan speed via encoder. Powered by a 24V supply, the system consumes 15W with all sensors active.

4.IMPLEMENTATION

In the context of carrying out real-time monitoring and vibro-mechanical analysis for integrity assessment of ventilation duct systems, the interoperability of information exchange is crucial. ZJET devices are intended to run in a networked environment that is protected from direct connection to the Internet by a firewall. It helps to reduce security concerns where data and command communication occur between different ventilators and other smart, connected devices [11]. When there is a need to access the system externally for maintenance or monitoring purposes, this is done via VPN VPN-permitted firewall to allow for strong and safe transmission.

Each ZJET device acts as a server and data source. Unlike traditional AHUs using Modbus RS-485 with limited speed, distance, and protocol flexibility, ZJET adopts Ethernet. This allows long-range, cost-effective communication, supports multiple protocols, and enables advanced features like browser-based real-time monitoring and web-based vibration analysis using standard protocols such as HTTP and FTP.

The transition to Ethernet-flavoured communication follows the Iso/Osi model and the capability of the system is improved in highly challenging scenarios such as long tunnels and mining areas. With the integration of the industrial SBCM, the fan unit is enabled to process acquired sensor data locally, perform analyses such as and ease maintenance [12]. This transformation minimizes reliance on centralized PLCs to enhance the operation and integrity of the ventilation systems in high-risk areas.

4.1. Software architecture

Real-time monitoring and vibro-mechanical analysis software designs are also developed for the system and subdivisions are utilized to handle complexity. Various programming languages are used to successfully implement the needs of different projects. The SBCM (Single Board Computer Module) software consists of different modules that are designed to run efficiently and effectively. The ADC module in C language enhances the system responsiveness when tracking the accelerometer data from the Digital Signal Controller (DSC). Likewise, the RS485 module also coded in C controls communication with pressure-sensing daughter cards [13]. The primary processing module, which utilizes Python, forms the center of the system; as such, it is responsible for the assimilation of data acquired from accelerometers, pressure modules, the IMU, and RTC via an IPC.

Python-based Flask web services enable fast data transfer, while ReactJS front-end provides access to sensor data and vibration analysis. FFT, Modbus TCP, and SPI are efficiently implemented using Python libraries. Time-critical tasks are handled in C, ensuring responsiveness in monitoring ventilation in high-risk areas.

4.2. Communications and data exchange

Due to the integration of multiple software modules, and hardware elements, both physical and logic interface were used for smooth integration. The following are the details of these approaches.

PLC ⟺ ZJET

The PLC communicates with the ZJET system via Modbus TCP/IP, replacing outdated RS-485 links. Acting as a receiver, the PLC gathers signals from the ZJET board and allows configuration updates. The Modbus server, coded in Python3, enhances flexibility and performance over traditional ventilation control methods.

Web browser ⟺ ZJET

A key ZJET system upgrade is its web-based interface, built with React and backed by a RESTful API using Python3 Flask. This allows real-time monitoring and configuration. Core services for accelerometer data processing relieve a Modbus server and can flag anomalies. Modules run as independent processes, coordinated via ZeroMQ for efficient inter-process communication, enabling scalable, platform-independent integration. This architecture enhances system flexibility, accessibility, and supports wider industrial applications through robust web services and signal processing capabilities.

5.VIBRATION PROCESSING AND ANALYSIS

The developed system surpasses conventional portable vibration analyzers from ADASH and IFM, offering advanced real-time measurement and analysis. Its architecture enables refined evaluation of vibration acceleration, specifically for verifying ventilation duct integrity in high-risk areas. Acceleration data is digitized and processed by a Single Board Computer Module (SBCM), where a Fast Fourier Transform (FFT) generates a 3 kHz frequency spectrum [13]. Using a flat-top window function for amplitude accuracy, the system integrates this data to calculate velocity spectra, compliant with ISO 10816 by excluding frequencies below 10 Hz.

Low-frequency vibrations (10 Hz–1 kHz) typically indicate unbalance or misalignment, while high-frequency signals (5–10 kHz) are linked to bearing defects such as inner/outer ring failures. These occur at specific frequencies like Ball Pass Frequency of the Outer Race (BPFO) and are often masked by motor noise.

To isolate relevant data, a Butterworth bandpass filter (500 Hz–2.5 kHz) removes unwanted frequencies. The Hilbert transform is then applied to extract the acceleration envelope, aiding in defect identification through its spectrum. This approach offers deeper diagnostic capability beyond basic RMS and frequency analysis, ensuring a robust assessment of structural and bearing-related issues.

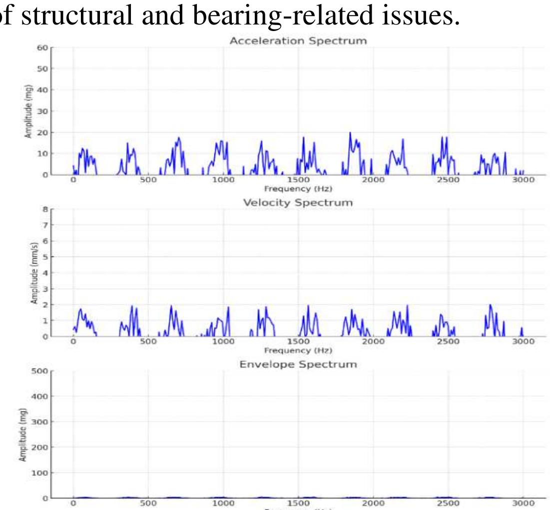

Fig. 2. Three spectra obtained from the analysis of acceleration data

The ZJET system processes all data locally within SBCM, utilizing its computational capabilities. It generates three distinct spectra: acceleration, velocity, and the envelope of high-frequency acceleration. These spectra provide a detailed graphical representation of vibratory conditions, allowing for precise diagnostics. Additionally, the system calculates RMS values for velocity (VRMS) and acceleration (ARMS), as well as two specialized RMS metrics: high-frequency acceleration (AHF, 500 Hz–2.5 kHz) and the RMS of the demodulated high-frequency envelope (AENV). These additional metrics enhance the ability to assess bearing conditions, surpassing traditional diagnostic tools.

Figures in the original explanation depict the recorded accelerometer signal during bearing failure, the spectrum analyses for acceleration, velocity, and envelope, and the comprehensive data processing workflow. This integrated approach ensures robust vibration analysis and fault detection, making the system a powerful tool for real-time monitoring in high-risk environments. It not only provides actionable insights for maintaining ventilation duct system integrity but also establishes new benchmarks for vibration analysis and diagnosis.

6. EXPERIMENTAL VALIDATION

Real-life operating fans were utilized to test and validate the proposed real-time monitoring and vibro-mechanical analysis system, and its outcomes are not based on simulation studies. The first experiments in the laboratory employed a voltage signal generator to introduce the characteristic waveforms in place of a sensor by imposing artificial square and triangle wave signals on the system. This enabled proper confirmation of the system's handling of temporary acceleration values and the quality of frequencies that are likely to be obtained. These preliminary tests have shown the correct functionality of the system regarding vibration data processing. To ensure accuracy and validity in taking and analyzing the vibrations of the system in use, a calibrated mechanical vibratory system, Model 699A02 Hand Held Shaker from PCB Piezotronics was used. This equipment gives one g RMS acceleration or 1 g peak amplitude at a frequency of 159.2 Hz. When the axial accelerometer was positioned on the shaker, it represented a high degree of accuracy in measuring both vibration amplitude and frequency in the designed system, in correlation with the theoretical values.

The system also performs the function of a web server with a user interface accessible through a browser by the IP address. By so doing, the user can set the desired IP address, the active probe(s), the respective vibration thresholds, the encoder resolutions or ratios and the RTC settings respectively. The system also includes the functionality for input calibration and fan tilt angle offsets. Configuration and calibration options are secured at the hardware level and are available through switches present in the primary printed circuit board map [14]. The web interface also shows real-time measurements of active parameters at the sampling frequency and allows direct control of the system's heater functionality. Vibration acceleration data is highlighted among the data that the web interface in essence provides. Sample RMS values of acceleration and velocity are displayed as well as the acceleration frequency spectrum, velocity spectrum, and the outer envelope of the acceleration spectrum [15]. These graphs are essential for proper diagnosis of the fan's conditions, and possible problems that range from bearing defects, imbalance or misalignments.

The system was evaluated using a fan with the following specifications: it has a 1 kW power rating, 50 Hz frequency, 230 V voltage, a mass of 60 kg and a diameter of 0.5 m. Two different setups were used for evaluation: a scintillator/decoder assembly to detect the IFM VSA001 accelerometer signal and the IFM VES004 system, which also employs the VSA001 accelerometer but cannot generate acceleration envelope spectra. The testing of the ZJET system revealed mean RMS acceleration values on the graphical output for effective analysis [16]. RMS acceleration comparisons between the ZJET and the IFM systems provided accurate confirmation that the two methods were nearly identical to the claims with any difference not exceeding 10%. The experimental results show that the ZJET system achieves the performance of other commercial systems, e.g. the IFM VES004 and the developed methods offer extra diagnostic features, e.g., the vibratory acceleration envelope spectrum. These capabilities make the ZJET system an enhanced technology for real-time tracking and vibro-mechanical analysis of ventilation duct systems in risky areas.

Fig. 5. Jet Fan under test

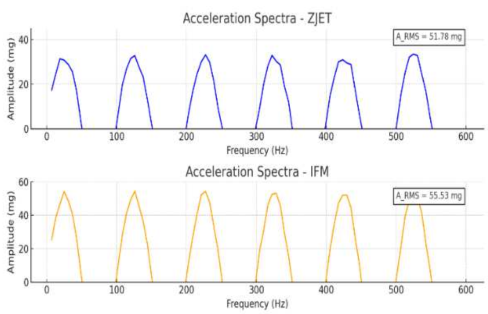

Fig. 6 Vibration results Jet Fan comparative

Table 1

Comparative results for a Jet Fan at 30Hz (1800rpm): ZJET versus IFM commercial equipment

	ARMS (mg)	VRMS (mm/s)	AHF (g)
ZJET	87.69	3.34	0.32
IFM	98.94	3.39	–

System testing compared ZJET against traditional tools like the IFM VES004, showing equivalent results for RMS acceleration and key indicators. However, measurement accuracy can be affected by sensor miscalibration, disrupted data transmission, and environmental factors such as temperature, EMI, and moisture. Regular calibration is essential to maintain performance, especially in high-vibration or extreme conditions. Validation was limited to a single fan type, requiring broader testing across various fan systems, speeds, and environmental conditions to improve reliability. Future validation should expand datasets to include diverse operating environments and failure types, enabling more comprehensive analysis of system limitations. This will also support wider industrial applicability. Additionally, future ZJET versions should integrate machine learning for real-time fault detection and self-adjustment, reducing error impacts. These advancements aim to enhance precision, resilience, and operational insight, ensuring ZJET's effectiveness in dynamic, high-risk ventilation scenarios.

Live data processing enables immediate fault detection, bypassing periodic checks. However, large-scale applications can strain computational capacity. Integrating edge computing allows faster localized processing. Experimental results show ZJET performs comparably to diagnostic tools. Expanding data samples and enhancing error analysis with machine learning could increase reliability for time-sensitive industrial risk monitoring.

7. CONCLUSIONS

This paper also introduces an innovative embedded system used for the ventilation system remote monitoring and high-level analysis in underground infrastructures. Compared with similar equipment manufactured by other companies, the equipment is optimal for its application; its compact structure is suitable for the specific conditions of the harsh working environment and some unalterable areas of road tunnel several kilometers high in the ceiling. Every ventilation device is a node within a TCP/IP Ethernet connection of a certain structure of all the ventilation units. Modbus TCP or HTTP can be built into devices and accessed externally with only one Ethernet cable. This also enables direct connection to a programmable logic controller PLC for overall system monitoring and controlling using TCP Modbus protocol, and web interfaces for monitoring and controlling the equipment.

Key parameters include but are not limited to, the temperature, differential pressure, RPM, inclination or position and even vibration acceleration. For condition monitoring predictive maintenance, vibration acceleration is computed through a sophisticated local computation process to detect mechanical problems such as misalignments and clearances, as well as bearing faults. The high-end and modular design of the hardware comprises a digital multiprocessor system of low-cost and power-efficient QUADER Digital Signal Controllers and an industrial Single Board Computer Module. SBCM has a processing capability to perform data analysis at the site and these facilities include frequency analysis of acceleration, velocity and envelope signals in assessing the mechanical condition. This low-cost embedded solution also overcomes the need for costly portable diagnostic tools for condition monitoring during test, assembly, transportation, storage, and continuous operation in a cost-effective manner for real-time and individual asset-level predictive maintenance.

8. FUTURE WORK

The system is currently in an evolutionary mode, and it is expected that the following improvement will be included in subsequent versions; a major concern is the training and testing of an advanced algorithm using machine learning approaches for more effective predictive maintenance. The current prototype captures a great deal of operational information and when combined with service hour and fault records the future looks promising for the creation of a strong prediction model. For instance, detailed diagnostics related to fault detection can be tuned using information obtained from the system to choose the right diagnostic approaches.

Another anticipated improvement relates to the means of connecting the system with commercial cloud, for example, AWS or Azure. Technically, this would open new possibilities for using the product, such as analysis, diagnostics, and the ability to scale without turning it into a simple data warehouse. However, it is still under testing, and it may be incorporated in the next version we are releasing.

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Monitorizare în timp real și analiza vibro-mecanică: asigurarea integrății tubulaturii a sistemelor de ventilare în medii de lucru cu risc ridicat.

Acest studiu prezintă un cadru cuprinzător pentru monitorizarea conductelor de ventilație în medii periculoase, abordând provocările operaționale. Folosind tehnologiile Industry 4.0, acesta folosește senzori avansați, procesarea datelor și comunicații Ethernet pentru fiabilitate și flexibilitate sporite. Sistemul monitorizează vibrațiile, temperatura și presiunea pentru a detecta defecțiunile din timp, folosind analiza de frecvență și pachetele de vibrații pentru a evalua starea de sănătate a mașinii. Dispune de un sistem multi-procesor pentru analiza datelor în timp real și instrumente de diagnosticare bazate pe web. Validarea experimentală arată performanțe comparabile cu metodele tradiționale, cu siguranță îmbunătățită, durabilitate și timpi de nefuncționare redusi, avansând întreținerea predictivă pentru sistemele de ventilație industrială.

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