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# Middleware and communication technologies for structural health monitoring of critical infrastructures: A survey

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ABSTRACT

Critical Infrastructure Protection (CIP) has become a priority for every country around the world with the aim of reducing vulnerabilities and improving protection of Critical Infrastructures (CI) against terrorist attacks or natural disasters, among other threats. As part of CIP, Structural Health Monitoring (SHM) is defined as the process of gathering basic information that allows detecting, locating and quantifying vulnerabilities early on (fatigue cracking, degradation of boundary conditions, etc.) thereby improving, the resilience of the CI. Recent advances in electronics, wireless communication and software are expected to open the door to a new era of densely connected devices sharing information worldwide, known as the Internet of Things (IoT), in which Wireless Sensor Networks (WSNs) play an important role. The combined use of IoT/WSNs together with industrial sensors in SHM provide an ad-hoc, inexpensive and easy way of deploying a monitoring system, where data can be shared among different entities. SHM requirements are challenging and diverse and therefore several different technologies may be used in the same deployment. At the same time the use of a middleware can substantially simplify and speed up the development of applications for SHM. Taking into account the challenges of SHM systems, this paper provides a review of the most novel and relevant wireless technologies and a state-of-the-art middleware for WSNs focusing on SHM specific requirements.



## 1. Introduction

Structural Health Monitoring (SHM) is defined as a process whose objective is to obtain information about the condition and behavior of a structure over time [1]. It is an important technique for monitoring the resilience of Critical Infrastructures (CIs) such as electrical grids, oil and natural gas systems, nuclear power stations or transportation networks. The monitoring process consists of the continuous compilation of the most representative parameters that indicate the state of a structure. The selection of these parameters depends on several factors such as the type of structure, its purpose, the construction materials and environmental conditions. In general terms, these parameters can be mechanical (stress, displacement, deformation), physical (temperature, humidity) or chemical (pH, oxidation of metal). Observation and compilation of parameters can be done both locally (observation of the behavior of a specific material) and globally (observation of the structure as a whole). Typically, innovative structures incorporating new building materials require local monitoring, while conventional structures as well as older constructions require global monitoring. The duration of the monitoring is also established according to the type of structure, which may be short (or temporary) or medium/long (or permanent) term. Continuous monitoring is being used more and more often, even in stages like the construction, which helps engineers to understand the real behavior of the structure while it is being built. It also helps detect construction errors that may affect the future operation of the structure.

A traditional, wired SHM system includes three essential components: a sensor system, an information processing system (including the acquisition, transmission and storage of data) and a health assessment system through the appropriate analysis of information. This traditional system has considerable disadvantages: 1) the high cost, as a result of long data communication cables; 2) low productivity and efficiency, since the deployment of thousands of cables is a labor intensive and time consuming task; 3) low flexibility because of having to deploy extra cables each time new sensors are added to the system. Continuous technological advances in Micro-Electro-Mechanical Systems (MEMS), inte-

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grated circuits and wireless communication are leading to the production of low-cost platforms that efficiently integrate computing, sensors and wireless communication capabilities. This has had a significant impact on the boom of so-called Wireless Sensor Networks (WSNs) [2]. As a way to overcome the disadvantages of traditional wired SHM systems, WSN-based SHM systems look promising. These systems have many advantages: 1) low cost, by eliminating the wiring of traditional systems; 2) high efficiency, since the installation of wireless sensor nodes is easy; 3) high flexibility, facilitated by the ease of updates, adding, removing and replacing nodes. In addition, the considerable reduction in the size and low cost of MEMS-based sensor nodes and the improvement in their performance make it possible to deploy dense wireless sensor networks, so that the quality of the SHM improves considerably by being able to analyze and correlate data from many strategic points of the CI.

However, while WSNs have been successfully used over the past 15 years in a wide range of applications ranging from environmental monitoring to energy efficient building management, current WSN-based monitoring systems do not meet the stringent requirements of Quality of Service (QoS) for the scope of the SHM of CIs, such as reliability, fault tolerance, synchronization, real-time response and efficiency in energy consumption [3]. In recent years, progress has been made in defining protocols and technologies that provide a certain level of these types of requirements [4]. However, their integration for the reliable development of SHM systems is a highly complex task and difficult to approach if a good methodology is not followed, taking into account the different requirements associated with the type of monitoring to be carried out. The experience of more than a decade has made it clear that a generic monitoring system cannot be built to supervise all CIs, rather it is necessary to carefully analyze each particular case in order to design the most appropriate system.

Relaying on our experience in past projects [5,6], this paper proposes a set of challenges to research and innovate in the context of WSNs for the SHM of CIs. Additionally, we draw attention to two important issues from these challenges, conducting a survey of communication technologies and middleware support. We analyze the communication technology traditionally used in the SHM of CIs and we study new alternatives that look promising in this field. The choice of which communication technology to choose according to the monitoring requirements (permanent or temporary, indoor or outdoor, short or long distance data transmission, continuous or eventual communication) is an important issue when building a specific system. On the other hand, the use of middleware for programming WSNs in general and WSN-based SHM systems in particular, due to the heterogeneity and density of the deployed networks, is of vital importance. A middleware has the ability to remove the programmer from complex aspects of WSN such as the handling of wireless communications (routing protocols, discovery of nodes, etc.), power management, microcontroller low-level programming and synchronization with other devices. A lot of surveys on middleware approaches for WSNs have appeared in the last decade [7–9], but only a few of them have focused on WSN-based SHM systems [10] or IoT-based SHM systems [11] and only some of those have centered on CI [3]. We think both are important issues and must be considered jointly. A deployed WSN-based SHM system can be composed of several communication technologies situated in different points in order to satisfy the multiple requirements established for a CI monitoring system. The use of a middleware that offers a good high-level programming model and abstracts the designer from low level issues, mainly the different wireless communication technologies used, is very important in general and crucial in the particular scope of SHM for CIs.

The rest of the paper is structured as follows. Section 2 outlines different challenges for WSN-based SHM systems. In Section 3 we analyze the different communication technologies and protocols commonly used in WSNs and we present new proposals for their possible use in the context of SHM of CIs. Section 4 reviews some of the existing commercial WSN solutions and research-based WSN deployments for SHM. Section 5 details middleware presented in the literature. Finally, conclusions are presented in Section 6.

## 2. Challenges of WSN-based SHM of CI

We participated in a Spanish project called Fastrack [5] funded by the Spanish Government's FEDER program. The main objective was the design of a new environmentally and economically sustainable slab track system for high-speed trains (faster than 250 km/h). In the context of this project, we designed a low-cost monitoring platform that is integrated in the slab track, inserted inside it during its construction, so that it can be used both during the installation and in the maintenance phases of the infrastructure [12]. By incorporating this monitoring functionality the slab track becomes an active element, capable of monitoring and reporting information about the environment such as vibration performance, distance and inclination and also assisting operators in the installation phase. Different communication technologies were analyzed and used to get information from the sensor platform [13]. In addition, we have developed a high level middleware called PS-QUASAR [6], based on a simple publish/subscribe model suitable for WSN-based CI protection to facilitate the system's programming.

Taking into account the lessons learned in these projects and in the KAMIC project [14], the project we are currently involved in, we propose the following challenges to improve research in the context of WSN-based SHM of CIs.

### 2.1. Encapsulated sensor nodes that allow their full integration into the CI

It is very important to design an adapted casing where the sensor nodes are installed, which in turn is inserted into the infrastructure being monitored, for example inside a hole made in the CI structure. The packaging has to be sealed and protected from unauthorized attacks and also from the weather. However, if proper attention is paid to how the casing is designed, this approach will allow operators to easily change the node if necessary (breakage, change of monitoring type, etc.) or remove it in order to change a dead battery. In this way, the monitoring system is integrated into the structure itself, either when it is first built or afterwards, obtaining what we could call an Intelligent Critical Infrastructure (ICI). This constitutes an important innovation with respect to the traditional deployments of SHM systems, which are carried out by placing the different devices with sensor nodes at different points on the structure to be controlled.

### 2.2. Self-installation of HW/SW components

The engineers in charge of an SHM system of a CI are experts in establishing the appropriate requirements and analyzing the structural health of the structures, but they are usually not knowledgeable about WSN technology. Considering this, ideally engineers should be provided with a kit of self-installing HW/SW components to facilitate their tasks. The kit can be configured per case study depending on their established requirements for the planned monitoring.

### 2.3. New methodologies implemented as decision support systems

The experience of more than a decade has demonstrated that a generic monitoring system cannot be built to monitor the structural health of all CIs, rather it is necessary to carefully analyze each particular case in order to design the most appropriate system. A methodology should establish the steps to be carried out in the construction of a specific system according to the monitoring requirements (permanent or temporary, indoor or outdoor, short or long distance data transmission, continuous or eventual communication) established by the engineer, the type of data analysis to be performed and the technology available. This methodology should be implemented in a software application that facilitates the work of the engineer responsible for designing the monitoring