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Real-time monitoring solution with vibration analysis for industry 4.0 ventilation systems

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Abstract

Predictive maintenance has revealed as one of the paradigms of Industry 4.0. This paper addresses a complete system for the acquisition, computing, monitoring and communication of ventilation equipment in underground tunnels based on TCP/IP protocol and accessible via WEB services. Not only does the proposed system collect different sensor data (temperatures, vibrations, pressures, tilt angles or rotational speed), it performs local data processing as well. This feature is the newest and most important of all those provided by the system design, and there is no equipment that offers a similar performance in current ventilation systems. This paper shows the design and implementation of the equipment (system architecture and processing), as well as the experimental results obtained.

Keywords Industrial Internet of Things (IIoT) · Predictive maintenance (PdM) · Real-time condition · Monitoring system · Signal processing · Vibration analysis

1 Introduction

The term industry 4.0 means the fourth industrial revolution. Many authors consider that it is too early to talk about a real fourth revolution [1, 2], that, although it will inevitably come, it is still in the future. On the other hand, some authors point to a 4.1 revolution, in terms of zero defects goal [3] among other objectives. In any way, it is also true that there have been some important technological advances in the present industry, and they have generated a new industry paradigm: additive manufacturing, connectivity, Industrial Internet of the Things (IIoT), cloud storage or predictive maintenance among many other concepts are currently hot topics in the

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Extended author information available on the last page of the article actual industry and constitute the present of the Industry 4.0. Nevertheless, as with any breaking technology, it is not free of security issues. IoT devices usually have less processing power and memory so they are more exposed to cyber attacks [4]. Anyway, for predictive maintenance (PdM), the capabilities of Industry 4.0 can be spectacularly useful. The Internet of Things can provide an intelligent perception of the state of any system in general. The set of detection, diagnosis and prognosis tasks is known as PHM (prognosis and health management) [5]; this concept is key to be able to predict which part of the equipment needs to be replaced and at what time, thus ensuring the continuous operation of critical systems [6].

Following this idea, the aim of this work is performing real time monitoring of ventilation systems in road tunnels.

Many diagnostic techniques have been proposed based on the analysis of different magnitudes (vibrations, flux, temperatures, power, etc.) to detect a wide range of electromechanical faults in rotating machines [7]. One of the techniques that offer more revealing results is the real-time analysis of vibrations in the domain of frequency [8, 9] and, more specifically, the evolution of the frequency content throughout the life of the equipment. Due to the high cost of vibration analysis equipment, it is not usual for one machine to have its own embedded vibration analysis system. Traditionally, in order for predictive maintenance to be implemented in industrial facilities, high-performance portable devices [10] are used to measure and analyse vibration frequency behaviour by periodically following a "route" of machine measurements within the factory. Subsequently, these data are uploaded from the portable equipment to the central system in charge of the maintenance, where the time evolution of the vibrations in each machine is analysed. In the case of tunnel fans, given the difficulty of access, this type of measurements and frequency analysis is not performed periodically, but only when operating problems are detected. Thus, the goal of this work is not only focused on implementing an adequate PdM, but on detecting unexpected events as well. Such a task must deal with the problem of having the monitored systems (the fans) located in polluted, hard-to-reach areas. The access to the equipment is also limited by service constraints and economical issues: it is convenient to interrupt the service the fewest amount of times and the shortest time period possible. This implies that the needed parameters must be reachable remotely. As a result of this need, and considering the long distances involved, the communication strategy becomes a very important issue, both for the technical specifications and for the installation costs. To sum up, the goal is obtaining a complete surveillance and monitoring system to detect abnormal situations and suitable to be used in a PdM program for a wide variety of fans of different sizes, powers and applications. In order to do so, several parameters, such as vibration, temperature, pressure, etc., will be measured, and the implemented system must be able to store, analyse and process the collected data, as well as to send them whenever necessary to a central point. Access to this system will be facilitated by implementing different protocols, such as ModBUS TCP and HTTP, using a single Ethernet interface.

The system has been called ZJET, and its industrial design is protected by a utility model registered in Spain [11].

Currently available ventilation systems typically rely on the use of the client-server Modbus protocol. This industrial standard is widely used by different types of devices such as sensors (temperature, pressure, etc.), inverters, heat pumps, etc. This protocol exhibits different variations, depending on the physical media and/or the format of the exchanged frames.

In the case of ventilation systems, it is common to rely on the Modbus RTU version that requires the use of a serial line (RS-485). This is one of the main disadvantages of current installations, as the required cabling technology is expensive, slow, prone to electromagnetic interference and does not allow other protocols to be used simultaneously.

One of the main goals of this contribution is to provide an alternative to those systems by using an Ethernet connection for the data transmission. This choice dramatically improves current ventilation systems as new features can be integrated, such as:

- Fast and reliable Modbus communication with the controller using the TCP version of the protocol.
- Remote access to the ventilation system for monitoring and diagnosis.

In addition, the board that comprises the main hardware result of our system has enough processing power and storage space to face more elaborated tasks, such as embedded vibration analysis, event detection and log, etc., which is something that it is not currently available on the market.

In the following sections, a complete description of the system, from both a hardware and a software perspective will be provided.

2 System overview

The equipment has been designed to be embedded in each fan to be monitored. It consists of a core element located in a housing attached to the fan casing and several pressure measurement modules, placed near the points of interest for the measurements in the fan duct, which allows air flow conditions to be known. Each pressure module is capable of measuring and digitizing several analog differential pressures and sending these values to the system core using an RS485 bus with a proprietary protocol. The full system is easily scalable and expandable depending on the fan dimensions. In the case of the prototype presented, two modules have been used, capable of sensing three different pressures each.

The red circle in Fig.1 shows the box housing where the monitoring system would be included. It is attached externally to the fan duct. The main sensors are housed in contact with the fan itself, and their connections are carried internally towards the housing box of the monitoring system core.

The equipment must be protected against the harsh environmental conditions that typically occur inside tunnels: extreme temperature, humidity or hydrocarbon particles in suspension. Another factor that has been taken into account is that, by being installed in the fan itself, the system may be exposed to a strong source of vibration; this has been foreseen in the fixing.

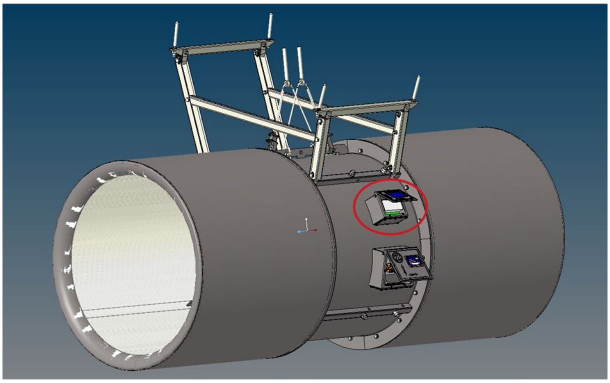

Fig. 1 Housing box for the monitoring system

2.1 Magnitudes and sensors

In addition to the pressures measured remotely by the corresponding distributed modules, the magnitudes monitored by the core system are the following:

- Analog temperature measurements at different points of interest: bearings, motor phase windings and external air.
- Digital temperature thresholds: to determine whether three critical temperatures are above or below a safety threshold value (thermal protections).
- Fan tilt angles: pitch and roll to determine whether the fan is correctly oriented or has been displaced due to an impact or an accidental detachment.
- Motor rotational speed and direction, by means of an incremental encoder coupled to the axis of rotation.
- Analog acceleration to process and analyse the vibratory conditions of the fan.
- Additional analog inputs available to monitor up to four other optionally connected magnitudes (gas detectors, humidity, etc.)

The parameters selected to be monitored are those that allow knowing if the working conditions of the fan are adequate or if the appearance of a fault due to abnormal operation is foreseeable. Failure detection and diagnosis is preferably performed preventively and not correctively: solving a fault is a more expensive practice, since it implies forced, unscheduled stops, to first detect and then solve damage to the equipment.

Fault detection and diagnosis require the use of suitable sensors. On the one hand, to know the flow of circulating air and determine whether it is the desired one, differential pressure sensors are used in different areas of the fan duct. On the other hand, there is a wide variety of sensors that can be used to collect data on the operating parameters of the electric motor with the purpose of detecting and monitoring faults. Temperature and vibration sensing have turned out to be the most widely used methods for decades to monitor electric motors. Most of the faults in electric motors can be classified into two groups: insulation faults and mechanical faults [12, 13].

Insulation faults cause damage to the stator coils and can cause partial short circuits in the windings; temperature rise in the windings can be an indication of this type of fault. But overheating of the windings can also be caused by damage in the insulation. Whatever the reason, it is interesting to know the temperature in the windings with respect to the temperature of the outside air. That is why temperature is one of the parameters of interest that are monitored in the system. Temperature measurements are carried out analogically to know the working conditions and also digitally to determine if certain temperature thresholds have been exceeded in the windings.

Mechanical failures are associated with bearing damage, rotor breakage, eccentricities, imbalances, and misalignment of the axis of rotation. The heating of the bearings can be an indication of anomalous friction and indicative of a problem; for this reason, temperature sensors are also placed in the bearings. On the other hand, the measurement of the vibrational acceleration is essential to carry out the subsequent processing and analysis in the frequency domain that is carried out online and locally by the designed system.

The ZJET system also has the ability to drive, from a remote supervisor system, an AC heating resistor by means of a digital output. The heating resistor is integrated in the fan to prevent moisture condensation when the fan is stopped. Checking the right activation of this resistance is very important, and for this reason there is also a digital input that allows detecting whether current is flowing through the heating resistor.

The measurement of the rotational speed and the direction of rotation of the motor is also necessary in order to know whether the working conditions are adequate and to relate them to the vibratory conditions that are being measured.

Sampling and digitization of most analog input signals do not present hard conditions to meet in terms of resolution and sampling frequency except in the case of vibratory acceleration, which must meet strict conditions regarding the sampling period and quantification.

On rotating machines, such as fans, vibration analysis is essential for predictive maintenance [14, 15]. The system that has been developed and is presented in this paper is not only hardware that transmits data: it is a system capable of locally performing a complete vibration analysis that facilitates online diagnosis. The main target is to achieve a real-time and continuous analysis of vibrations in the frequency domain. To do this, the system samples and digitizes the acceleration analog signal generated by a unidirectional accelerometer, placed in a direction radial to the axis of rotation (inclination of 45º is recommended by manufacturers).

Temporary acceleration values in packets or “windows” of 2048 values that are continuously updated with new data are employed to calculate Fast Fourier Transform (FFT) and obtain the vibration frequency spectrum at a local level. A frequency spectrum up to 3 kHz is more than sufficient for a complete diagnosis of mechanical vibrations, and for this reason the sampling frequency established for acceleration has been 6 kHz, in accordance with the Nyquist–Shannon theorem. The rest of the analog variables that are recorded in the equipment are magnitudes with slow temporal evolutions and can be sampled with frequencies of tens of hertz.

2.2 External communications

On a physical level, the equipment has an Ethernet 1000BASE-T connection with an RJ45 connector on the board. The equipment acts as a Web server that displays a web interface accessible through a browser by means of the board's IP address. In addition to the Web interface, and also using the Ethernet connection, each ZJET unit has been designed to act continuously as a slave device of a top supervisory unit using the industrial protocol Modbus TCP/IP. In this way, from a higher hierarchy system, it will be possible to monitor all fans that are in a certain tunnel and have a ZJET embedded system.

Additionally to real-time remote monitoring, the system is also capable of acting as a data logger in two different situations: generic event log for any of the monitored variables (value out of a configured range) or a remote request for temporary registration sent from the central control system. As the system relies on a Single Board Computer Module (SBCM), time and date of events are provided by the underlying operating system. Nevertheless, as the chosen SBCM does not feature a real time clock module (RTC), one has been included in this development to allow the system to restore the time and date in case of a power failure or a reboot. Even though this circuit can exhibit some clock skew, it should be taken into account that all the boards will be synchronized with a central controller (or even with a Network Time Protocol server when a connection to the Internet is available); therefore, precision does not pose an issue. This log of events and temporary values is stored in a non-volatile flash memory present in the device, so that it can be later downloaded when necessary. Consequently, it is not required to upload these events to a central system, as there is plenty of local storage available, but it is a feature that the company could study for a future revision. It must be taken into account that the device will raise an alert when such an event happens; therefore, the intervention of an operator will be quick.

Another benefit of the use of a Gigabit Ethernet interface, as opposed to the classical Modbus serial approach, is the fact that unless a catastrophic event occurs, the device will always be remotely accessible, for both hardware maintenance and diagnostics (logs download, spectra analysis, etc.), and software upgrade through an SSH/SFTP connection.

3 System architecture

3.1 Multiprocessor system and internal communications

The hardware design is based on the use of a multiprocessor system. The tasks to be developed in the global system are divided between the processors according to their main characteristics:

- A low-cost SBCM that contains the main elements of a small Raspberry Pi computer (64-bit quad-core processor; SDRAM and eMMC Flash memory). All this is integrated onto a small (55mm × 40mm) board that is attached by means of two mezzanine connectors to the base PCB designed for the application.
- Several Digital Signal Controllers (DSCs) to complete the distributed monitoring system and meet some special real-time requirements necessary for the application.

As far as the SBCM is concerned, the full flexibility of the SoC (system-on-chip) processor is available, i.e. there are many more General Purpose Input/Output (GPIOs) and interfaces available than in a standard Raspberry Pi, while the use of the module in a customized system like the one described here is eased because the same module integrates the most critical hardware elements. The ZJET system takes advantage of its high computation and processing benefits, its high communication performance (I^2C[1], SPI[2], UART[3], Ethernet are employed) and its high non-volatile storage capacity.

The main difficulty in the development of the hardware and the application lies in the frequency analysis of vibration acceleration in real time. This is the most significant and distinctive feature of the equipment compared to any other online monitoring system for ventilation equipment. As explained in Sect. 2.1, it is necessary to ensure that all the vibration acceleration values are obtained continuously, at a sampling frequency of 6kHz.

The SBMC module used does not have an analog-to-digital converter (ADC), and the sampling and digitization of the analog signals must therefore be performed by external elements. The DSCs in our system do have 12-bit ADC modules, which are adequate for the majority of the analog magnitudes, but not for vibration acceleration. The measurements and tests carried out with the equipment led to the conclusion that a 16-bit resolution is necessary for the vibration conversion so that the subsequent processing shows good results. For this reason, a single-ended 16-bit single-channel external ADC (MCP33131-10) has been specifically selected for digitizing vibration acceleration. To obtain the digitized values with this integrated circuit, it is necessary to provide a digital pulse that indicates the start of the conversion. The digitized value obtained will be collected by means of an SPI communication in which the ADC plays the role of slave device.

Generating a periodic digital signal at constant time intervals that marks the sampling period is something that cannot be accomplished by SBMC modules due to real-time limitations of their operating system. The tests carried out also revealed the limitations of the SBCM when trying to establish a periodic SPI communication at the rate required for the collection of all the data available in the slave ADC.

The important conclusion is that SBCM modules present limitations for real-time operation in applications where it is necessary to digitize analog signals with

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[1] Inter-Integrated Circuit.

[2] Serial Peripheral Interface.

[3] Universal Asynchronous Receiver-Transmitter.

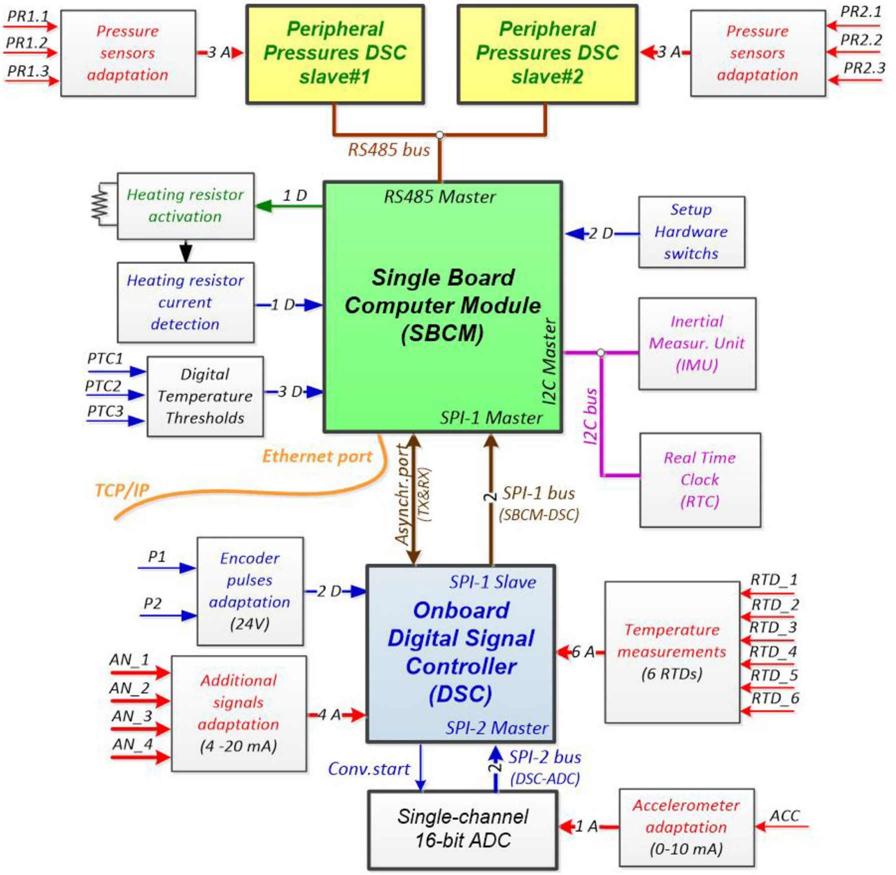


Fig. 2 System architecture block diagram

the requirements imposed by vibration acceleration. To solve these problems, the system architecture was established according to the block diagram shown in Fig. 2, where all the elements and their connections are represented. In this figure, the red arrows represent analog input signals, the blue arrows represent digital inputs, the green arrow is a digital output, and the rest of the connection lines correspond to internal communications (I2C, SPI, RS485 and asynchronous port).

In this solution, the DSC present on the board that constitutes the core of the system is in charge of interacting directly with the external ADC, both to establish the sampling period and to collect the values through an SPI communication in which the onboard DSC acts as a master. The real-time acquisition requirements are perfectly achievable by the DSC and the values are stored internally in its memory, as a temporary storage buffer. Since the processing power resides in the SBCM, the digitized data must be transferred via another SPI communication in which the DSC now plays the role of a slave and the SBMC acts as the master of the communication. In this way, the requirements for the SBMC to sample and collect values at a rate equal to the vibration sampling frequency disappear.

In addition to this fundamental functionality for the equipment developed, the onboard DSC is in charge of the rest of the analog signals (with the exception of pressures, which are managed by the RS485 slave DSCs). It also takes care of the necessary timing to measure the rotation speed of the shaft, combined with the counting of external pulses from the encoder. Thus, the SBCM is perfectly complemented by the characteristics of the DSC, whose internal modules (ADC, timers, counters, SPI and UART communications modules) are used for an efficient real-time operation in our system.

The two onboard processors communicate with each other through a double channel for data transfer: a full-duplex asynchronous serial port and a half-duplex SPI synchronous serial communication in which the SBCM acts as bus master to receive the data collected by the DSC. As already mentioned, only the sampled and digitized vibration acceleration is sent through this SPI channel.

Through the asynchronous serial port, messages are exchanged between the SBCM and the DSC using a proprietary protocol by means of which the SBCM sends commands to request the value of a certain digitized magnitude or to set up some parameters, e.g. pulses per revolution for the available encoder, active signals for a given fan or alarm thresholds for each magnitude.

To achieve the full system operation, a series of additional electronic functional blocks are needed: signal adaptation circuits, power supply and communication drivers.

3.2 Signal adaptation circuits

In order to monitor the fan with all the functionalities indicated in Sect. 2.1, a series of electronic adaption stages for sensors and transducers were designed. They provide the electrical signals adapted to the levels that can be connected to the processors.

- The Single Board Computer Module can only work with digital inputs/outputs operating between 0V and 3.3V. Connections to this module are as follows:
  - There are 3 temperatures in different zones of the fan (bearings and windings) whose values should not exceed a certain safety temperature. Detection of this situation is achieved by using the outputs of 3 analog comparators whose input voltages depend on PTC-type thermistors.
  - A relay controlled by one of the SBCM digital outputs is used to connect the fan heating resistor to the AC mains in order to prevent moisture condensation if necessary.
  - To verify that the heating resistor is active, a Hall effect sensor is used to detect current flow through it.
  - Fan tilt angles (pitch and roll) are obtained by processing the 3-axis static acceleration provided by an Inertial Measurement Unit that acts as a slave in an I2C bus, where the SBCM is the master. Another slave on the same I2C

Fig. 3 Assembly of the accelerometer

bus is the Real Time Clock that locally provides time and date for the event log.

- The Digital Signal Controller and the external ADC accept signals in the range of 0–5V, according to their supply voltage. All analog signals from the sensors are normalized to this voltage range by means of the corresponding adaptation circuits.
  - To measure the six analog temperatures, Resistance Temperature Detectors (RTD) are used in a 3-wire connection to compensate the lead resistance.
  - Pressure sensors are used to measure the differential pressure between two air inlet ducts in several zones of interest for the measurements in the fan.
  - The vibration measurement is carried out with a single-axis accelerometer, mechanically coupled to the fan housing. Figure 3 shows the inside of the fan duct, where the assembly of the VSA001 accelerometer in charge of measuring vibrations on the motor casing is shown. The sensor characteristics are: acceleration range of ±25 g with a frequency range from 0 to 6 kHz.
  - Another 4 analog input currents could be connected and digitized by the DSC. These signals can be used to measure other types of magnitudes that could be of interest in a particular installation.

  In addition to the analog signals mentioned above, the Digital Signal Controller is also in charge of measuring the speed and the direction of rotation of the fan by means of an incremental encoder coupled to the rotation axis.

The full system is powered directly from the AC mains through the use of a 24-volt switching power supply integrated in the PCB. From that voltage, the rest of the continuous and stable voltages required for the operation of the system are obtained using several onboard DC/DC switching converters. The maximum total

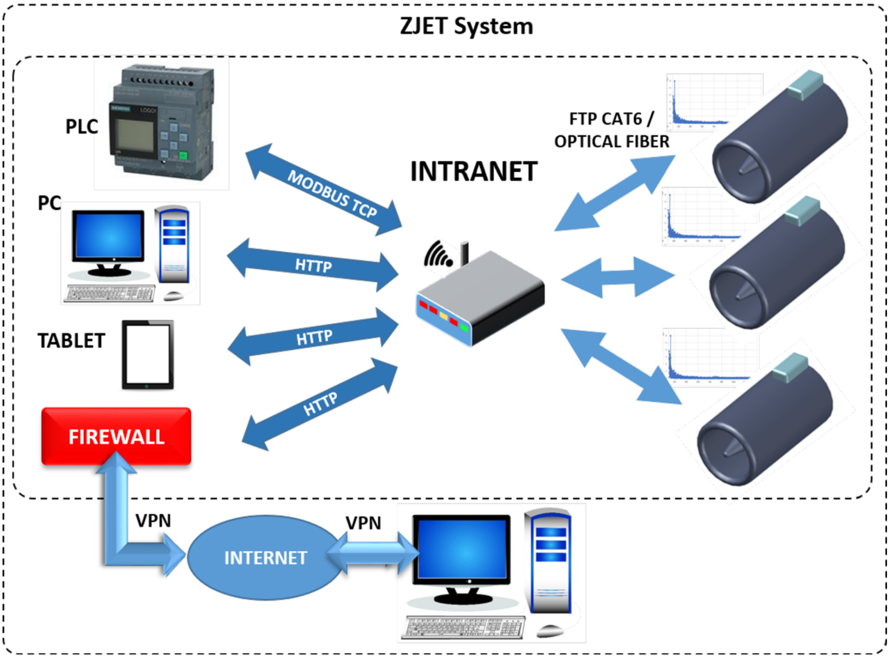


Fig. 4 Communication architecture in ZJET equipment

power consumption at the AC mains power input is 15W, which occurs when all input sensors are connected to the system.

4 Implementation

Information exchange is one the basic pillars of remotely controlled/managed systems, and it is also one of the key IoT offerings [16]. Additionally, data transfer speed and security are two common issues that need to be considered and conveniently taken into account [17]. ZJET devices are connected within a local area network not directly accessible from the Internet as there is a firewall device placed in between. Thanks to this approach, it is not really necessary to implement any additional security measures for the data/commands exchange between the ventilators and the other devices connected to the network. In case it is necessary to access the installation from the outside for maintenance, monitoring, etc., it will be accomplished through a VPN (Virtual Private Network) firewall [18], which enables a safe environment to do so. This well-known approach does not make it necessary to use additional security measures to protect the installation, see Fig. 4.

Taking into account that every ZJET device is a data source, they can be viewed as servers that provide information to the other devices in the network (consumers/clients). Current ventilation systems usually rely on a single PLC (Programmable Logic Computer) responsible for the configuration and monitoring of the ventilators in a typical installation (SCADA). This is usually carried out using Modbus over an RS-485 serial line (Remote Terminal Unit, RTU), which poses several drawbacks:

- Distance is limited by the type of cable to be used (shielded twisted pair)
- The maximum communication speed is limited by this physical layer and furthermore
- RS-485 does not support more than one communication protocol, which clearly limits the amount and nature of the information that can be exchanged.

The aforementioned issues were the starting point of our work; consequently, a new architecture was proposed to overcome them. With the replacement of the RS-485 lines with a standard Ethernet wiring, those problems are fixed and new opportunities appear to make ventilation systems more resilient and easier to maintain:

- Modbus TCP can be also run on an Ethernet network concurrently with the rest of TCP/IP protocols.
- Distance is no longer an issue, as fibre optic media can be used. The same applies to cabling costs, as fibre prices are lower than the copper-based cable counterparts.
- As was previously mentioned, an Ethernet cable allows the TCP/IP stack to be run; therefore, multiple communication protocols can co-exist seamlessly on the same physical media. This implies that information exchange can be used in multiple ways (HTTP, FTP, etc.), which makes new functionalities possible, such as sensor data access and online vibration analysis using a web browser, for instance.

Besides the introduction of a new physical media, which indeed poses many advantages for the installation and deployment of ventilation systems in a typical environment (long tunnels, mining sites, etc.), taking on the ISO/OSI model shows the greatest benefits of the proposed approach. As was stated before, the amount of information that can be collected by the control boards of every single fan unit, interconnected using the classical approach, is very limited. In addition, the electronics present in those control boards are very constrained in processing power as they are aimed at getting data from different onboard sensors and transfer them to the controller (PLC), unless dedicated and expensive hardware is included to fulfil additional tasks (vibration analysis). With the use of a bespoke board featuring an industrial SBCM, a fan unit becomes more capable and able to process sensor readings locally and perform additional tasks, while making its routine maintenance and failure detection easier. This obviously increases the complexity of the software required to run the system, giving rise to the architecture described in the following chapter.

4.1 Software architecture

Given the complexity of the requirements of the proposed system, a distribution of different tasks involved was required. For this purpose, different languages were used in the implementation to give answers to several project challenges and needs.

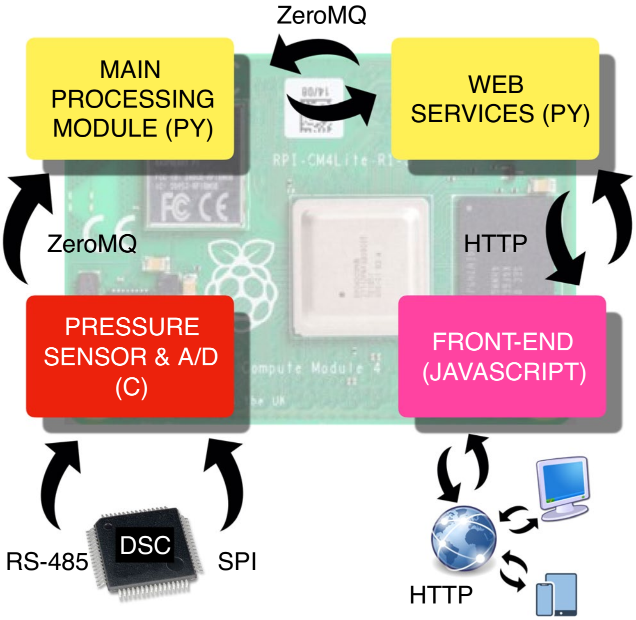


Fig. 5 Software architecture in ZJET equipment

The architecture of the SBCM software is composed of different modules (see Fig. 5) listed below together with the programming language used in each case.

- ADC module. Written in C to achieve maximum responsiveness, it collects the accelerometer data sent by the DSC when available.
- RS485 module. Also written in C, it handles the communication with the daughter cards that collect pressure data.
- Main processing module. Written in Python, it constitutes the core of the software that runs on the SBCM. It receives data from different sensors, some attached to the DSCs and some others directly to the SBCM, such as the IMU and the RTC. It also gets acceleration and pressure data from the previously introduced modules, by means of an IPC (Inter Process Communication) mechanism.
- Web services. Written in Python using the popular Flask module, they constitute a big improvement over currently available systems, as they introduce an additional way to exchange information with the fan.

In addition to the aforementioned components that make up the back-end of our platform, a web based interface (front-end) has also been developed using ReactJS and Node.js. This interface allows users to access all the sensor data provided by the board, while it also makes it possible to carry out maintenance, since a valuable vibration analysis is also available.

As already mentioned, different software modules developed for this project have been implemented using three different languages: Python, C and Javascript. The first one was chosen as the primary language for this implementation, as there is a vast amount of modules available to accomplish many heterogeneous tasks, such as SPI and serial Asynchronous communication, a rapid FFT implementation, data structures, Modbus TCP, etc. Nevertheless, Python is far from being the best choice for multi-threading and time-sensitive processes. To overcome this limitation, C was also used on the SBCM to implement the critical parts that require a lower-level programming language.

4.2 Communications and data exchange

In order to allow various software modules and hardware components to exchange information, different physical and logical communication protocols were used. The selected approaches are explained in detail in the following lines.

4.2.1 PLC ⟺ ZJET

These two systems exchange information using the TCP version of the ModBus protocol. This is a huge improvement over current ventilation systems that typically rely on a RS-485 serial interface, making the wiring more costly and less feature-packed. The PLC is mainly used to monitor all different parameters/signals the ZJET board provides, in addition to enabling the systems' administrator to modify some of the configuration parameters, such as the IP address, the threshold for a vibration alarm, etc. The ModBus TCP server has been implemented using the Python3 *modbus* module.

4.2.2 Web browser ⟺ ZJET

Another big improvement over currently available systems is the possibility to monitor different signals, and to be able to modify the aforementioned configuration parameters, using a standard Web interface. For this purpose, a responsive front-end was developed using Facebook's React JavaScript library [19]. In addition, a RESTful API was implemented using the Python3 *Flask* module to provide Web services for the aforementioned front-end component. This also makes it possible for the company to introduce additional applications that rely on those very same web services. The presented approach enables all the involved software components to interact with the aforementioned data acquisition and processing module.

Both the ModBus server implementation and the Web services rely on a third component which is the core of the software architecture. This process is responsible for the data acquisition and processing, which includes checking different inputs for off-the-chart values and also the advanced processing of the accelerometer signal that will be conveniently discussed in the following section. As the modules we are considering constitute separate processes, some IPC (Inter Process Communication) mechanism is needed. For this purpose, the powerful and platform-independent ZeroMQ framework [20] was used.

5 Vibration processing and analysis

The designed system can replace and exceed the performance offered by the use of expensive portable vibration measurement equipment, analysers and data collectors provided by reference companies such as ADASH [10] or IFM [21]. Processing and analysis carried out in the system are explained below.

5.1 Digitization and processing of vibration acceleration

As they have been exposed with the system architecture, digitized acceleration values are transferred to the SBCM, which is in charge of carrying out the complete processing to calculate the FFT. The frequency spectrum is obtained up to 3kHz with a frequency resolution that can be configured by the user and depends on the number of values considered. Additionally, Flat Top window functions can be applied to improve amplitude accuracy [22]. Once the frequency spectrum of the acceleration has been obtained, the frequency spectrum of the velocity can be calculated from the acceleration by directly integrating each component in the frequency domain. For a pure sinusoidal signal, the mathematical relationship between the amplitude of the acceleration and the vibratory velocity is established by the corresponding angular frequency (ω). Equal component values of vibration acceleration produce higher values of the spectral components of velocity when appearing at low frequency, since the velocity component is obtained by dividing the acceleration component by w. Digital filtering is carried out by eliminating the components below 10Hz, as established by the ISO 10816 standard.

Once the velocity spectrum has been obtained, the RMS value of the vibration velocity can be calculated through the composition of all the components at different frequencies.

5.2 Vibration analysis and diagnosis

RMS value of the vibration velocity as established by ISO 10816 standard to evaluate machine vibration by measurements on non-rotating parts is not really useful to make a diagnosis about the origin and reason for the vibrations. Not even the frequency spectrum of the acceleration allows a full diagnosis. For that reason, a processing of the temporary acceleration data captured is carried out in the ZJET system. In the spectrum of vibration accelerations, two different frequency ranges can be distinguished:

- At low frequencies, between 10Hz and 1kHz, vibrations appear that are multiples of the machine’s rotational speed, due to misalignments, imbalances and mechanical clearances.

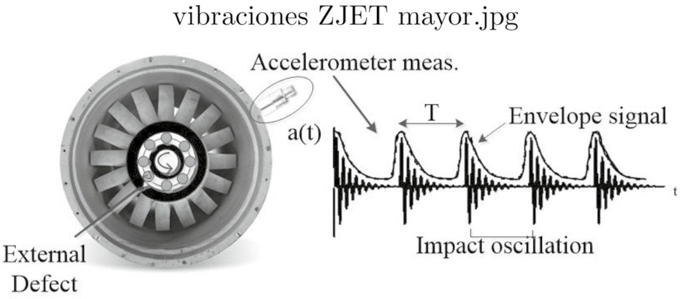
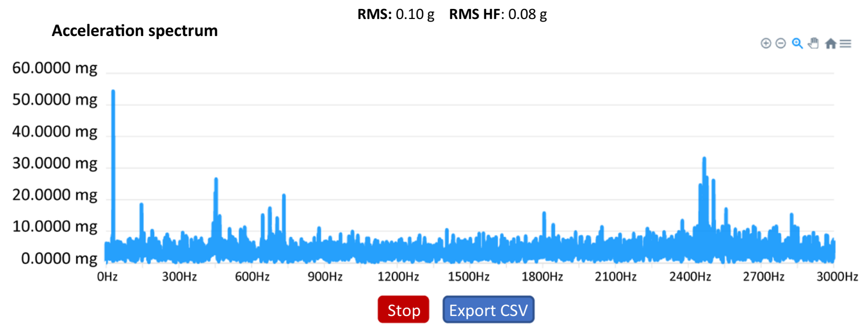


Fig. 6 Accelerometer recording due to breakage in the outer ring of the bearing

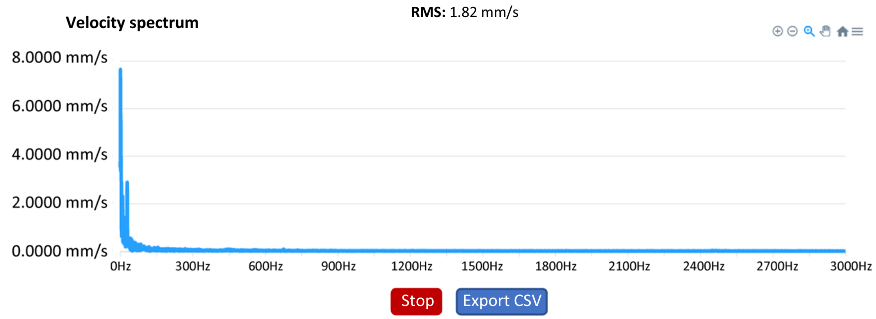
- At high frequencies, between 500Hz and 10kHz, vibrations appear due to bearing failure.

High-frequency vibrations due to bearing failure "disappear" or have little weight in the velocity spectrum when dividing by a high frequency value. In addition, the frequencies of vibrations due to bearing failures do not seem to present a direct relationship with multiples of the machine's rotational speed. This is so because the frequency recorded with the accelerometer is that of the mechanical resonance of the impact due to the passage of the bearing ball over an external or internal defect. Fig. 6 shows the record that an accelerometer would collect when the ball bearings pass over a breakage in the outer ring. In that case, it would be interesting to know the frequency of one ball passing over the external defect ($1/T$), i.e. the frequency of occurrence of the "impacts", known as BPFO (Ball pass frequency of the outer race), not the resonance frequency of the impact itself, which has a higher frequency content.

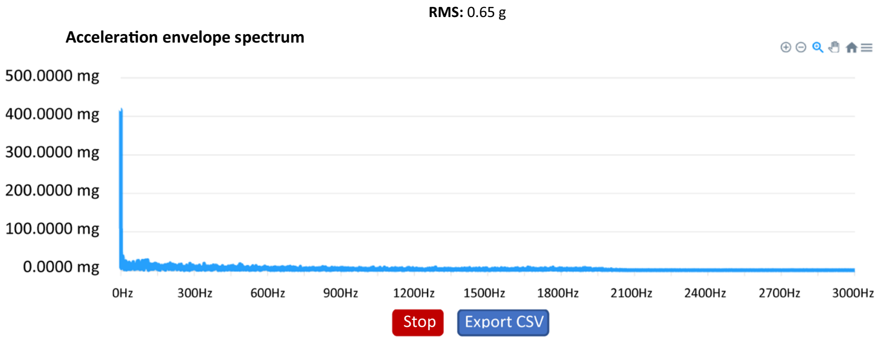
The acceleration spectrum is not totally useful as a tool for detecting bearing failures, but the demodulated acceleration signal spectrum is. The "demodulated" signal is the envelope of the acceleration signal and contains the information of the frequency of occurrence of the impacts (Fig. 6). Mathematically, the modulus of the analytic function of a temporal signal is the envelope of the original one [23]. In our system, before obtaining the envelope that allows us to assess only the bearing defects, a Butterworth band-pass filter is applied in the time domain, between 500Hz and 2.5kHz. In this way, the low-frequency components of the vibration acceleration that are proportional to the speed of the motor rotation (imbalances, asymmetries and clearance) and the high-frequency noise are eliminated. From this already filtered acceleration signal, the time envelope signal is obtained by employing the Hilbert transform. This transform gives us the imaginary part of the analytic signal; the real part is the signal itself and the module of the analytic signal is the envelope in the time domain. It is possible to apply a FFT on this envelope to obtain the spectrum that shows the frequencies of appearance of the defects (impacts) in the bearings. All the processing that has just been explained is also carried out locally in the ZJET system, taking advantage of the computing power available in the SBCM processor. In this way, from the sampled and digitized vibration acceleration values,



(a) Acceleration spectrum



(b) Velocity spectrum



(c) Acceleration envelope spectrum

Fig. 7 Three spectra obtained from the analysis of acceleration data

through the processing that has just been detailed, three different spectra are provided (see Fig. 7) to analyse the vibratory conditions: acceleration, velocity and envelope of the high-frequency acceleration.

In addition to the graphical representation of these three spectra, overall RMS values are calculated that allow the quantification of vibratory conditions. In a

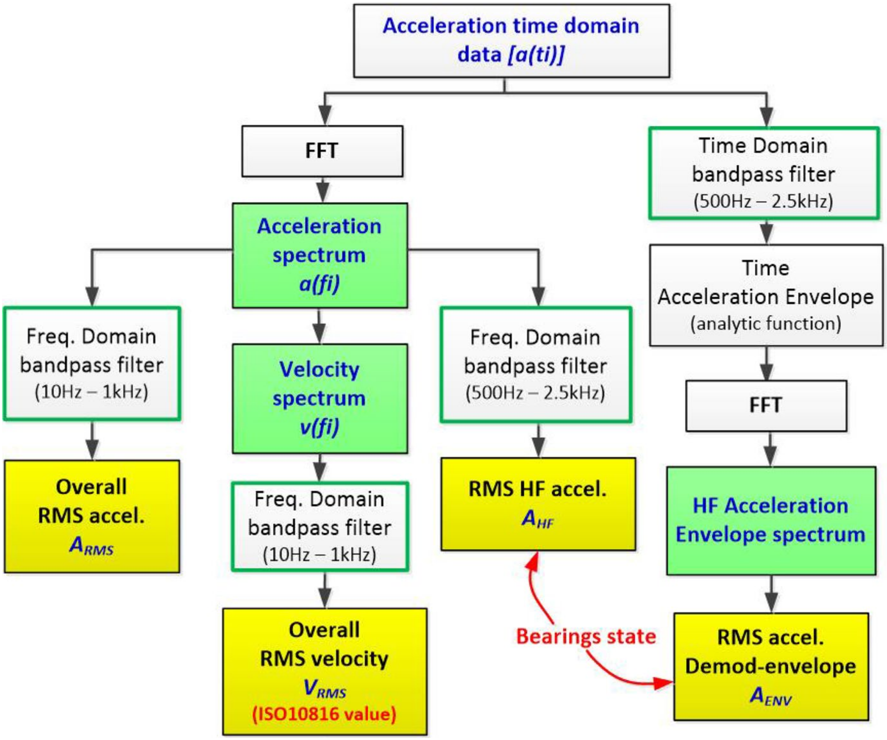


Fig. 8 Diagram of the data processing for vibration analysis

similar way to generic vibration diagnostic equipment [10], RMS velocity (V_{RMS}) and RMS acceleration (A_{RMS}) values are provided. Additionally, two other RMS values can be obtained: one of them corresponds only to the high-frequency acceleration, A_{HF} (500Hz to 2.5kHz); the second one is the RMS value corresponding to the demodulation of the high-frequency acceleration envelope, referred to as A_{ENV}. These two values allow a better assessment of the overall condition of the bearings, although they are only provided by specific measuring instruments. Figure 8 shows the complete data processing diagram that is carried out internally in the designed system.

6 Experimental validation

The results presented in the paper are real results obtained in a working fan: there are no simulation results. During the preliminary testing phase of the equipment in the laboratory, before the system was embedded in the fan, a voltage signal generator was used to introduce known waveforms to replace the signals provided by the sensors. Thus, for example, periodic waveforms whose harmonic content was known (square, triangle waves, etc.) were used to replace the signal supplied by the accelerometer in charge of measuring the vibrations. The objective was to be able to verify that the processing of the temporary acceleration values was correct and that the frequency spectrum obtained was as expected.

In order to verify the validity of the measurement and processing of the vibrations, a calibrated mechanical equipment that generates a known standard vibration (Model 699A02 Hand Held Shaker, from PCB Piezotronics) was used in a later phase. This piece of equipment is intended for rapid checking of vibration measurement, monitoring and recording systems using vibration transducers, as is the case in the designed system. Model 699A02 allows a precise adjustment of the measurement instrumentation, providing a standard acceleration level of 1 g RMS or a peak value of 1 g (it is possible to select between these 2 values), with g being the acceleration due to gravity. The vibration frequency is fixed and has a value of 159.2 Hz. The results obtained with the designed system, placing the axial accelerometer of the designed system on the Hand Held Shaker, showed great precision, both in the measurement of the amplitude of the vibration and in the frequency.

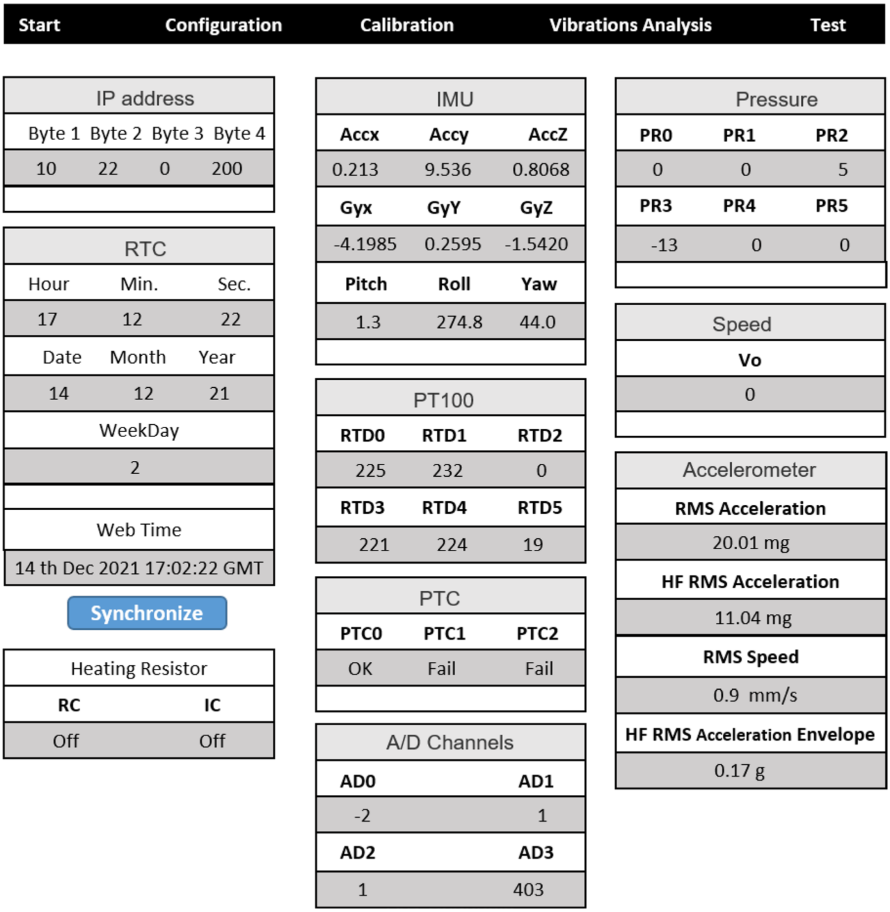
The equipment can act as a Web server, showing an interface accessible through a browser using the board's IP address. By means of this web interface, it is possible to configure the IP address, complete the signals setup (active sensors, vibration threshold and encoder ratio), set the time and date of the RTC and perform a calibration of the inputs (including the fan tilt angle offsets) used to measure the physical quantities that will be used in that particular equipment. Configuration and calibration access are hardware protected by means of one of the two switches that are located in the main printed circuit board. The other one is used to set the IP address (defect or configured value). Additionally, the web interface presents the real-time measured values of the active magnitudes according to the sample frequency (Fig. 9). It is also possible to control the heater situation.

Vibration acceleration has a special treatment and visualization. As well as the acceleration and velocity RMS values, the web interface graphically shows the frequency spectrum of the acceleration, the velocity and the acceleration envelope Fig. 7. The information provided by these graphs allows a complete diagnosis of the condition of the fan and the origin of the vibrations (bearings, imbalances or misalignment) can be established from these graphs. In order to evaluate the system previously described, specially vibration, a fan with the following specifications was used: 1.1 kW, 50 Hz, 230 V, 60 kg, ⌀=0.50m (Fig. 10). The evaluation has been carried out using two different pieces of equipment:

- ZJET processing. It uses the IFM VSA001 accelerometer.
- IFM equipment [21]: VES004, Parameter setting software for vibration diagnostic electronics. This system uses the same accelerometer as ZJET; however, the value or spectrum of the envelope cannot be provided.

Figure 11 shows the acceleration spectra obtained with both processing systems for one of the tests carried out, with the Fan rotating at 1500 rpm (25Hz)

Table 1 shows a comparative of the results obtained in another test, with a jet fan rotating at 1800rpm.



IP address

Byte 1	Byte 2	Byte 3	Byte 4
10	22	0	200

RTC

Hour	Min.	Sec.
17	12	22
Date	Month	Year
14	12	21

WeekDay
2

Web Time
14 th Dec 2021 17:02:22 GMT

Heating Resistor

RC	IC
Off	Off

IMU

Accx	Accy	AccZ
0.213	9.536	0.8068
Gyx	GyY	GyZ
-4.1985	0.2595	-1.5420
Pitch	Roll	Yaw
1.3	274.8	44.0

PT100

RTD0	RTD1	RTD2
225	232	0
RTD3	RTD4	RTD5
221	224	19

PTC

PTC0	PTC1	PTC2
OK	Fail	Fail

A/D Channels

AD0	AD1
-2	1
AD2	AD3
1	403

Pressure

PR0	PR1	PR2
0	0	5
PR3	PR4	PR5
-13	0	0

Speed

Vo
0

Accelerometer

RMS Acceleration
20.01 mg
HF RMS Acceleration
11.04 mg
RMS Speed
0.9 mm/s
HF RMS Acceleration Envelope
0.17 g

Fig. 9 Web interface

The RMS acceleration value is also shown superimposed on the graph in Fig. 11. Table 1 compares these same values, together with the RMS value of the speed obtained in a different test (the graph of the acceleration frequency spectrum is not shown for this case). The IFM device does not represent the spectrum of the vibratory acceleration envelope, nor does it provide its total RMS value; for this reason this value does not appear in Table 1. The difference between the RMS values of the total acceleration measured by the ZJET equipment and by the IFM commercial equipment is less than 10% in all the tests carried out.

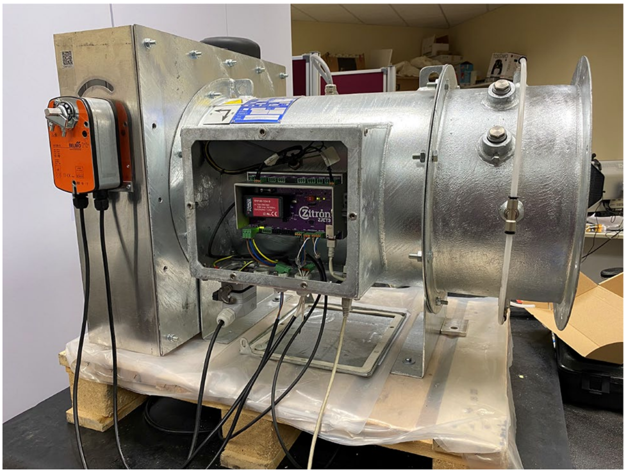


Fig. 10 Jet Fan under test

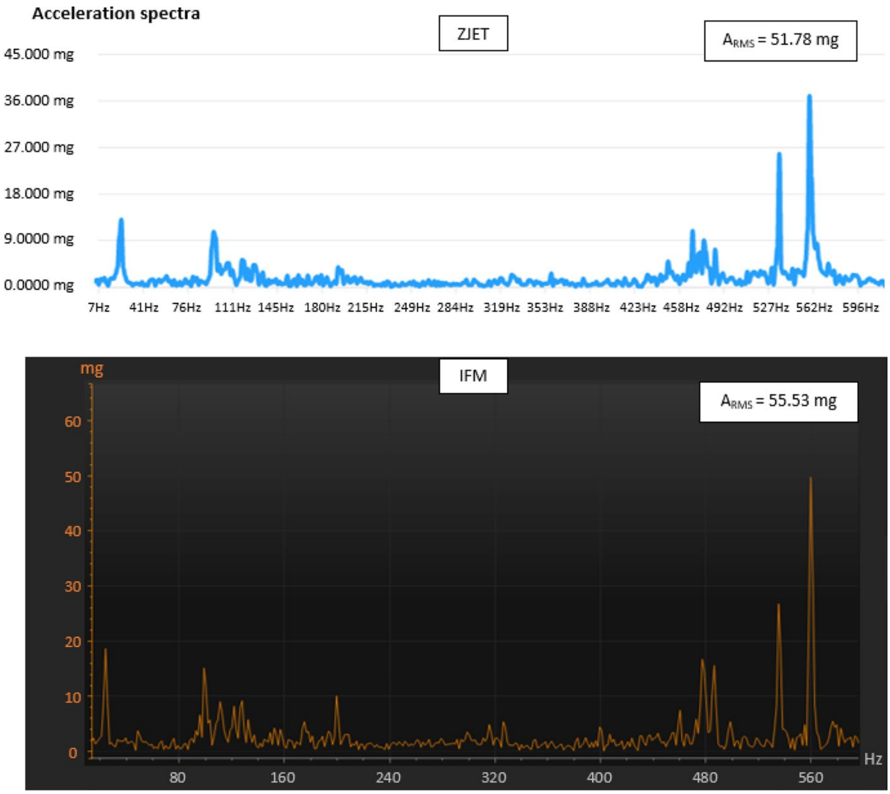


Fig. 11 Vibration results Jet Fan comparative

Table 1 Comparative results for a Jet Fan at 30Hz (1800rpm): ZJET versus IFM commercial equipment

	A_{RMS} (mg)	V_{RMS} (mm/s)	A_{HF} (g)
ZJET	87.69	3.34	0.32
IFM	98.94	3.39	–

7 Conclusions

In this paper, a new embedded equipment for remote supervision and advanced analysis of ventilation systems for underground infrastructures has been presented. The hardware design has been fully adapted to the application. Each piece of equipment monitors the status of a fan that is part of a global ventilation system, each of which is subjected to harsh working conditions and in inaccessible positions (the ceiling of a road tunnel with several kilometres in length may be the case). Each embedded device is a node of a TCP/IP over Ethernet network in which all the fans of a specific infrastructure are located. Each device can act as a ModBUS TCP server or HTTP server, using a simple cable as an external connection. Therefore, the system is externally accessible from a PLC that acts as a supervisor of the global system using the TCP version of the ModBus protocol and also from a Web browser to access Web services to monitor or configure the equipment. In this way, it is possible to monitor the main magnitudes of interest for each fan: temperature, differential pressure, rotational speed, inclination/orientation and vibration acceleration. The last-mentioned magnitude has a special computational treatment at the local level, as it is key to predictive maintenance. The hardware design is based on the use of a multi processor distributed system consisting of Digital Signal Controllers (low-cost microcontrollers) and a Single Board Computer Module adapted for industrial applications (low-cost and small size computer). The computational power of the latter enables local vibration processing: frequency analysis of acceleration, velocity and acceleration envelope to determine the mechanical condition of the fan (misalignments, clearances, bearings, etc.). This has been achieved with a low-cost embedded system that allows a very comprehensive vibration analysis to be performed on-site. Normally this can only be achieved with specific high-cost portable equipment for machine diagnostics. Thus, predictive maintenance can be ensured continuously, in real time and individualized for each fan.

8 Future work

The system described in this paper is in continuous development: there are a number of features that will be added in the near future.

The biggest and more important feature of all will be the development of a machine learning model for predictive maintenance [24]. As the current prototype is able to collect different parameters from the ventilation system, once a certain amount of units are manufactured and deployed in real working environments, these data in combination with the information from the faults that might appear after a certain amount of service hours will allow us to develop the aforementioned prediction model. For some specific characteristics, such as the diagnosis of faults in bearings, an effective method can be chosen from among all the possible ones [25–27], based on the data provided by the designed system.

Another improvement that could be considered is the use of a commercial cloud platform such as AWS or Azure. From a strictly technical point of view, this will pose a sensible choice as it opens many other possibilities for the product, besides data storage. Nevertheless, this feature is currently under study by the company and it might be also included in a future release.

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Data Availability Data sharing is not applicable to this article, as no data sets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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