DESIGN OF AN IOT INFRASTRUCTURE DURING BRIDGE RENOVATION: A PRACTICAL EXPERIENCE FROM MOSORE PROJECT

Stefano Rinaldi[1], Paolo Ferrari[1], Alessandra Flammini[1], Adriano Reggia[2], Giovanni Plizzari[2], Giulio Maternini[2]
[1]Department of Information Engineering, University of Brescia, Brescia, Italy
[2]Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy

Abstract

In recent years, the Internet of Things (IoT) paradigm has been widely used in many industries, increasing data availability. The Sustainable and Resilient Mobility (MoSoRe) project aims to improve sustainability and resilience in mobility by applying the IoT paradigm. IoT paradigm enables real-time Structural Health Monitoring (SHM) of bridges and road infrastructures. The purpose of this study is to present the practical experience gained during the MoSoRe project in designing and implementing an IoT infrastructure for SHM of a renovated bridge. The methodology used reduces the impact of sensor installation on infrastructure.

Introduction

The Internet of Things (IoT) paradigm has seen widespread adoption in a variety of industries, including construction sector. The spread of this paradigm has been aided by the decrease in the cost of electronic systems, which has allowed the integration of microcontrollers in a greater number of devices, as well as the evolution of protocols and communication systems (Fernandes Carvalho *et al.*, 2019), which has facilitated sensor integration and information sharing. This information integration has enabled the development of previously unthinkable services and applications.

IoT systems are now used in a variety of applications. For example, they are widely used for the management of ventilation systems in school buildings (Tagliabue, Re Cecconi, *et al.*, 2021), they are used to monitor building user preferences (Audrito *et al.*, 2023) and they are used to improve the overall building sustainability (Tagliabue, Cecconi, *et al.*, 2021).

IoT systems are also used in other industries, such as Structural Health Monitoring (SHM) (Ardani, Eftekhar Azam and Linzell, 2023). This application has fully embraced the benefits of the IoT paradigm, such as the integration of data collected from various sensors, such as accelerometers (Kordestani, Zhang and Masri, 2023), and more broadly distributed measurement systems (Li *et al.*, 2010). In some cases, time synchronisation systems are required to correlate the information collected at different points of the measurement system, as suggested in (Liu *et al.*, 2010). These monitoring techniques have been used not only on newly constructed bridges, but also on renovated bridges, as in (Zhan, Long and Gui, 2020). In general, to extract information from heterogeneous sources, most of these systems require tight integration with ICT systems, as in (Yin, 2021).

The goal of the research presented in this article is to present practical experience in conducting a bridge renovation project near Bassano Bresciano, Italy, and in integrating it into a supervision and monitoring system using several types of IoT sensors. The information gathered about the SHM of the bridge will be combined with data from other road infrastructures to optimise the sustainability and resilience of mobility for the users, which is one of the goals of the MoSoRe research project, which is funded by the Lombardy region, Italy.

The structure of the paper is as follow. The following section introduces the Sustainable and Resilient Mobility (MoSoRe) project, whose goal is to show how the availability of digital information can improve the sustainability and resilience of mobility and the infrastructure that supports it. The third section provides a brief overview of the renovation process of a bridge, part of the MoSoRe project. The fourth section describes the design of the digital infrastructure for monitoring the intervention. The fifth section presents the preliminary results of the experimentation. Finally, the results are summarised in the closing section.

The MoSoRe project

The MoSoRe Project focuses on mobility resilience, proposing solutions for road infrastructures, charging infrastructures for electric vehicles, ICT infrastructures, and a new vector that allow users to move around safely, calmly, and within expected times, even in the presence of events or emergency situations. The integration between the road infrastructures and sensors with the rest of the ICT platforms involved in the project is shown in Figure 1.

In terms of road infrastructure, there are three main goals: developing new materials and monitoring tools for innovative structural recovery interventions, performing a jacketing intervention on a bridge and tracing its state of health, as well as developing predictive diagnostic tools; road surface wear monitoring systems, experimenting with data fusion between information from specially developed sensors and information already available from various sources; Innovative traffic monitoring and emergency or crowding management systems.

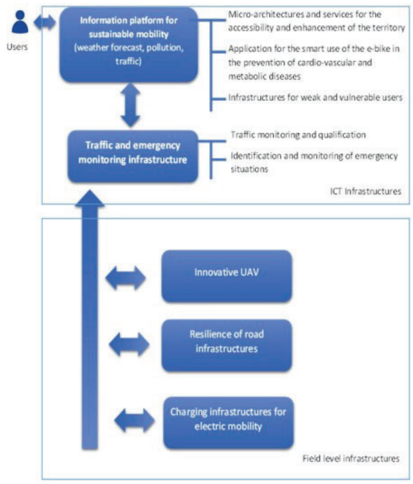

Figure 1: The interaction between field level road infrastructures and ICT infrastructures in the MoSoRe project.

In terms of electric recharging infrastructure, the goal is to develop smart recharging stations that increase the resilience of the electricity grid through accumulation systems and integrated renewable sources, abandoning the concept of complete recharging in favour of partial recharging, which takes into account vehicle profiling, driving style and driver range anxiety, traffic to get to the destination, and any recharging points along the route that can reduce recharging; the charging stations that will be built will have modular architectures that can recharge cars, e-bikes, scooters, wheelchairs for the disabled, and drones (Rinaldi, Pasetti, Flammini and Maternini, 2021) (Rinaldi, Pasetti, Flammini, Ferrari, *et al.*, 2021).

In addition to the traffic and emergency information system, which can be useful to the bodies proposed for traffic channelling interventions, the project aims to develop a user platform that allows him to access information on traffic and emergencies, recharging stations, but also information on cycle paths, the most beautiful, least polluted routes, the health benefits of walking or cycling, tourist routes, and routes designed for the disabled.

The main targets of MoSoRe project are:

1. *Infrastructure for the resilience of transportation facilities*. The target is to provide the infrastructure manager (province, highway company, etc.) with information and services relating to infrastructure maintenance and interventions required for safety, even in the event of an emergency or the need to channel traffic (civil protection, accidents, gatherings, natural disasters, etc.).
2. *New building materials for road infrastructure recovery*. The project focuses on the development and testing of a new high performance smart concrete for jacketing reinforced concrete structural elements deteriorated by use and time, such as pillars and beams in viaducts and bridges. The recovered element, in addition to restoring the degradation, will allow for more efficient monitoring in the years to come, thanks to the development of post-intervention predictive diagnostic services made possible by the material's smart characteristics, its integration with pre-existing or installed sensors during the intervention, and its connection to the ICT platform, Spatial Data Infrastructure (SDI), for road infrastructure monitoring.
3. New infrastructures and solutions for road surface monitoring and predictive diagnostics. A stratification of pre-existing information (year of construction, type of material, design methods and characteristics) in conjunction with the network of information, derived from sensors integrated in the car, the ability of electric vehicles to make the best use of acoustic information, information derived from drones and visual monitoring systems, and, more broadly, data derived from the web (weather data, traffic quantification and typology data, precautionary or corrective interventions -e.g. salt spreading, hole coverage, etc.-), feeds the ICT – SDI platform. This platform enables efficient and long-term monitoring of road infrastructure. As a result, the operator can optimise inspections and corrective actions, as well as assess the impact of traffic channelling interventions in the event of emergencies or accidents.

The renovation works: Bridge jacketing

The bridge involved in the testing of the MoSoRe project is located in the municipality of Bassano Bresciano (BS), Italy, along the SP45 bis road. Figure 2 and Figure 3 show the status of the bridge before the renovation, while Figure 4 shows a detail of the deterioration of the bridge. The solution adopted by the MoSoRe project for the renovation of the bridge is based on jacketing (Adriano, Morbi and Plizzari, 2018).

The adopted solution is to cast a very fluid fibre-reinforced concrete around the structural element, forming a new skin a few centimetres thick. In terms of performance, the concrete in the Jacketing solution belongs to the category of very high-performance concretes. The fibres inside provide ductility and extremely high residual strength to the material.

This new layer has important characteristics:

- *Durability:* This solution has an extremely high durability, thanks to the unique chemical structure of the concrete mixture, which prevents aggressive agents from penetrating the concrete, as well as the negligible risk of cracking. Ordinary maintenance costs can be significantly reduced because of this high durability, ensuring a longer useful life of the work.
- *Strength:* As the solution interacts with the deteriorated structure, its bearing capacity and ductility increase. Both factors are critical for increasing the structure's seismic resistance. Because of the presence of steel fibres, the Jacketing solution responds to seismic events by generating a slew of small cracks that allow

the structure to deform without collapsing, ensuring the safety of people.

- *Fire resistance:* The solution also improves the structure's behaviour at elevated temperatures. The residual compressive strengths of the material are approximately 60-70% of the original ones up to 750°C.

Figure 2: The status of the bridge before the renovation. Rear.

Figure 3: The status of the bridge before the intervention. Front.

Figure 4: Details of deterioration of the bridge.

Jacketing was validated at Product Innovation Center of Italcementi i.lab in collaboration with the University of Brescia and the University of Naples Federico II. Full-scale tests on pillars and beams reinforced with the Jacketing solution allowed the performance of the reinforced elements to be validated.
The results show that the useful life of the works can be extended by one hundred years and that the resistance of the elements can be six times that of the original elements. As a final validation, tests on a 1:4 scale bridge pile compared to the size of a real pile were performed. The bridge pier was initially damaged to simulate a 50-year exercise before being reinforced with the Jacketing system. When subjected to seismic action, the pile withstood large deformations and demonstrated excellent post-cracking strength. Another critical aspect is the dimensioning and verification of reinforced sections. Along with the technological solution, a forecast calculation model was created and validated in full-scale tests at the laboratories of University of Brescia (Reggia, Morbi and Plizzari, 2020).
The experience acquired from the laboratory validations allowed us to plan the implementation of this solution for the bridge renewal as part of the MoSoRe project. Figure 5 depicts the renovation project. The monitoring system was designed at the same time, to optimize the installation costs of sensors and monitoring system. The design of SHM is shown in Figure 6. The structure of the overall monitoring system, including sensors and the data acquisition system, is detailed in the next section.

The SHM monitoring system

The parameters monitored by the SHM

SHM systems collect a variety of parameters from bridges in order to monitor structural integrity and performance over time. In particular, the designed SHM system collect the following key parameters from the bridge:

Acceleration: The SHM system employs accelerometers to measure the vibration and acceleration of the bridge in response to traffic loads, which can be substantial on the road under consideration. This information is used to detect any unusual or excessive vibrations that may indicate structural damage or fatigue.

Strain: Strain gauges are used to measure how the bridge structure deforms under different loads. This information can assist engineers in determining the stress levels within bridge components and identifying potential areas of weakness or fatigue. Strain gauges are installed in the parts of the bridge that are most affected by potential deformation in the use case under consideration.

Temperature: the designed SHM system also monitors the temperature of bridge components for changes that may indicate material degradation or structural damage.

Humidity: Humidity sensors are used to monitor moisture levels within the bridge structure, which can have an impact on its structural integrity over time. In the case under consideration, we use impedance sensors to estimate the level of humidity in the structure.

Traffic load: SHM systems also collect data on the weight and frequency of vehicles crossing the bridge, which can assist engineers in determining the impact of traffic loads on the bridge structure as well as monitoring any changes in traffic patterns over time.

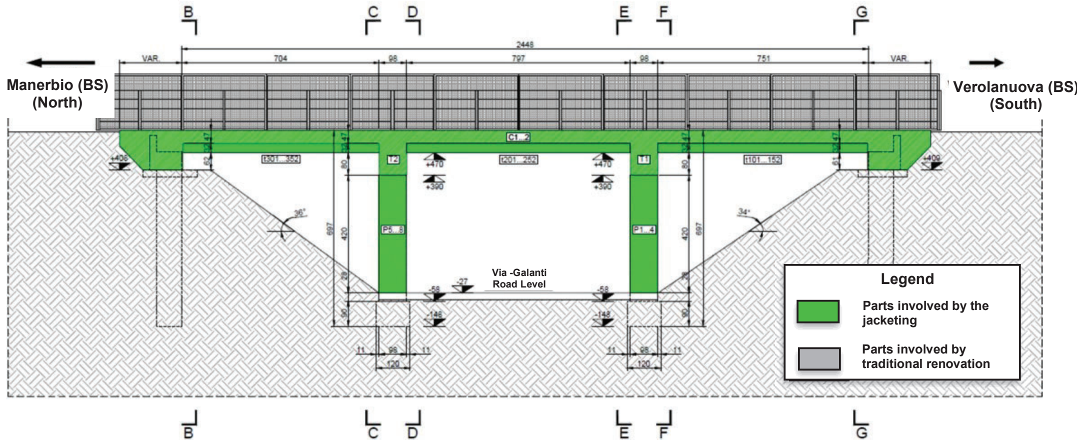

Figure 5: The design of the renovation of the bridge.

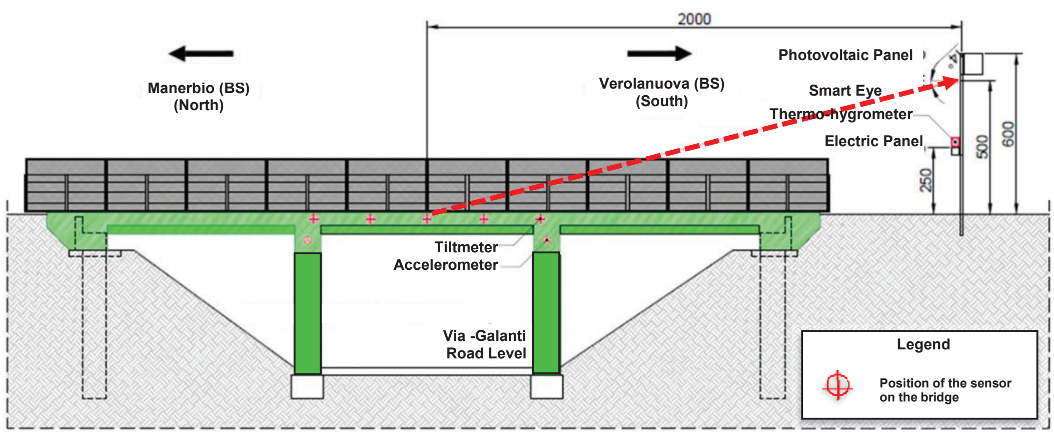

Figure 6: The design of the monitoring system to be installed during the renovation phase of the bridge.

The design of the monitoring system

To evaluate the SHM, a distributed monitoring system capable of collecting various parameters from the renovated bridge was implemented. The system is completed by a remote data collection information system hosted on the servers of the eLUX laboratory of the University of Brescia. The goal of the remote information system, as described in the previous sections, is to integrate data from various information sources positioned on road infrastructures and to support users of these infrastructures and the companies responsible for their maintenance about the SHM of the road infrastructures. The devices in the field communicate with the remote monitoring system using the Message Queue Telemetry Transport (MQTT) protocol. The architecture of the monitoring system is depicted in the *Figure 7*. A 4G industrial router (Siemens Scalance M840) connects the monitoring system on the bridge with the supervisory system. The router connects the system to the Internet and, thanks to the integrated firewall functions, ensures the security of the system against unauthorized external access. The router is linked to the servers of the University of Brescia via a Virtual Private Network (VPN) to allow remote management and supervision of the system. The data transmitted by the local SHM system is collected by a remote server, hosted by the eLUX lab of the University of Brescia. The server offers users the capability to store, to visualise in real time the data (through a dedicated web-based dashboard) and to perform an analysis of the KPI. The remote system is also able to raise an alarm when the bridge is go beyond a predefined critical alert threshold. The sensors and monitoring systems communicate with one another via a Local Area Network (LAN). A 10/100 Ethernet switch with Power Over Ethernet (PoE) support was used to set up the LAN network. As a result, all the devices that comprise the monitoring system are powered by the same cable that is used for communication, lowering system installation costs. The monitoring system consists of a supervision edge device (created with a suitably programmed Raspberry PI board) whose task it is to interface and process data from Smart Sensors that have a communication interface but do not support MQTT communication or the data model required by the remote supervisory system.

The edge device is fully programmable, even remotely, and provides local computing capacity for dedicated data processing, such as data compression generated by sensors to reduce data transmission. Sensor Acquisition Boxes (SABs) round out the monitoring system. The SABs allow data to be collected from analogue and digital sensors located directly on the bridge sections to be monitored. Every SAB is outfitted with an I/O Edge device (implemented through a suitable Raspberry PI board). The system is powered and linked to the rest of the monitoring system via a 10/100 PoE Ethernet connection. The maximum allowed distance between the remote SABs and the Ethernet Switch is 100 m. Figure 8 shows a simplified block diagram of the SAB. *Figure 9* shows the SAB prototype connected to a biaxial inclinometer and a triaxial accelerometer supplied by STM Microelectronics, a MoSoRe project partner. The prototype is placed and installed on the renovated bridge. Figure 6 shows the position of each SAB on the bridge, as well as the sensors that each SAB interfaces.

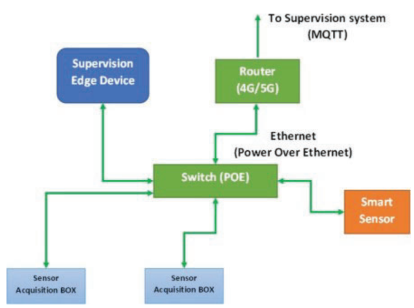

Figure 7: The architecture of the SHM monitoring system.

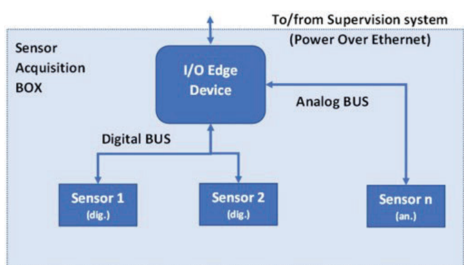

Figure 8: The block diagram of the sensor acquisition box designed during the MoSoRe project.

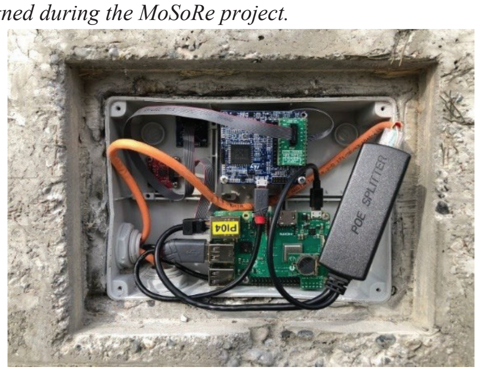

Figure 9: The prototype of SAB1 installed on the renovated bridge. SAB1 is equipped with a triaxial accelerometer and a biaxial inclinometer.

The deployment of the monitoring system

The type of sensors that must be installed and their position to monitor the SHM were defined during the design phase of the renovation of the bridge located in Bassano Bresciano, Italy. In particular, the position of the sensors on the bridge, as shown in Figure 6, has been defined during the design phase by using proper simulation: the sensors were placed in positions exhibiting the larger deformation. The sensors that have been installed in detail are as follows:

- one environmental temperature and relative humidity sensor, UTAC from Nesa s.r.l., with RS-485 Modbus output, connected to the supervision edge device;
- one digital tiltmeter from Sisgeo s.r.l. with an RS-485 Modbus output, connected to the supervision edge device;
- eight strain gauge used to estimate the strain of the bridge, connected to the supervision edge device through an analog acquisition board;
- one camera equipped with Artificial Intelligence board able to classify the type of traffic and the speed of vehicles on the bridge. The camera is provided by Smart Eye;
- one sensor used to estimate the change of impendence of the jacketing layer; the sensors has been designed by University of Brescia and it was connected to a SAB for data transmission;
- five bi-axial inclinometer sensors placed along the bridge to be monitored. The sensors have been designed by University of Brescia with the support of STM microelectronic, partner of the MoSoRe project. The sensors have been connected to a SAB for data transmission;
- five tri-axial accelerometers placed along the bridge to be monitored. The sensors have been designed by University of Brescia with the support of STM microelectronic, partner of the MoSoRe project. The sensors have been connected to a SAB for data transmission;

The last three types of sensors were built with ST Microelectronics components, installed at various points along the bridge structure and deployed into the jacketing layer. The sensors were programmed, configured, and validated at the electronics laboratory of University of Brescia. The complete list of installed sensors is shown in Table 1. After the proper operation of sensors was confirmed, they were installed at the Bassano Bresciano (BS) bridge. The data collected by the sensors is transmitted using MQTT protocol via the SABs to the supervision system, which is installed in the server room of the eLUX laboratory of University of Brescia.

Table 1: The list of the sensors installed on the renovated bridge and their sampling time.

Sensors	Num.	Sampling time	Position
Environmental Temperature	1	60 s	Pole

Environmental Relative Humidity	1	60 s	Pole
Concrete temperature	10	60 s	Beam/Pile
Biaxial tiltmeter (reference)	1	0.5 s	Beam
Biaxial inclinometer	5	10 ms	Beam/pile
Triaxial accelerometer	5	40 µs	Beam
Strain gauge	8	10 ms	Pile
Concrete Impendence	1	4 read per day	Beam
Traffic qualification	1	1 s	Pole

The sensors installed on the bridge structure were installed during the renovation phase of the bridge. *Figure 10* shows the position of the sensors after renovation. Take note of how the sensors are integrated into the jacketing layer.

Figure 10: The positioning of the sensor on the bridge. Note the integration of the sensor into the jacketing layer.

The results

This section contains data collected by sensors installed on the Bassano Bresciano bridge on October 28, 2022, beginning at 5.00 p.m. The system is set up to send a continuous stream of information to the supervision system in real time. Figure 11 and Figure 12 show data from the thermo-hygrometer installed near the Bassano Bresciano bridge on, respectively, environmental temperature and relative humidity. This data is collected by the system to compensate for the data provided by the inclinometer and accelerometer sensors, if necessary. The graphs show the trend of ambient temperature and relative humidity, which were sampled every 60 seconds over a 72-hour period. The temperature and relative humidity trend illustrate the typical daily cycle. The data generated during the same time interval, but over a shorter time horizon, of the data transmitted by one SAB installed on the Bassano Bresciano bridge are shown below. SAB1 has a triaxial accelerometer sensor as well as an inclinometer. The acceleration information provided by the biaxial inclinometer has been appropriately processed to estimate the inclination value of the sensors, by means of proper trigonometric formulas. Figure 13 shows the trend of the normalised inclination, i.e., the variation of the angle with respect to the average value of the angle caused by sensor installation, over an observation interval of about 160 seconds. As shown in the figure, the passage of vehicles of varying weights causes a different inclination of the sensor located on the bridge.

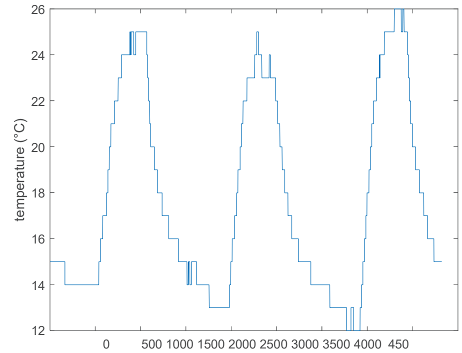

Figure 11: The environmental temperature monitored starting from 28 October, 17:00. Observation interval 72 hours.

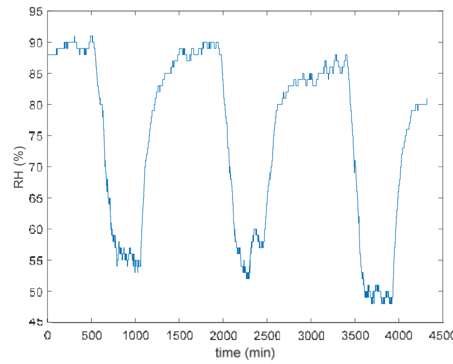

Figure 12: The environmental relative humidity monitored starting from 28 October, 17:00. Observation interval 72 hours.

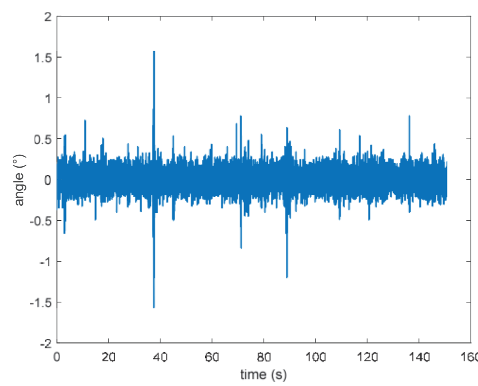

Figure 13: The normalizedang (Sampling time: 10 ms). monitored by SAB1 startl ing from 28 October, 17:00. Observation interval 160 s.

The normalised inclination value has been processed to obtain the value Root Mean Square (RMS) of the normalised inclination to improve the interpretation of the data provided by the digital sensor and to facilitate the detection of the passage of a heavy vehicle. The RMS value has been estimated on a moving window of one hundred samples. Figure 14 depicts the trend of the RMS value of the normalised inclination. It should be noted of how easily identifiable the heavy vehicle passages on the bridge are. As a result, by imposing a threshold on the RMS value, it is possible to easily classify the events of interest.

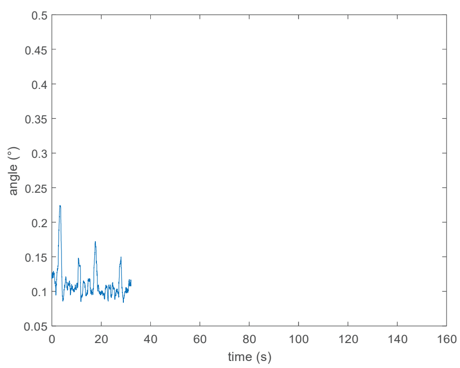

Figure 14: The RMS of angle (Sampling time: 10 ms). monitored by SAB1 starting from 28 October, 17:00. Observation interval 160 s.

Figure 15, Figure 16, Figure 17 show the normalised acceleration value, which has been compensated by the average value due to the installation position of the sensor connected to SAB1, respectively on x, y, and z axes. The sampling interval is 40 µs. Due to the limited capacity of the serial communication channel of the ST prototypes created, it only allows burst and non-continuous acquisitions compared to inclinometer sensors, limiting the possibility of continuously monitoring the passage of heavy vehicles. The figures show a 7.5-second observation interval. The information content of the tri-axial accelerometer sensors was found to be limited with the respect to the inclinometer, despite a significant increase in the cost of managing the data flow.

Discussion

The practical experience gained during the installation of an IoT system on a bridge for SHM allowed to define of a guideline that apply in similar situations. In details, the critical points are:

The importance of careful planning: Before installing an IoT system on a bridge for SHM, it is crucial to have a clear understanding of the design of the bridge, construction, and expected behaviour, which can be estimated though proper simulations. This understanding should guide the selection of appropriate sensors, installation location, data analysis techniques, and data visualisation tools.

The need for robust and reliable communication: An IoT system relies heavily on communication between the sensors and the central data analysis and visualization systems. The system should be designed to be resilient to network outages, electromagnetic interference, and other potential sources of disruption.

The importance of data security: Data collected by an IoT system for SHM may contain sensitive information about bridge performance and maintenance requirements. It is critical to ensure that the data is properly protected against unauthorised access or misuse. Modern cybersecurity techniques should be used during the design of the data acquisition system.

The value of real-time data analysis: One of the key benefits of an IoT system for SHM is the ability to collect and analyse data in real-time. This can provide early warning of potential problems, allowing for timely repairs or maintenance.

The need for ongoing maintenance and calibration: The effectiveness of an IoT system is limited by the sensors and data analysis tools it employs. Regular system maintenance and calibration are required to ensure that the data collected is accurate and dependable. During the deployment phase, an appropriate data acquisition system maintenance and update service should be provided.

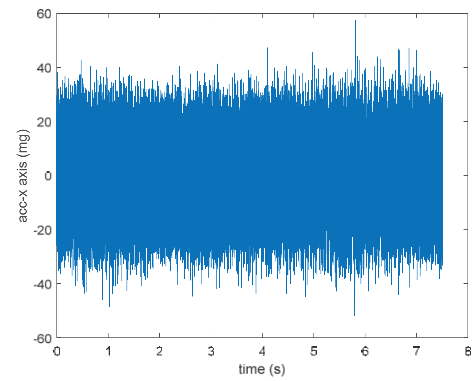

Figure 15: The normalized acceleration on x-axis (Sampling time: 40 µs). monitored by SAB1 starting from 28 October, 17:00. Observation interval 7.5 s.

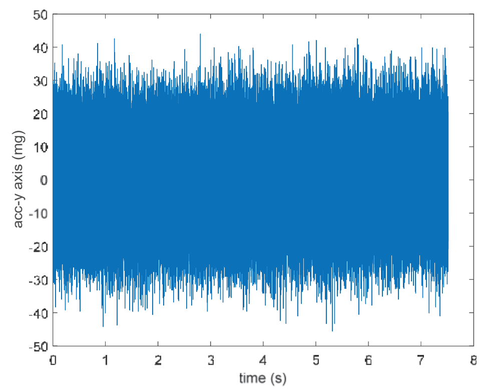

Figure 16 : The normalized acceleration on y-axis (Sampling time: 40 µs). monitored by SAB1 starting from 28 October, 17:00. Observation interval 7.5 s.

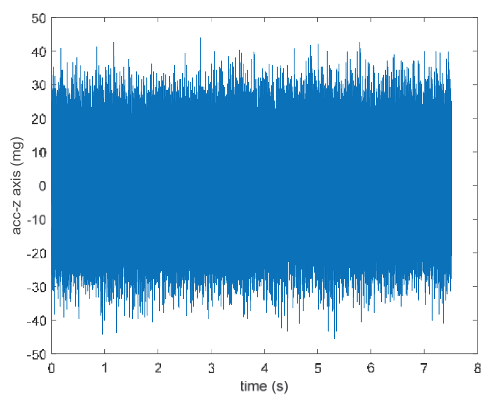

Figure 17: The normalized acceleration on z-axis (Sampling time: 40 µs). monitored by SAB1 starting from 28 October, 17:00. Observation interval 7.5 s.

Conclusions

In recent years, the Internet of Things paradigm has revolutionised several industries, including the construction sector. The increased quantity and quality of information has enabled the development of previously unthinkable services and applications. The research described the practical experience gained while developing an IoT system to monitor the SHM of a bridge near Bassano Bresciano, Italy. The monitoring system was designed in close collaboration with the renewal work of the bridge, allowing installation costs to be minimised. The system developed is a close integration of information collected from several types of road infrastructure, which is run through the information system of MoSoRe project. Because of this integration, the development of services to improve sustainability and resilience of the mobility has been made possible.

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