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Bridge Health and Monitoring System

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Abstract:
Bridge Health Monitoring (BHM) systems have become integral in ensuring the safety, reliability, and longevity of bridge infrastructures worldwide. As bridges age and are subjected to increasing traffic loads and environmental stresses, the need for continuous and effective monitoring becomes critical. This paper explores the advancements in BHM technologies, with a focus on the integration of wireless sensor networks (WSNs), machine learning algorithms, and Internet of Things (IoT) platforms. The system must interface and integrate the actual practice mainly based on visual inspections and combine the response of a number of different reliable sensors, installed on the structure to monitor the progress of damage, with enhanced realistic deterioration models. The system and the sensors were developed to cover the parameters for the most important deterioration mechanisms: corrosion of reinforcement in bridges, carbonation of concrete, freeze-thaw cycles, alkali-silica reaction and mechanical damage, as well as the changes in the structures behaviour and safety: static deformation, strains; crack widths and vibrations (frequencies, amplitudes, accelerations and vibration modes). This study delves into more sensor types used in monitoring structural integrity, such as accelerometers, strain gauges, and displacement sensors, and discusses the methodologies employed in data acquisition and analysis. Challenges related to the scalability, cost, and accuracy of these systems are analyzed, highlighting areas where further research and technological innovations are required. Through a series of case studies, the paper illustrates the practical applications of BHM systems and their role in predictive maintenance and real-time decision-making. The conclusion offers insights into future directions for research and development in BHM, emphasizing the need for more advanced sensors, improved data processing techniques, and enhanced integration of IoT technologies to meet the growing demands of modern infrastructure.

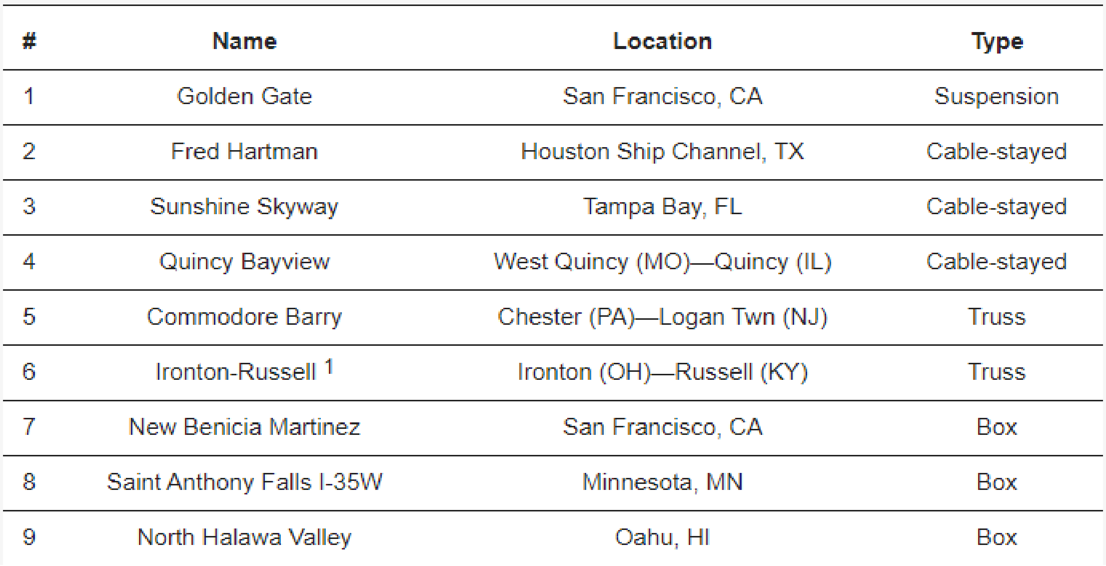
Keywords: Bridges, Structural Health Monitoring (SHM), Wireless Sensor Networks (WSNs), sensors

Introduction:

The structural integrity of bridges is paramount to the safety and efficiency of transportation networks. Bridges are vital components of infrastructure that enable the movement of goods and people, connecting communities and fostering economic growth [1]. However, the aging of bridges, coupled with increased traffic loads and environmental factors such as temperature fluctuations, corrosion, and natural disasters, poses significant challenges to their longevity and safety [2]. Traditionally, bridge inspection has relied on manual methods, which, while effective, are often time-consuming, labor-intensive, and subject to human error [3]. As a result, there has been a growing interest in the development and implementation of Bridge Health Monitoring (BHM) systems, which utilize advanced technologies to continuously assess the condition of bridge structures in real-time [4]. BHM systems are designed to detect early signs of structural damage, allowing for timely maintenance and repair, thereby preventing catastrophic failures and extending the lifespan of the bridge. These systems typically consist of a network of sensors that measure various physical parameters such as vibration, strain, displacement, and temperature [5]. The data collected by these sensors are then transmitted to a central processing unit, where it is analyzed to identify any anomalies or signs of deterioration. The integration of wireless sensor networks (WSNs) and the Internet of

Things (IoT) into BHM systems has further enhanced their capabilities, enabling remote monitoring and real-time data processing. Additionally, the application of machine learning algorithms in data analysis has improved the accuracy and efficiency of damage detection and prediction [2]. As traditional non-destructive evaluation (NDE) maintenance can do little when flaws start or become critical between two inspections, there is a growing interest in cost-effective structural health monitoring (SHM) strategies. SHM shifts the maintenance paradigm from "time-based" to "permanent-based" where a network of sensors monitor the structure of interest 24/7 in order to flag, locate, and quantify damage as it happens [6,7,8,9,10,11]. Besides the scope of detecting damage at the earliest possible stage, reliable SHM systems may monitor certain bridge parameters to assess a bridge's performance under various service loads, to verify or update the rules used in its design stage, and to prioritize maintenance and rehabilitation. In 2011, Xu and Xia [12] listed nine major bridges (**Table 1**) in the U.S. equipped with health monitoring systems.

Table 1. Bridges in the United States instrumented with sensing systems prior to 2011 according to Table 1.1 of ref. [12].



#	Name	Location	Type
1	Golden Gate	San Francisco, CA	Suspension
2	Fred Hartman	Houston Ship Channel, TX	Cable-stayed
3	Sunshine Skyway	Tampa Bay, FL	Cable-stayed
4	Quincy Bayview	West Quincy (MO)—Quincy (IL)	Cable-stayed
5	Commodore Barry	Chester (PA)—Logan Twn (NJ)	Truss
6	Ironton-Russell [1]	Ironton (OH)—Russell (KY)	Truss
7	New Benicia Martinez	San Francisco, CA	Box
8	Saint Anthony Falls I-35W	Minnesota, MN	Box
9	North Halawa Valley	Oahu, HI	Box

In any bridge health monitoring, sensors directly or indirectly measure external loading (wind, seismic, and traffic), structural responses (strain, displacement, and acceleration), environmental parameters (temperature, humidity, and rain), and environmental effects (corrosion). The sensors are connected to dedicated hardware/software for storage and, ideally, for real-time assessment. The aim is to offer interested readers a holistic perspective of recent and current state-of-the-art bridge health monitoring systems and to extract a "general paradigm" that is common to many real structures. In this paper, the issues related to the physical parameters considered as damage precursors or damage indicators and the challenges associated with the health monitoring of bridges including the drift of wireless sensing are presented. Some of the most important factors that degrade a bridge are discussed from the perspective of their detectability with the sensors. In essence this SHM system is capable of determining and evaluating the serviceability, the reliability of the structure, and the remaining functionality in terms of durability [13]. The system must interface and integrate the actual practice mainly based on visual inspections and combine the response of a number of different reliable sensors, installed on the structure to monitor the progress of damage, with enhanced realistic deterioration models. SHM system implemented on bridges includes five operations of acquisition, validation, analysis, prognosis, and management of the system. The system and the sensors were developed to cover the parameters for the most important deterioration mechanisms: corrosion of reinforcement in bridges, carbonation of concrete, freeze-thaw cycles, alkali-silica reaction and mechanical damage, as well as the changes in the structures behaviour and safety: static deformation, strains; crack widths and vibrations (frequencies, amplitudes, accelerations and vibration modes). A SHM system can contribute to damage assessment in main five levels [14]:

- Level I - Damage detection when identifies that damage has occurred
- Level II - Damage location, when identifies that damage has occurred and determines the location of damage
- Level III - Damage typification, where identifies that damage has occurred, location of damage, and estimates the type of damage
- Level IV - Damage extent, where identifies that damage has occurred, location of damage, estimates the type of damage and evaluates the severity of damage
- Level V - Damage extent, where identifies that damage has occurred, location of damage, the type of damage, the severity of damage, and evaluates the remaining useful life of the bridge or viability state

1-SHM methodology

The success of a SHM system depends on the following 2 stages (Sousa and al. 2016, Sousa et al. 2013): • Design and implementation of the SHM based on a multidisciplinary team

- Knowledge extraction and decision-making supported by the SHM data

STAGE 1– Design and implementation of the SHM

At the design stage, the following steps are covered [**Fig. 1**]:

Step 1.1. The collection of information related to bridge, including geometry, materials, boundary conditions and loading conditions.

Step 1.2. The design of a SHM system and equipping the structure with a sensor system, which will determine the timing of the degradation process.

Step 1.3. The development of a full 3D model in the laboratory based on Finite Elements (FE) Analysis method.

Step 1.4. The acquisition of the measurements in order to characterize the parameters for the most important degradation processes.

Step 1.5. The sending of the physical, chemicals and dynamics parameters measurements through a wireless system to a zonal centre of monitoring (laboratory), where they will be centralized, registered, processed, and analyses.

Step 1.6. The establishment of upper and lower bounds of the values of the physical, chemicals and dynamics parameters (critical level alert set), in the 3D FE model of bridge.

Step 1.7. The analysis of the parameters on the 3D FE model that simulates the original structure of the bridge, to identify the mechanisms of the flexibility, of the inertia and the damping that govern the response of the bridge for each degradation mechanism [15].

Step 1.8.The calibration of the 3D FE model in order to include “critical parameters”, the parameters for the most important deterioration mechanisms: corrosion of reinforcement in bridges, carbonation of concrete, freeze-thaw cycles, alkali-silica reaction and mechanical damage, as well as the changes in the structures behaviour and safety: static deformation, strains; crack widths and vibrations (frequencies, amplitudes, accelerations and vibration modes).The calibration of the 3D model in laboratory will be applied at the beginning of the bridge's exploitation, being considered as dynamic testing at T0 time.

Step 1.9. The implementation of the database of dynamic marks at the T0 for all bridges built in SHM system.

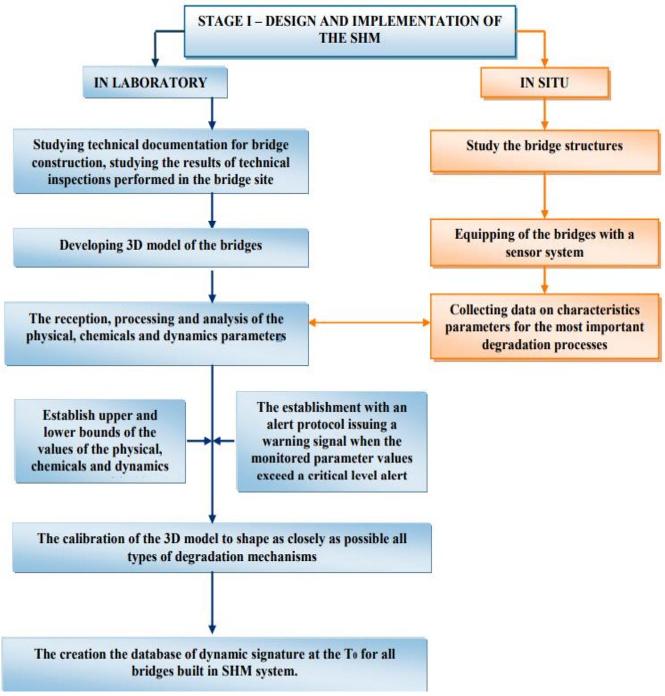


Fig. 1 - STAGE I– Design and implementation of the SHM

STAGE 2– Knowledge extraction and decision-making supported by the SHM data

At the knowledge extraction and decision-making supported by the SHM data stage, the following steps are covered [**Fig. 2**]:

Step 2.1. Monitoring of the temperature and relative humidity, which allows in real time the identification of occurrence of fog and frost on the monitored bridge. In this case, the protection protocol has to start in real time and consists of releasing visual and sound signals in order to reduce the driving speed, to increase the distance between the vehicles, to direct quickly the police and ambulance towards the specific sector, to deviate the circulation towards local deviation variants, to put in function a heating system installed on the bridge that will remove the frost.

Step 2.2. Monitoring of the chemical parameters enables the identification of the appearance moment of the process of carbonating the concrete followed by the corrosion of the steel reinforcing roads [16], [17].

Step 2.3. Monitoring of the bridges enables the identification of the moment in which, under the action of the traffic, or after the production of a catastrophic event (earthquake, floods followed by the erosion of the substructures, terrorist's attacks, etc.), the deformation state of the bridge exceeds the admissible value, and achieves a critical level of alert.

Step 2.4. By comparing with the permanent and continuous monitoring process of the physical and chemical parameters and structural deformations of bridge, the monitoring of the dynamic parameters is applied periodically (frequencies, amplitudes and specific forms of vibrations) in an interval of maximum one year, and compulsory, after the production of some catastrophic events (earthquakes, floods followed by the erosion of the substructures, accidents caused by the percussion of the constructive elements, heavy transportations, terrorists attacks etc.).

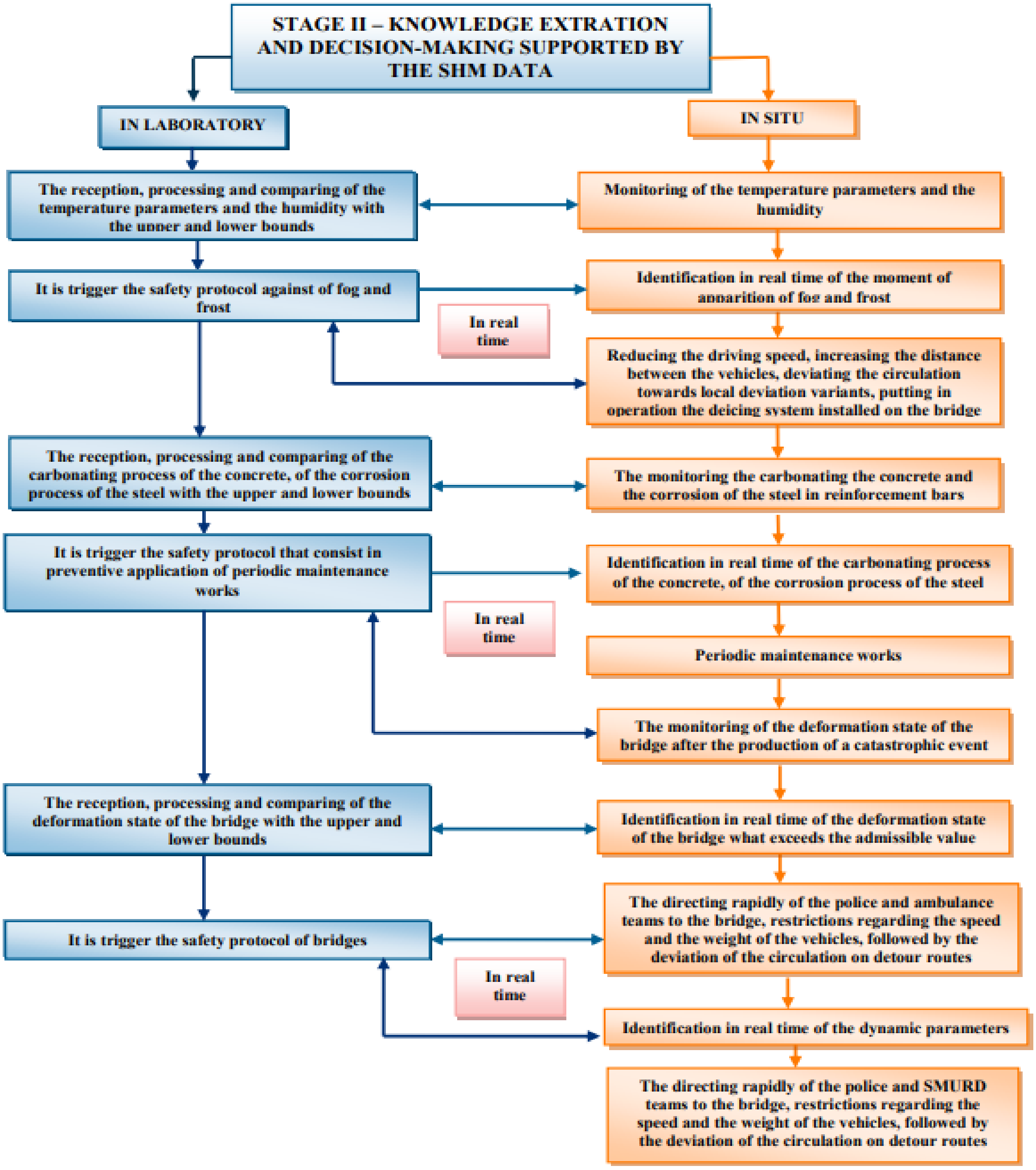


Fig. 2 - STAGE II– Knowledge Extraction and Decision-Making Supported by the SHM data

Step 2.5. Each the dynamic testing of the bridge performed in situ is followed in the laboratory by a process of recalibration of 3D model of each bridge. If monitoring of the dynamic characteristics to the T_i step does not identify significant changes in the dynamic mark of the bridge from the T_{i-1} step, then the technical condition of the bridge is diagnosed as being “adequate”.

Step 2.6. Monitoring process continues in successive steps on the entire duration of exploitation of the bridge until, as a result of the structural monitoring of the bridge, in T_z step, will be identified modifications with significant values of the dynamic characteristics in relation with the dynamic mark of the bridge from the T_{z-1} step [18]

The use of permanent monitoring systems has several advantages once the system is installed: (i) to reduce the operating costs of inspections and maintenance by 25%, and the traffic-related costs by 30 % by reducing the number and extent of site inspections and (ii) to reduce the overall life costs of bridges by 10 % by applying the improved lifetime prediction models already from the design stage.

2-Parameters Affecting Bridge Condition

Modares and Waksmanski [19] sorted SHM sensing systems by parameters and provided details of sensor types, accuracy, range, and operating temperature. The considered parameters were (in alphabetical order): corrosion, cracking, displacement, fatigue, force, settlement, strain, temperature, tilt, vibration, water level, and wind. In addition, they classified the types of sensors as either contact or noncontact. With progress in technology, new sensing capabilities are developed and two excellent reviews on the subject were published by Sharyatpanahi [20] and Moreno-Gomez et al. [21], while a review focusing on sensors for concrete monitoring was presented by Taheri [22].

Data inference is a critical part of any bridge health monitoring because diagnostics and prognostics will be eventually made based on the processing of the data streamed from different parameters (sensors). For bridge condition evaluation and prediction, both short and long-term factors should be considered. The analyses conducted by the [23] made evident that most SHM implementations do not rely on a single non-destructive evaluation method, e.g., strain measurements, because an SHM protocol based on a single parameter is not able to monitor all factors that are critical to a bridge. As such, integrated systems that contain different sensor types are warranted.

2a-Stiffness Loss

The loss of stiffness in any given structural component is considered by many a reliable indicator of damage. As such, several methods were proposed for the detection and localization of stiffness losses. Some of the localization methods rely on the detection of irregularities in the deflected shape of the structure [24,25,26,27]. These methods are based on the determination of the modal characteristics of the structure and in particular on the accurate determination of the deflected shape. This can be achieved by using a high spatial resolution of sensors, high quality measurements, and reliable signal processing. One of the major advantages of vibration-based damage identification methods is the possibility of detecting damage at a global level using sensors not necessarily deployed close to the location of damage, which is typically unknown. The estimation of stiffness loss can be made by using response-only approaches, which are based on the use of sensor data only, and/or by using physical-based models, such as finite element models.

2b-Corrosion Evaluation

Corrosion in metallic parts such as cables, reinforcements, connections, or girders may degrade bridge performance. Monitoring corrosion is therefore necessary to identify critical degradation that needs maintenance. Over the last 20 years, some researchers have investigated this topic. Morris et al. [28] investigated the effects of local variables on rebar corrosion process and proposed a criterion for rebar corrosion evaluation based on measurements of concrete electrical resistivity. Two exposure conditions, namely seashore environment and partial immersion in a saline solution, were selected. Two water-to-cement ratios and various initial chloride ion additions were selected for the experiment. The results showed that the electrical resistivity can be used to evaluate the potential of steel corrosion. Additionally, concrete mix design, environmental exposure conditions, and initial chloride concentration have an effect on rebar corrosion process. No specific bridges were monitored or tested as part of this study.

Deeble Sloane et al. [29] proposed a strategy to monitor the eventual corrosion of the high-strength steel wires of suspension bridges. The strategy is based on a sensor network that assesses indirectly the environmental conditions and deterioration of the main cables. The strategy was tested on a full-scale mock-up cable recording temperature, relative humidity (RH), and corrosion rate levels. The tested sensor network was able to provide suitable clues about the interior environment of the cable. Although the observed trend was not consistent throughout the cross section of the mock-up cable, the RH values were strong indicators of corrosion rate levels. The same group later applied the same strategy on the Manhattan Bridge [30,31]. The field data showed that corrosion levels increased with the relative humidity level increasing, and relative humidity did not vary with cable depth. It is noted here that detection of corrosion in bridge structures is quite a significant issue and the fact that the scientific literature is not as rich as for other issues shall not mislead the reader. Problems with corrosion losses and diagnostics on pre-stressed rebar or post-tensioned tendons, for example, exist and are typically addressed by using conventional or advanced non-destructive evaluation methods.

2c-Time and Temperature-Dependent Factors

Time-dependent and temperature-dependent deformations have been a concern for decades because creep and shrinkage affect concrete structures over time, whereas thermal strain and thermal stress may mask damage-related effects and live load disturbances.

A number of models were proposed to predict temperature effects and to predict time-dependent factors such as sustained live load. Ghali et al. [32] investigated both short-term and long-term behaviour and performance of the Confederation Bridge in Canada. This bridge is a 12.9 km structure made of box girders, such as the one on display in **Figure 3**. The study analysed the time-dependent properties of concrete and compared field measured deflections to predicted deflections. Creep was estimated using CEB–FIP MC90 and ACI (American Concrete Institute) 209 codes. Ten-cylinder creep tests were conducted by using the least square fitting of the measured creep coefficients; a best-fit predictive creep equation was developed. For shrinkage, six (6) cylinders were taken to measure the free shrinkage. Measured shrinkage strain was used to obtain the predictive shrinkage equations. With other material parameters, creep and shrinkage equations were employed to analyse the deflections. After the analyses of long-term deflection, all the analyses were conducted again to induce the variation of temperature during the same time intervals. The result showed that with consideration of temperature effects, the predicted results became closer to the measured ones.

Fig 3. Display of a typical segment of the Confederation Bridge

Robertson [33] presented the results of nine years of vertical deflection monitoring data of the North Halawa Valley Viaduct. The author found a disagreement between the theoretical design predictions and measured vertical deflections, and proposed an improved creep and shrinkage model, as it was believed that the sensors' data were reliable. In support of the improved creep and shrinkage models, numerous laboratory tests were conducted and four existing predictive models were considered: the ACI 209 model, the CEB-90 model, the short form of Bazant B3, and the Gardner model. A conclusion of the study was that the short form of the Bazant B3 model predicts long-term creep best, whereas the Gardner model predicts the long-term shrinkage best. These two models were combined and applied to the North Halawa Valley Viaduct. The outcome was the agreement between the model predictions and the sensors' field data.

3-Sensing technologies for SHM in bridges

Since the field of bridge SHM has significantly developed over the last several decades, this article mainly focuses on the state-of-the-art of the smart sensors in SHM installed on the cable-stayed and suspension bridges. This section summarizes the recent development and applications of smart sensing systems, including the fibre optic sensors (FOS), piezoelectric sensors, vision-based displacement measurement systems, and magneto strictive sensors (MsS) [42]. The purpose of developing these smart sensors is to solve the limitations of traditional sensors (such as resistance strain gauges, wired accelerometers, etc.) in measurement accuracy, and to measure new structural characteristics, such as electromechanical impedance and guided waves [43]. In the health assessment of bridge structures, the displacement of bridge piers has always been an important measurement index. Because the traditional displacement sensor cannot obtain the required reference point, it is difficult to directly measure the displacement of the bridge pier, especially when the size of the bridge pier is large, the measurement becomes more difficult. [44]. The global navigation satellite system is one of the promising technologies for displacement sensing [45]. Table 1 compares the major applications of the FOS, lead zirconate titanate (PZT) sensors, global navigation satellite system (GNSS)-based dynamic monitoring, and MsS in SHM of the cable-stayed and suspension bridges [46,47].

3a-Fiber Optic Sensors (FOS)

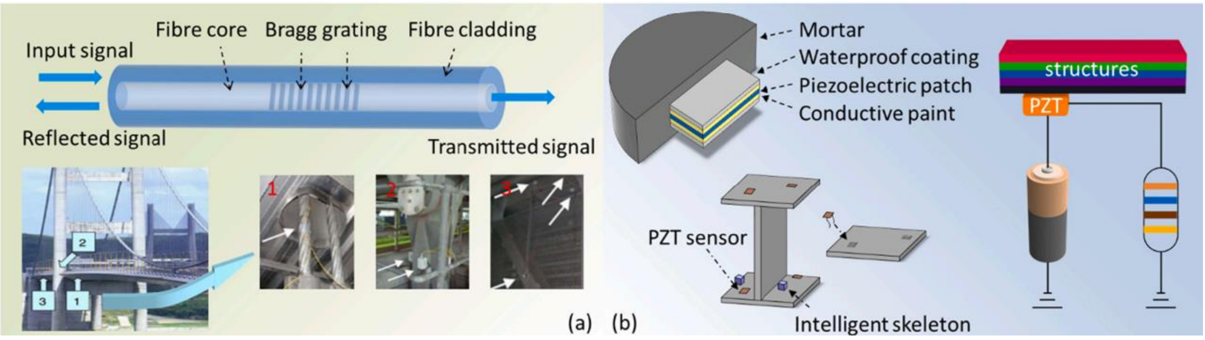
Based on the sensing principle, FOS can be categorized into the types of fiber Bragg grating (FBG) sensors, extrinsic Fabry-Perot interferometric (EFPI) sensors, and optical time-domain reflectometry (OTDR) sensors [48,49]. The most valid FOS technique that satisfies the effective monitoring requirements of bridge status is FBG, which has become a reliable monitoring tool among all the FOS techniques in bridge SHM [50]. Fig. 1(a) shows the information regarding the major applications of the FOS in SHM of the cable-stayed and suspension bridges [51,52]. Liu and Jiang (2008) developed the SHM system for the first cable stayed bridge across the Yangtze River in China [53]. Both the FBG based overloading vehicle recognition and remote real-time cable force monitoring systems were successfully operated using the sensing technology in this study. Xu et al. (2016) used the Integrated Distributed Fiber Optic Sensor (DFOS) to monitor a suspension bridge with a length of 1108 m. The monitoring results showed that DFOS could achieve high-density strain and temperature measurement on large bridges [54]. Chan et al. (2006) installed the FBG sensors on the hanger cable, rocker bearing, and truss girders of Hong Kong's landmark Tsing Ma bridge (TMB) [55]. The experimental results showed that the data monitored from the FBG sensor is very consistent with the monitoring results obtained by the original SHM system of the bridge, which proved the reliability of the FBG. Li et al. (2011) described the crafting procedures of the optic FBG sensors and the layout methods among the bridge stay cables [56]. He et al. (2013) combined the optical FBG sensor and Brillouin optical time-domain analysis/reflection sensing technology, and successfully applied it to the force monitoring of cables [57]

3b-Piezoelectric sensors

Piezoelectric sensors are based on the sensing technology that uses piezoelectric transducers to measure the impedance of the main structures. Commonly used piezoelectric transducers mainly include the PZT and macro fibre composite (MFC) [46,58,59,60]. PZT is based on the ceramic piezoelectric materials that are capable of detecting the changes in pressure, acceleration, temperature, strain, or force by converting these changes into electrical charges or signals and vice versa [61,62]. Impedance measurement applications for SHM have been applied in different forms [61,62,63]. Fig. 1(b) highlights the sensing techniques in the research field of the PZT on the cable-stayed and suspension bridges [61,88]. Maruccio et al. (2016) proposed a new method using a new type of piezoelectric textile to monitor the bridge deck and cable vibration caused by the environment of a cable-stayed bridge in Italy [64]. In order to detect acoustic emission in civil engineering structures, Lu and Li (2008) developed a new cement-based piezoelectric composite sensor system [65], and measured the piezoelectric performance and sensitivity of the cement-based piezoelectric composite sensor system. Song et al. (2008) proposed the concept of smart aggregate and introduced the basic working principle of smart aggregate [66]. He used a variety of different types of concrete structures (concrete cylinders and concrete frames, etc.) composed of smart aggregates to conduct test experiments to prove the reliability of smart aggregates. Sun et al. (2008) combined piezoelectric ceramic sensors and ultrasonic methods to form a new non-destructive monitoring method [67]. This method can be used to monitor the dynamic elastic constant of concrete bridges and structural damage such as cracks.

Table-2 Comparative study for different sensors used for health monitoring of structure

Sensors	Type	Material	Main detected parameters	Working principle
FOS	Optical	Optic Fiber	Multiple (strain, temperature, acceleration or displacement, etc.)	Light refractivity
PZT	Wired, electrical, Wireless	Piezoceramic material	Strain, corrosion, and acceleration	Piezoelectric effect

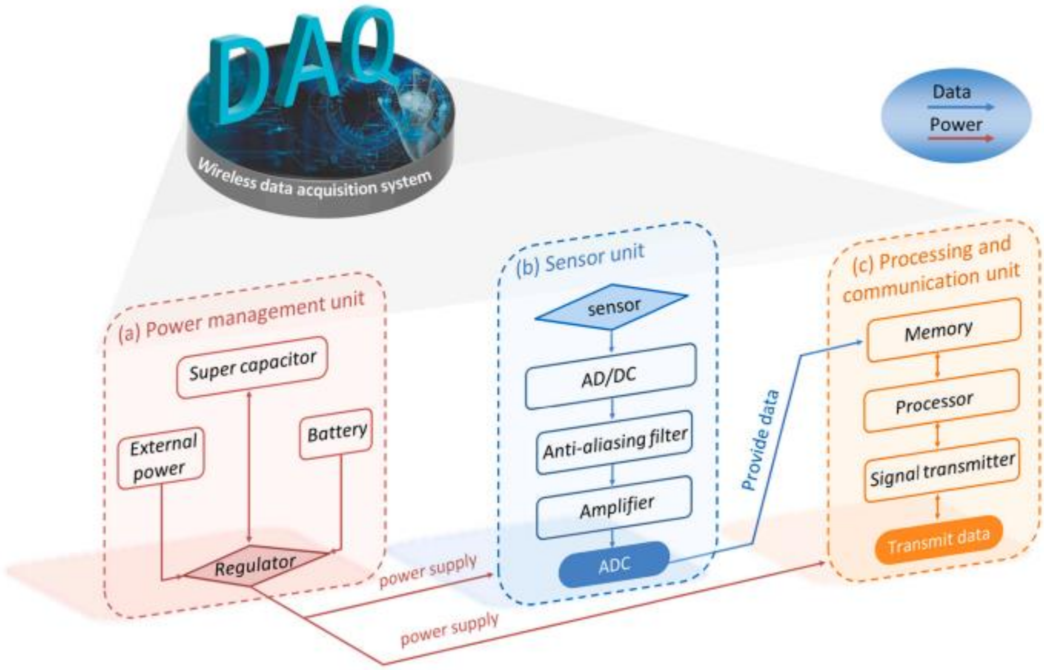


4-Wireless Sensor Technologies and Sensor Drift

The cost of traditional wired SHM systems, due in part to cabling networks, is detrimental for the deployment of high-density sensor systems or for usage in long-span bridges. SHM using wireless sensors can overcome the limitations of traditional wired methods with many attractive features such as wireless communication, on-board computation, battery power, ease of installation, and so on. Many groups worldwide, including researchers at the University of Illinois at Urbana Champaign [34,35,36,37] have successful implemented wireless sensor technologies for SHM and demonstrated the efficacy of such technologies in measuring structural acceleration, strain, and displacement responses over full-scale applications [38].

Wireless smart sensing (WSS) are devices that have sensor, microprocessor, radio frequency transceiver, memory, and power source integrated into one small-sized unit and are characterized by their capabilities of sensing, computation, data transmission, and storage, all achieved by a single device. They are increasingly considered as SHM platforms because they represent an alternative to their wired counterparts. WSS are attractive because their cost is lower cost (including cost for labour) due to the absence of long cables and due to the widespread production of micro-electro-mechanical sensors. The wireless communication allows flexible network topology and enables a decentralized monitoring scheme as opposed to the centralized scheme of wired systems [39].

Smart sensing platforms generally feature several characteristics: (1) on-board CPU; (2) small size; (3) wireless communication and data transmission; and (4) low-cost. Many WSS platforms have been developed and applied in SHM. They include the Mica series, iMote series, and Xnode. The Xnode is an advanced wireless sensing platform with several critical features such as reliable wireless communication, high-fidelity analog-to-digital converter, expandable data storage, high-precision synchronized sensing, user-configurable middleware software library, automated long-term operation of wireless network, and so [40]. Based on advanced wireless sensing platforms, many kinds of accompanying sensor boards have been developed to interact with the wireless sensing platforms for achieving diverse sensing capabilities. Because the measurement environment, frequency range, and budget may be different for the purpose, various types of external sensor boards for WSS were developed for acceleration, high-sensitivity strain, and environmental measurements [41].



The functional block diagram of the wireless data acquisition system. (a) Power management unit. (b) Sensor unit. (c) Processing and communication unit

Conclusion:

Since the early 1980s there has been an increasing awareness of the deterioration and lack of performance of civil infrastructure systems. As the Romanian's infrastructure grows and existing infrastructure ages, evaluating the condition of existing bridges and monitoring the engineering behaviours of new bridges become more significant. There have been many debates and conferences on the road administration agency, professional organizations and academia, during which they analysed the causes that lead to many road accidents and established a strategy for avoiding them in the future, mainly based on the implementation of Structural Health Monitoring (SHM) systems on bridges. The system must interface and integrate the actual practice mainly based on visual inspections and combine the response of a number of different reliable sensors, installed on the structure to monitor the severity of a structural damage, with enhanced realistic deterioration models. The success of a SHM system depends on the following 2 stages:

- Design and implementation of the SHM based on a multidisciplinary team
- Knowledge extraction and decision-making supported by the SHM data.

Intelligent sensing technology can accurately obtain the status information of the monitored object and is an indispensable part of SHM. At present, a variety of smart sensing technologies have been successfully applied to the monitoring of engineering structures. There are mainly four types of sensing technologies widely used in SHM: fibre optic sensors, piezoelectric sensors, global navigation satellite system and magneto strictive sensors. The noted sensing technologies have their own advantages and disadvantages and different application scenarios.

Wireless transmission has excellent advantages over wired transmission. Wireless sensor nodes do not impose to deploy cables, which significantly reduces the system's total cost. In particular, the popularity of wireless transmission methods such as ZigBee enables the bridge health monitoring system to achieve wireless data transmission with low cost, low energy consumption, and high fault tolerance, which significantly improves data transmission efficiency.

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