SHM-BOARD

Hi-Performance Board

For Data-driven Structural Health Monitoring (SHM)

Designed by WEST Aquila S.r.l.

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SHM-Board Characteristics

The SHM-Board is a high-performance device for real-time structural health monitoring of private and public buildings and infrastructures, such as bridges, towers, pillars, etc. Accurate and continuous monitoring of the structures' vibrations helps program a prompt intervention to avoid or limit the structural risks and the direct or indirect consequences to people and goods.

This board is an evolution of a previous device developed in collaboration with the University of L'Aquila; the previous experience leads to notable performance improvement.
The board is based on a low-power microcontroller (MCU) made by ST Microelectronics (STM32F4 family), a 32-bit microcontroller offering several high-performance communication interfaces. The board also includes a slot for micro-SD cards for local data storage.

A tri-axial MEMS accelerometer is connected to a 24-bit Analog-to-Digital Converter (ADC) mounted on the board. The ADC has eight channels and can simultaneously sample them at a frequency of up to 64 kHz; the board locally elaborates the vibration data to reduce the quantity of data to transmit remotely.
The board fully complies with the typical requirements of SHM applications, which typically require data sampling up to 200 Hz.

System Architecture

In the typical use case, the SHM-Boards are connected over the LAN Ethernet + PoE to a local aggregator (gateway). The triaxial accelerometer's data are 24-bit each and generated at 100 Hz. After an eventual local computation aimed at reducing the amount of the total transmitted bytes, such data are continuously transmitted to a remote server, which handles their storage and allows for event detection and the off-line analysis of the historical traces/records to track down the behavior of the structures over long periods so that any small change in the way they react to random input forces might lead to the presence of structural anomalies.

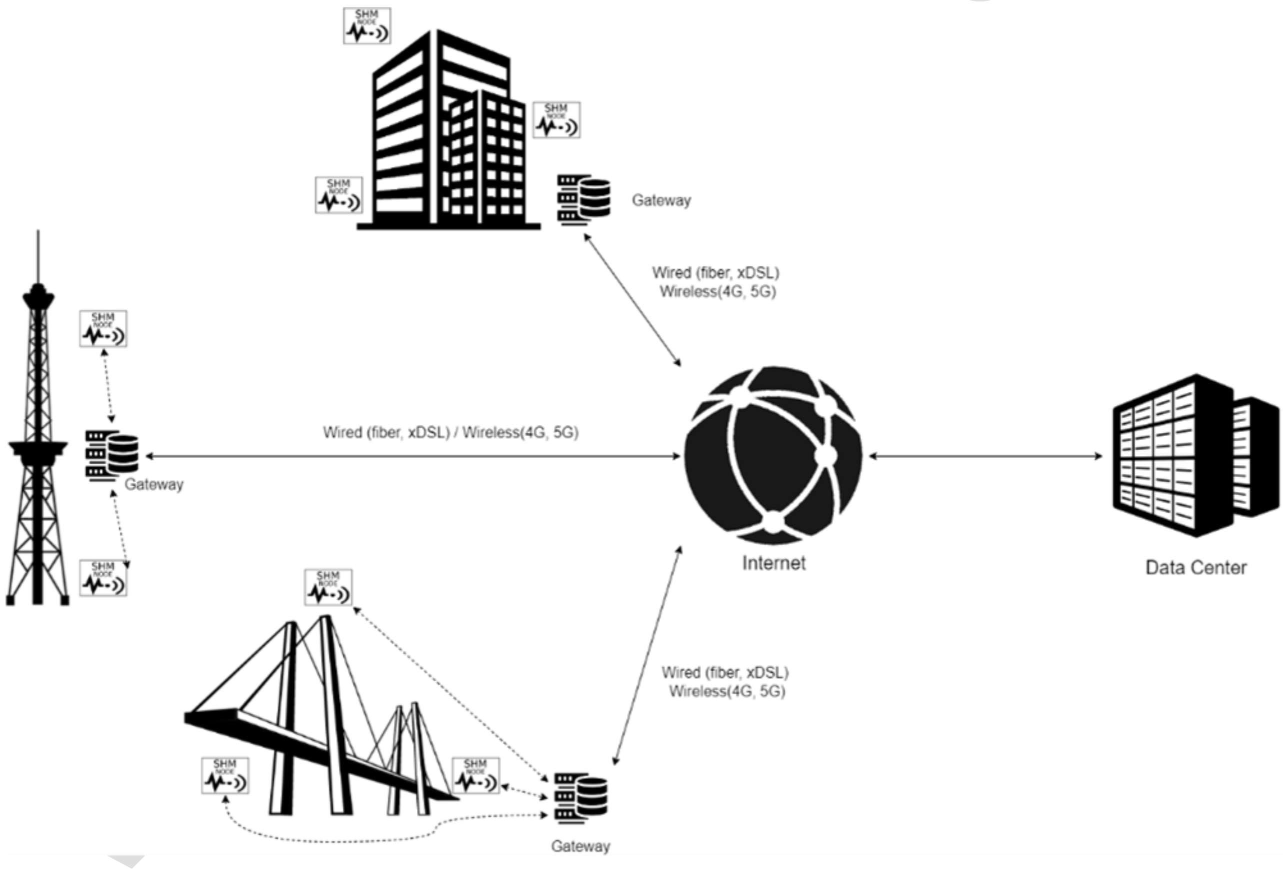

Figure 1: Reference architecture for the structural health monitoring based on the SHM-Board

Installation Examples

Figure 2 shows an example installation for a geometrically simple four-floor building. In contrast, Figure 3 illustrates the connections between the networking and power elements as well as the data flow from the SHM-Boards to the SHM-Router through the SHM-Gateway, which compacts the sensor measurements and runs a preliminary local analysis for event detection and structural health monitoring.

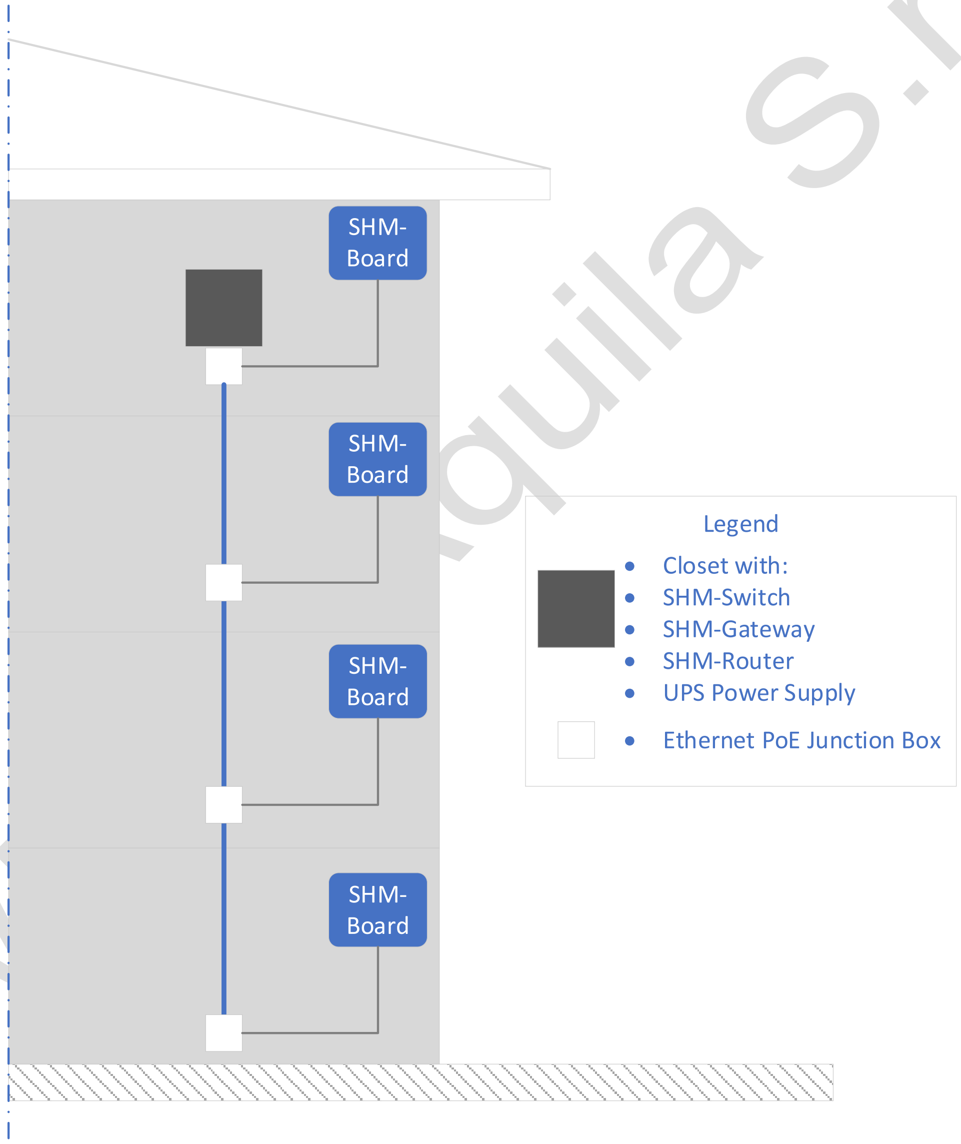

Figure 2: Installation example for a geometrically simple building.

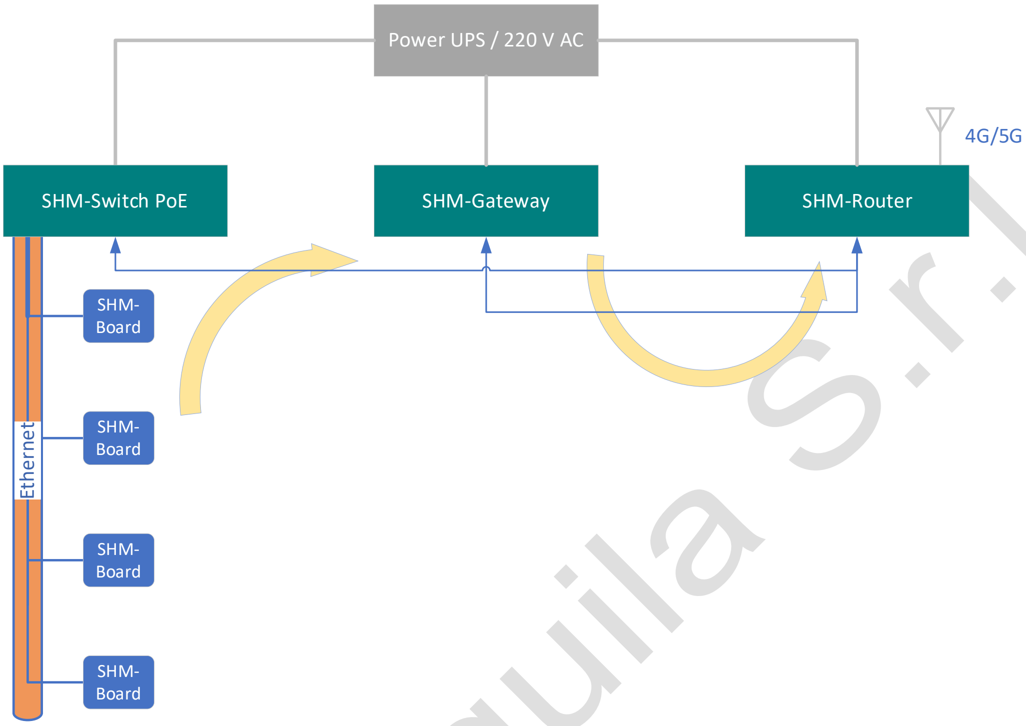

Figure 3: The scheme's networking elements and data flow from Figure 2.

Analogously, Figure 4 presents an installation scheme of the SHM-Boards along a bridge or viaduct. In this case, groups of SHM-Boards are connected to SHM-Switch PoE, and there is a fiber optical link between the switches (in this configuration, in a ring-based topology) to ensure connectivity over long distances to the single SHM-Gateway and SHM-Router, placed on just one side of the structure.

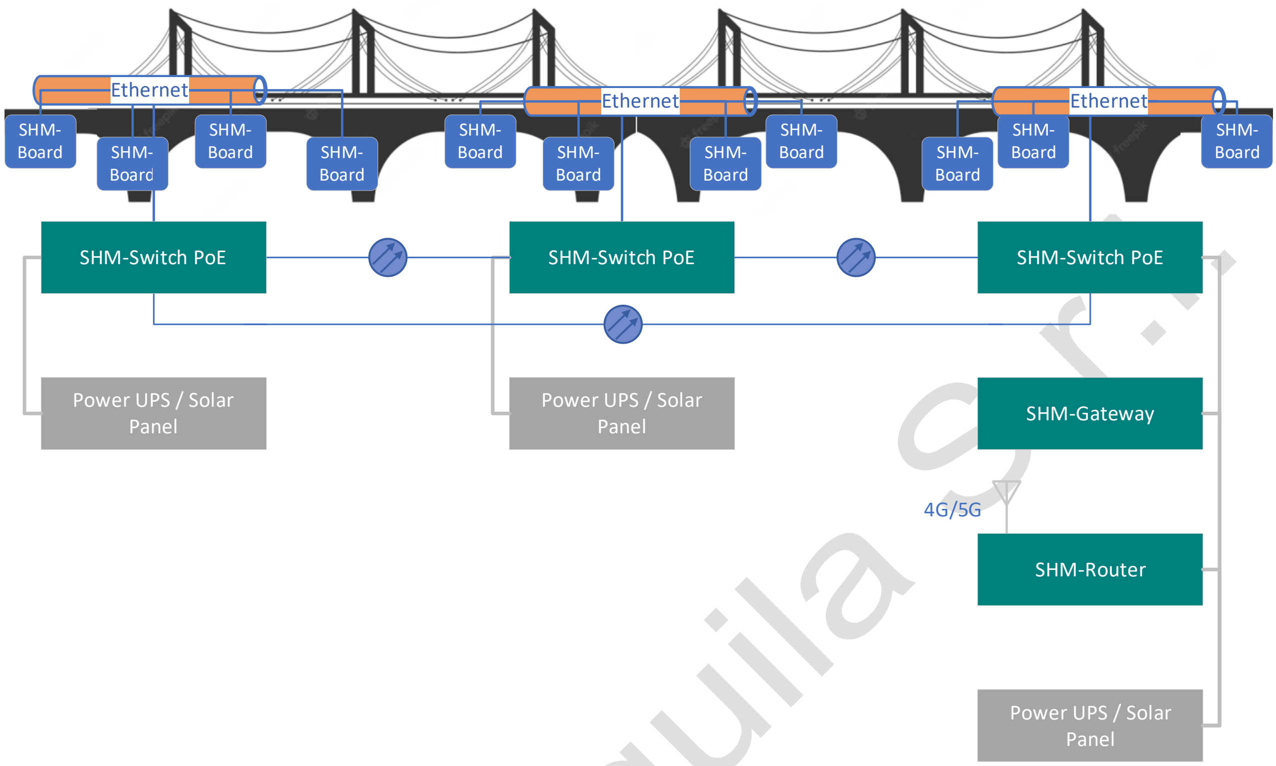

Figure 4: Installation example for a bridge/viaduct.

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Innovation Aspects of the SHM-Board

Most of the solutions available in the market are based on proprietary platforms, often made with heterogeneous components that must work together. For instance, some solutions foresee a Wi-Fi-based communication channel to send data and reports and assume a pre-existing wireless network is available. This approach has clear limitations regarding bandwidth saturation due to the network's promiscuous usage, e.g., when at home, the resources would be shared with daily activities, including teleconferences, streaming, or online gaming.

Other solutions use commercial external USB devices to provide remote connection through UMTS or 4G/LTE; these devices often suffer from interfacing issues due to driver adaptations from diverse manufacturers.

Our solution is based on a hardware platform on which there is complete control since it was entirely designed (HW) and programmed (SW) by our development team. This grants a high level of flexibility and adaptability to different application needs: the compatibility with several external sensors guarantees the possibility of adapting the platform's configuration to monitor modern and ancient/historical buildings, bridges, viaducts, trellis, etc.

The system architecture is a three-tier network that fully exploits the possibility of in-network data processing at multiple layers to favor the analysis, detection, and real-time reaction against an event while keeping at its minimum the probability of generating false alarms, often due to the local- or human-related factors, and that is typical of those solutions where no similar data aggregation and in-network filtering are present. In this context, WEST has recently been granted a patent to protect the uniqueness of this solution.

Furthermore, the proposed system differs from the other solutions available since it foresees the sharing of information from all the active installations so that the probability of raising false alarms is kept low while the approach is fully distributed. In this context, the timing synchronization among the different nodes of the network is of paramount importance for allowing the prompt and accurate reconstruction of the structures' response, i.e., to align the accelerometer's traces coming from the different sensors.

On the other hand, the proposed system allows storing all data from each sensor on a remote server without reducing the frequency of sampling the signals or sending the reports, i.e., without strict limitations on the duty cycle, which characterizes the other solutions. This feature allows offline analyses of the gathered data and enables the continuous development of training algorithms for machine learning to detect events. At the same time, however, the system can generate customized reports according to the user's needs. This allows for a concise presentation of the acquired data, making it easily readable by users of different backgrounds without compromising the possibility of performing specific structural analysis.

The system can also automatically reduce its sampling frequency and duty cycle of the data reporting to save energy when the nodes operate on quasi-exhausted batteries. Similarly, each SHM-Board can store data over the available SD local memory to overcome any temporary lack of connectivity with the SHM-Gateway. In contrast, any lack of connection from the SHM-Gateway and the remote server is automatically handled by storing the data on the SHM-Gateway local disk and is sent to the remote server as soon as the connection is again available.

Besides these aspects, WEST's development team is available to discuss with the customer to evaluate the implementation of additional features to solve specific user application requirements.

Monitored Parameters

The SHM-Board integrates a low-noise triaxial MEMS accelerometer to measure vibrations that excite the structure. This system allows for dynamic monitoring for assessing the damages to the facility, which includes a complete solution to measure and analyze the vibrations of civil buildings and infrastructures.

In typical scenarios, every SHM-Board is physically attached to the structure under monitoring, and the system should include enough boards to cover the entire construction. For instance, installing one SHM-Board on each floor for geometrically simple buildings might be enough.

Through the acquisition in real-time of the measurements, the system allows for the following:

- Identifying the modal frequencies of the structure and monitoring how they vary over time to detect the presence of damages as consequences of seismic events or just because of the aging effects.
    - Output-Only Modal Analysis during intervals long enough to allow filtering of the natural frequencies from the environmental noise due to ecological reasons (wind, rain, or daily/seasonal temperature variations) or artificial ones (vehicular traffic or the possible presence of work constructions in the surroundings).
- Understanding if the vibrations represent a disturbance or damage factor for the structure and the people living there.
    - Vibrational Analysis, with which it is possible to detect in real-time the magnitude of the vibrations in terms of spectral analysis (amplitude and frequency) to be compared with the thresholds defined by the international limits (UNI, DIN).

Besides the acceleration measurements, the system allows for monitoring of parameters related to settling, deformation, expansion, and contraction of cracks in walls and displacement of jointures, as well as degrading conditions due to environmental phenomena, through the integration of the proper external sensors. Such sensors include:

- Clinometers allow taking control of the structure's verticality (to be kept within given limits) or the static angular variation of the structural elements (to estimate the deflection of the floors, walls, and beams).

- Crack meters, which allow measuring variations of positions between two close points in joints, cracks, and gaps to control the evolution of the mutual distance between the anchor points, are used to monitor the growth of the cracking conditions or the effects of settlings or subsidence.
- Hygrometers for indoor applications. Several techniques, such as contact-based or infrared-based solutions, allow monitoring of the environmental humidity of surfaces. Thermobalance or capacitance sensors are used to measure the moisture within the materials such as wood. The latter assesses the humidity using ferrules that measure the material's conductivity between them or a sphere-shaped sensor that measures the material's dielectric constant through a high-frequency approach.
- Thermometers for indoor applications. They are used to monitor either the air or the surface temperature.
- Weather stations include one or more of the following sensors.
  - Anemometers. They measure the wind's direction and speed and can be implemented as fan probes or based on ultrasound technology. The latter's advantage is the higher accuracy while avoiding mechanical moving parts, so they are generally more robust and last longer.
  - Rain gauges. They measure the intensity of rain precipitations and their characteristics based on a counter of millimeters of water falling during a predefined interval. Such a measurement corresponds to the so-called "rainfall height."
  - Hygrometers. They measure the air humidity through accurate capacitance sensors and express it as a percentage of relative humidity.
  - Thermometers. They measure the air temperature through thermo-couples, thermo-resistors, optical pyrometers, or infrared cameras.
  - Barometers. They measure atmospheric pressure.
- Force sensors through load cells. They are used to monitor the tension status of lands, rocks and blocks, foundations, and concrete walls and to measure the excitation of concrete- and steel-made structures. They are used in monitoring the tension status of tie rods in working conditions and containment structures, such as walls, diaphragms, and bulkheads.
- Flood detectors. They are used in areas where there's a chance of losing liquids (generally, water and oil) that could expose people or goods to dangerous conditions if not repaired in time. The typical use case of these devices is to monitor the presence of liquid on the floors.

The system designed in this way is tailored to structural monitoring to stress possible vulnerabilities in terms of the shape and balance of the structures. Nevertheless, the system can integrate other sensors to forward their data through the same communication reference architecture (Figure 1) to offer added value monitoring services.

Some of these sensors do not need to send the measurements continuously but require working on a trigger mode (for instance, the flood sensor), i.e., they activate when a relevant event is detected; they can be powered through batteries and equipped with their own low-power radio communication interface.

The final configuration of the whole sensing system, the types of each sensor, and their placement and number are design parameters that should be fixed according to the specific application and installation requirements. More complex systems, which eventually include monitoring any chemical parameters other than physical ones (e.g., the measurement of the gluing status between different materials or sections of a wall), require ad-hoc configuration planning.