Faculdade de Engenharia da Universidade do Porto

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Civiónica - Uma Área Interdisciplinar Emergente

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Chapter 1

Introduction

Civil structures are the backbone of our society. We depend on them to keep up the lifestyle that we are use to. This statement can be easily supported if we think about the transportation network that we rely on. The need of roads, bridges and other structures date from the early years of civilization. Nowadays these infrastructures are directly related to the economic success of a nation and are an important parameter to rank the life quality in a certain place [1].

The main goal of this document is to show and discuss ways to preserve and maintain these important constructions which are the support of the modern world.

1.1 Motivation

The importance of the structures that compose the transportation network is undeniable but as any other construction they need maintenance to keep working properly. Most of the infrastructures that we use nowadays were built 50 years ago and have suffered from decades of bad maintenance and overuse, leading to the acceleration of their deterioration (REF). The lack of attention for the state of these buildings resulted on an unsatisfactory condition of our infrastructures and there is now a need to replace or rehabilitate most of them. Also, we have to understand that most of the bridges and roads were constructed to support the demands of that time and we know that these requirements have changed drastically. The increase of traffic density and the weight augmentation of the new cargo vehicles contributed to the appearance of new requirements [2]. Thus, the estimated lifetime of a structure, calculated by the time it was built does not apply due to the change of the conditions that the building is subjected to.

The engineers are not only interested in keeping the old structures working, as the world and society develop the infrastructures have to keep up with evolution, new technologies, materials and methods of construction are being developed and there is a need to test them in a more accurately way.

The problems described previously are not new in anyway, and the engineers have relied on their experience to detect behaviours that could lead to structural failures. However with the increase of new structures with higher degrees of complexity, it is essential to find new ways of structural monitoring that are more accurate and reliable. In addition, with the development of new sensors and data acquisition systems, civil engineers start to apply techniques based on electronics to extract reliable information from the structure behaviour. They found it advantageous to work together with electrical engineers to develop solutions that could monitor and even detect structural damage without human intervention. A new field of studies with the name Civionics was born.

In short, the expansion and development of new infrastructures and the need of keeping the old ones working with high safety levels, led to the search for new methods of structure monitoring. When data acquisition systems evolved, becoming relatively cheap and capable of providing accurate information about the state and behaviour of a construction, engineers understood that this was the solution they have been looking for. However, there are still requirements to be achieved. In this document it will be shown some of the new topologies and advances on the field of Civionics and structural health monitoring. The goal is always the same, more and better data as well as trying to keep the costs acceptable.

1.2 Aim and Research Objectives

The construction sector is not always open to new ideas and most of the times prefer to use old and outdated methods that they can understand. There are additional costs when installing innovative monitoring systems in a structure and for these systems to be accepted they have to prove themselves worthy. This research will show the advantages and disadvantages of using wireless sensors to build a structural health monitoring system as well as provide a comparison between the different architectures that are used nowadays.

It will also be developed and implemented a wireless sensor system capable of measuring useful data for structural studies. This equipment will be tested and the results discussed giving the reader an understanding of the applicability of the solution proposed.

The objectives of this thesis can be gathered in the following list:

- Discuss and study the importance of Civionics and Structural Health Monitoring;
- Study and compare the various types of transducers and the technologies they use, with emphasis on MEMS sensors;
- Compare the different types of solutions available and discuss the use of systems based on wireless sensors;
- Design and implement a solution based on wireless sensors that can achieve the requirements later defined;
- Test and validation of the design proposed.

1.3 Work Methodology

In order to achieve all the goals proposed a work methodology was defined. First of all there was a need to understand what structural health monitoring stands for and what are the primary requirements of this kind of systems, e.g. what are the main parameters that have to be measured.

Afterwards a state of art revision was made in order to identify the technologies already proposed and their main characteristics. The review made focus primary on architectures based on wireless sensors. The goal was to elaborate a document where all these equipments were described and discussed giving the reader an idea of the problems and limitations that this kind of systems have. At this point it was made a clear division between the different elements that make up a wireless based system and was also presented the most important technologies used in each of these subsystems.

The next step was to determine the requirements that the solution to be developed should fulfil. All the requirements were discussed in order to achieve an agreement between all parts involved.

As the study of various transducers used in structural health monitoring systems are one of the subjects of study, several tests were made to determine the differences between some of the most known technologies. It was given special attention to sensors based on MEMS technology.

At this point the design of a solution began. The architecture and concept design were developed and the construction/implementation phase started. The reader will find later on in this document all the justifications and decision made when choosing the hardware and the topology of the system.

The final goal is to validate the proposed solution, a number of tests were though through in order to obtain accurate results. All experiments made are well documented and the conclusions obtained are discussed at the end of this document.

1.4 Outline of the Document

The outline of the document is not already defined as it is not possible to know with certainty the path that the project here proposed is going to take.

For time being it is possible to give an expectation of what will the document be. Chapter two introduces the background studies. It is discussed various types of structural health monitoring systems and the components of a wireless smart sensor platform. It is also made an overview of the wireless sensors available in the market.

Chapter three will present the system requirements which represent the start point for the development of a solution. They are all discussed and justified.

Another objective of this research is the study of the sensors used for SHM. Chapter four will discuss this matter taking special attention to the microelectromechanical systems (MEMS).

The chosen wireless sensor platform is discussed in detail in chapter five. It is also presented some tests made to validate this unit and prove that is the more suitable for the application in question.

Chapter six shows the complete architecture of the system and present the results obtained. The discussion around these results is also made given the reader an idea of what was accomplished.

Last chapter represents the conclusion of this project. It defines also possible future work.

Chapter 2

Background Studies

This chapter presents the research made before the start of the project. It starts by giving the reader a definition of Structural Health Monitoring (SHM) and explains the different types of existing systems.

Afterwards it is presented the state of art. The main focus of this subchapter is the discussion of wireless sensors development and the presentation of various technologies used for the different modules.

The conclusion of this chapter includes a discussion of the various problems encountered when trying to develop a SHM system using wireless sensors.

2.1 Structural Health Monitoring

The concept of Structural Health Monitoring is related to the process of implementing a damage recognition system for aerospace, civil and mechanical infrastructures [3]. The aim is to give a diagnosis of the "state" of the structure at every moment during the lifetime of the construction. Other goal is to detect the appearance of damage, thus a definition for this phenomenon is needed. For the purpose of this research, damage is defined as a violation of the designed characteristics. In other words, when the state of the structure is different from the one specified in the design it is possible to say that the structure is damaged.

Although SHM can be seen as an improved way to make Non-Destructive Evaluation (NDE), it is much more than that; it involves the integration of sensors, smart materials, data transmission and processing ability inside the structure. It is so integrated that can be considered part of the structure in a way that can even change the initial design [4].

The SHM system should be able to provide useful and reliable information about the condition and integrity of the infrastructure at any given time, in this way it can help to prevent catastrophic situation, allow for short-term verification of innovative designs and improve the maintenance effectiveness [5].

It has already been given a swift overview about the meaning of Structural Health Monitoring; however it is important to know that sometimes a SHM system does not integrate all these features.

These systems can be used in a wide range of structure types, from aerospace, mechanical devices and civil structures, however in this document SHM will always be related to civil structures with the main focus being bridge structures.

Next, it is discussed different categories and classifications based on the complexity of the system and his ability to detect damage.

2.1.1 Classification of different types of Structural Health Monitoring Systems

There are a wide variety of tests that can be made to infer about the integrity of a civil structure. The reason for having this variety is because it is impossible to evaluate all the characteristics of the structure (that ultimately define its state) with only one type of test. Thus the SHM system has to be adapted to the type of test desired in order to maximize its efficiency. The next image shows the division of SHM systems according to the type of test and expected information.

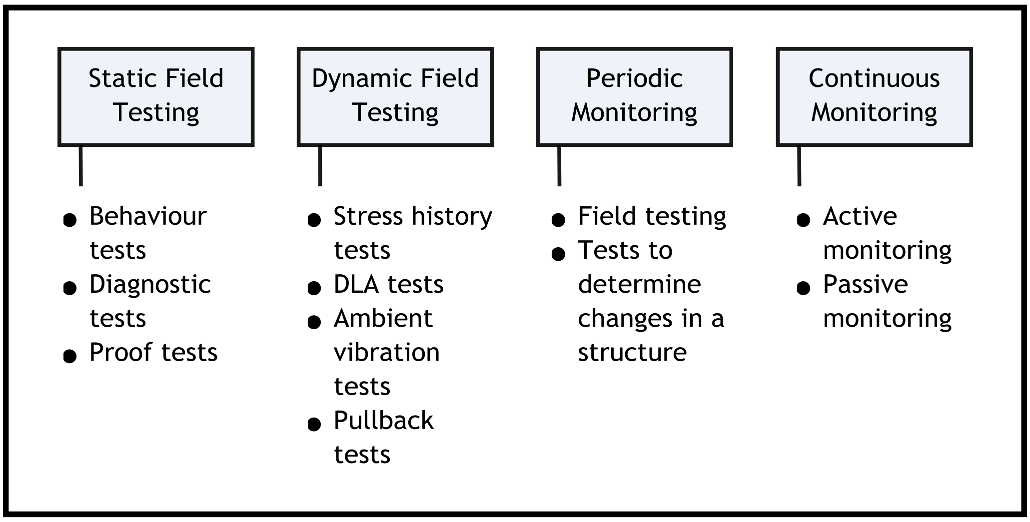


Figure 2.1 - Subsystems of a Structural Health Monitoring (adapted from [5])

Static Field Testing is based on the use of static loads, they are the easiest to perform and for that reason the most common. These tests infer about the ability of the structure to withstand loads as well as provide data on the deflection that that it suffers under the influence of a certain weight. The information provided enables the evaluation of the stiffness of the construction and the assessment of its short-term safety. The wide use of these methods is due to the easy interpretation of results, however dynamic effects such as shock, vibration and resonance are not studied in such trials [5].

Within the category of Static Field Testing are subcategories that represent different types of tests possible with static charges. The Behaviour Tests are used to study the mechanical behaviour of the structure at to validate analytical methods employed to describe it. The test loads are within the parameters defined in the design for the normal use of the structure.

As for the Diagnostic Tests, they are performed to study the response of a given component of the structure in order to understand his importance and interaction with the rest of the elements. This way it is possible to assess where does the structure need to be strengthen. The type of load applied is the same of the used on the behaviour tests.

To complete this category there are the Proof Tests. These are the hardest and the most dangerous tests of this category. The load applied exceeds the design parameters and have to be increased really slowly while the structure is monitored. If the load is to heavy it can lead to permanent damage and for this reason these tests have to be conducted with extreme caution. The goal is to assess the structure's capability to withstand loads greater than the nominal.

The second category mentioned, Dynamic Field Testing, tries to assess the dynamic behaviour of the structure. Since the structure under analysis in this research is a bridge the methodology presented here is directed to such buildings. The load applied in these tests is usually a vehicle that crosses a bump constructed on the bridge dynamically exciting the structure. The size of the bump the weight of the vehicle and its speed can be changed in order to get different ranges of excitation. These tests are performed to get information about the resonance frequency of the building allowing the comparison with the frequency response of mathematical models.

In this category are also presented four new subcategories. Stress Tests History aim to indentify the stress that certain parts of the structure are subjected to. Usually the components under investigation are the ones critical to the survival of the building. The data obtained can be used to calculate the lifetime of the construction before failures due fatigue occur.

Dynamic Load Allowance Tests or DLA Tests are used to determine the dynamic amplification factor. This factor is the result of moving loads, when the load is not static its motion affects the behaviour of the structure leading to a different response to a certain weight. Performing these tests allow the calculation of the amplification factor being than possible to determine the maximum weight that the bridge can in reality handle [6].

Another way to obtain the resonance frequency of a construction is by using natural phenomenon such as wind to stimulate the structure. Tests using this strategy are called Ambient Vibration Tests. This area is still in its initial development phase and there are still many problems to overcome. The main struggle is to control the exact level of excitation that the bridge is subjected to, it is important to monitor the surrounding environment with a great level of precision to be able to extract useful data from these trials. The correct placement of the sensors in this kind of method is more crucial than in others, which leads to the need of an expert that has a vast knowledge in the field of structures [7].

The last group of tests on this category are the Pullback Tests. They are usually applied to bridges when the wind is not enough to excite the bridge laterally. It is necessary to build a system that pulls the bridge in the lateral direction and then drop it, the information provided by these tests is the same provided by Ambient Vibration Tests. The need of an additional structure to excite the construction under test is a restriction that makes this kind of method underutilized.

The last two categories presented in figure 2.1 are not characterized by the type of load used but by the periodicity of the measurements. Periodic Monitoring refers to tests that only need a system that collect data at certain time intervals. This type of tests is related to field observations which are tests performed on the local. This kind of trials is the most common and they are particularly effective when there is a need to understand how changes in the structure have affected its performance. Static Field Testing usually use periodic monitoring as there is no need to be constantly collecting data when the structure is not under investigation.

Finally, it is presented the Continuous Monitoring category, as the name suggests monitoring takes place continuously. Due to the increased complexity and costs of this type of SHM it has only been used recently, usually it is only applied to constructions of great value or that are in high risk environments. The continuous monitoring systems fall into two categories, the most common acquire data and store them so that they can be interpreted later, the most modern and sophisticated send data as soon as it is received to be analyzed in real time.

The need to classify SHM systems in categories according to the information desired and the type of test performed is understandable but there is another approach to categorize these systems. This one is based on the damage identification process, the capability of the system to detect damage to what extent.

The damage identification process is usually structured into the following levels [1]:

- Damage detection, where the presence of damage is detected;
- Damage location, systems that can determine where is the damage located;
- Damage typification or quantization, where the type and the quantity of damage is inferred;
- Damage consequences, where the severity and consequence of the damage is assessed.

An increase on the detail of the damage characterization leads to a need of a more sophisticated system which means higher costs (Figure 2.2). For this reason it is of the best interest to determine what kind of information is really interesting for a specific application/structure [8].

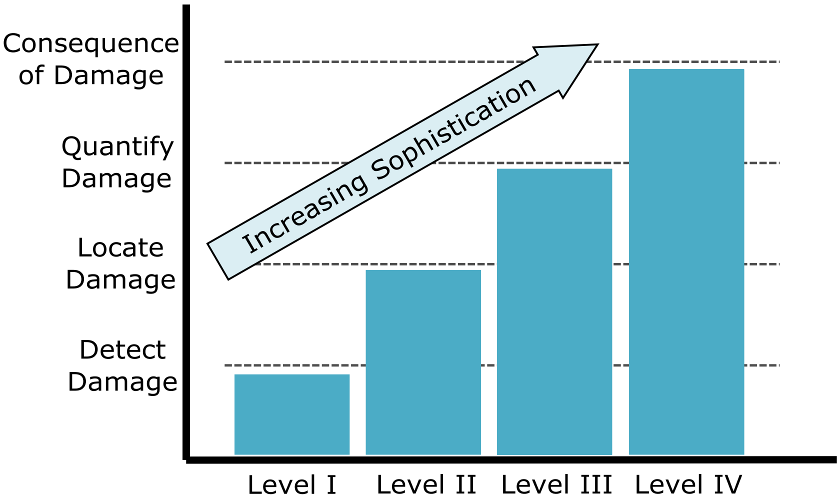


Figure 2.2 - Classification of different systems relative to their performance (adapted from [2])

2.1.2 Composition of Structural Health Monitoring Systems

Ideally a SHM system should provide information about significant damage in a structure when commanded. This information can be transmitted by a local area network or sent to a remote outpost to be processed and interpreted. In any case a wide range of equipment has to be used to integrate a system capable of extract data from a group of sensors, process, transmit and report to the end user. Being a system formed from such a large variety of devices it can be divided in subsystems depending on the role of each. As it was already said there are different types of systems for different applications so the structure here presented has to be seen as a generalization which is used by most of the SHM systems [2].

Typically a modern SHM system will consist of six common components, namely:

- Acquisition of data, a sensory system;
- Communication of information;
- Intelligent processing and data analysis;
- Storage of processed data;
- Damage detection algorithms;
- Interface with the user, retrieval of information.

The next image shows how these subsystems interact and allows a better understanding of the concept. Notice that this is only a typical architecture, not all the SHM systems have all these modules and some other have extra equipment installed to fulfil some specific requirements.

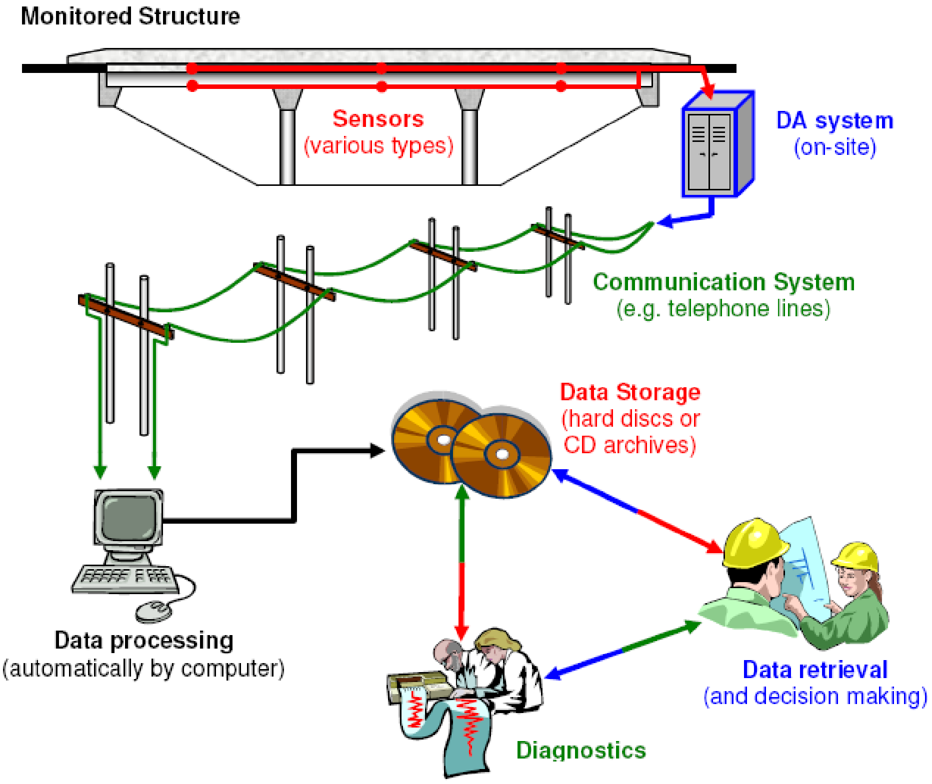


Figure 2.3 - Typical SHM system architecture [2]

The first module presented in figure 2.3 is the sensory system. This is one of the most important parts of a SHM system. If the sensor net does not work properly you cannot extract any reliable information about the structure. Typically these sensors are resistive strain gauges, vibrating strings, inclinometers, temperature sensors, accelerometers, linear displacement sensors and lately fiber-optic sensors. Once again the sensors used vary from application to application and depend mainly on the measures required by the owner of the structure and the existing conditions. Correct selection of sensors is essential to the success of any SHM system. It is required to take special attention to the following factors:

- Resolution, related with the precision required;
- Bandwidth, depends on the frequency of the phenomenon one wants to measure;
- Power consumption, crucial for wireless sensor networks;
- Reliability;
- Robustness;
- Durability;
- Physical size;
- Limitations in terms of signal transmission;
- Cost.

Another big issue when deploying sensors in a structure is the place where they are attached. Even high quality sensors cannot produce useful data if placed in the wrong places, there is a need to study the structure and realize the key points of the construction and where it is worth to put these transducers.

The review and study of the sensory part of a SHM system is one of the aims of this research and have a dedicated chapter further ahead. At this point it is interesting only to understand its importance as well as some of the issues that the designer has to have in consideration.

Next it is presented the data acquisition module which is, combined with the sensory part, perhaps the most important part of the system and the main focus of this work. The data acquisition module is responsible for acquiring the signal provided by the sensor net and transform it into something more than an electrical magnitude. In the case of a resistive strain gauge sensor the electric signal that the acquisition module receives has to be turned into strain which is the measurement that has interest to the analyst.

The complexity of the data acquisition system (DAS) has been increasing and there are many issues to take into account when choosing the device that will perform this role. One of the biggest concerns is about the data sampling. A well thought data acquisition algorithm has to capture the adequate amount of data. As one might expect, structures which are heavily instrumented will generate a large amount of data which can easily become unmanageable if the system is not set up efficiently. Data sampling should be high enough in order to get all the valuable information from the sensors but not so high that would overwhelm the rest of the system. Decisions regarding appropriate sampling rates should be based on the type of phenomenon that is supposed to be measured [2].

There is a great amount of characteristics that the designer has to have into account when choosing the data acquisition system for a certain application. However it is possible to name a few factors that should always be matter of study:

- Resolution, usually referred to the number of bit of the analogue-to-digital converter;
- Sampling frequency, previously discussed;
- Processing power;
- Embedded communication module, important to transmit data to a remote post;
- Power consumption;
- Cost.

These two modules are the backbone of a SHM system and are usually integrated with the structure under evaluation. One issue that has to be addressed is the connection between these parts. If it is a wired solution the cables should be protected against electromagnetic noise and the data should be transmitted in current instead of voltage. This is even more critical when the construction has large proportions. It also helps to have a signal conditioning system to clean up the signal coming from the sensor of noise. The conditioning can be made right at the output of the sensor, at the input of the DAS or at both. It is also advisable to have digital signal conditioning made by the data acquisition system. The weight of the cables and their distribution in the structure has to be considered, if not it can affect the behaviour of the structure.

New technologies have been proposed to take care of some of these transmission problems. Using fiber-optic sensors will eliminate most of the problems related to noise, however it brings some other problems that will be discussed on another chapter.

The use of a distributed system where each sensor or small group of sensors has an independent data acquisition module that communicates through a wired or wireless network is also a solution. Wireless communications are evolving rapidly and it is expected they will be increasingly used for SHM of very large structures in the future. The application of these technologies in monitoring systems is the main focus of this dissertation.

Returning to the structure shown in figure 2.3, the communication system refers to the mechanism of transfer of data from the site were the information is gathered to a remote post where the data will be processed and analysed. This allows engineers/owners to monitor the structure remotely eliminating the need for site visits. The transfer of data can be done using telephone lines, internet or even wireless systems like cellular transmission [9].

Afterwards the information sent by the communication system to a remote post is processed. The main purpose of this part of the process is to eliminate irrelevant data. Superfluous information can be caused by digital noise that has to be removed or by the influence of environmental phenomena, usually temperature changes, that has to be compensated in order to obtain the right measures. It is also important to arrange the data in a way that it can be stored more efficiently without sacrificing its integrity. In more sophisticated systems, neural computing and artificial neural network techniques may be employed (REF). For example, on bridges with low to medium traffic only heavy trucks will generate changes in the sensors readings that are interesting to monitor. Using a good data management algorithm means that only the information valuable is stored. In this example the readings from when a heavy truck passes.

Modern systems with distributed processing are able to process data from the sensors on site, reducing the amount of information that has to be transmitted to the remote station [10].

Data storage is the next module in the list. The need to have system that store all the data collected is obvious. Dependent on the type of system and on its purpose the storage equipment can have different characteristics. One of the biggest concerns is the medium for storage that should allow data to keep uncorrupted for many years. Also, and depending on the amount of sensors and the data sampling rates the storage device should have the capability to store all the relevant information. Most of the systems do not save raw data and only store processed or analysed information reducing the amount of space needed. Unfortunately, this does not allow for reinterpretation at a later time.

The latter two subsystems are more related with the understanding of the behaviour of the structure. At this state the data is studied in order to diagnose any significant damage in the building. Sophisticated systems are already making the diagnosis automatically, using complex algorithms, but typically this process requires the intervention of experts in the area.

It was shown the typical composition of a SHM system, this research will focus on the wireless sensors solution and will mainly concern with the sensory and data acquisition subsystems.

2.2 Structural Health Monitoring systems based on Wireless Sensors

The importance of structural monitoring in undeniable, these systems usually offer long term cost reductions as they enable to reduce the maintenance of a construction. However, the initial price is still pretty high. As it was discussed previously a SHM is composed of sensors, data loggers, computers and connecting cables. These devices have to be purchase and installed which leads to a substantially increase of the initial cost of the structure. Most of the SHM systems incorporate coaxial wires for communication between sensors in order to guarantee reliable measures. The installation of this cables is generally very expensive and labour-intensive, it was estimated that in tall building the use of this wires add an excess of $US5000 per sensing channel [11]. It was also determined that this cost increases exponentially with the increase of sensors [12].

Recently, smart wireless sensors have been considered as an alternative way for reducing the costs maintaining the SHM system reliable. This technology integrates the sensor itself with the data acquisition and communication system over a single platform. Since the communications between the numerous platforms is wireless it is possible to reduce the use of full-scale cables reducing the installation cost of the system. Furthermore the integration of computational modules allows the increase of the overall computational power enabling the utilization of distributed architectures [11].

These systems can be composed by several different modules but it is possible to define a typical structure of a wireless smart sensor platform. The next scheme shows how these platforms are integrated and the role of each one of the elements.

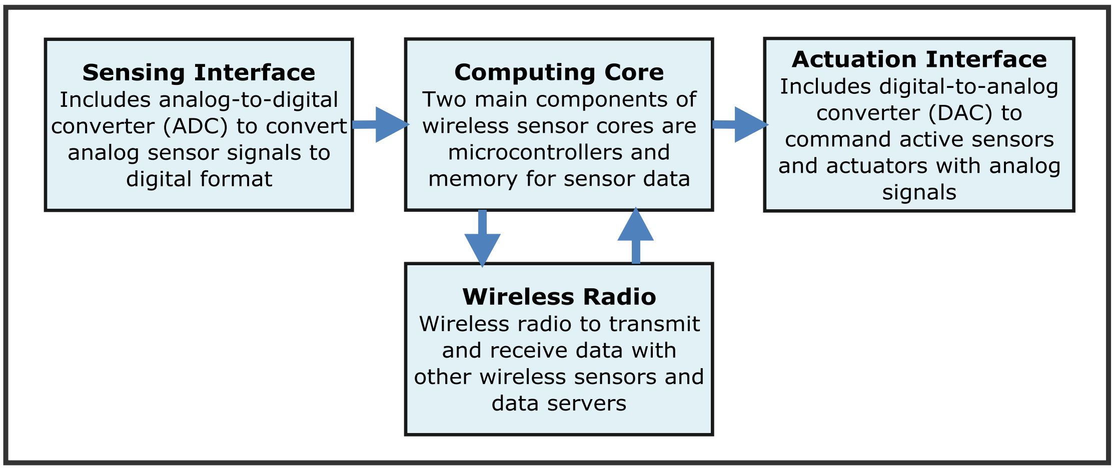


Figure 2.4 - Functional diagram of the various components of a Smart Sensor platform

2.2.1 Sensing Interface

Smart sensors must contain an interface to which sensing transducers can be connected. The sensing interface is mainly responsible for converting the analogue signal coming from the sensor output into a digital representation that can be processed by digital electronics. Typically this interface consists of anti-aliasing filters, current to voltage converters and other circuits capable of conditioning the signal to then be sent to the analogue-to-digital converter (ADC). The ADC is perhaps the most important component of the sensing interface, and its choice has to be made with regard to the system requirements. The main factors when selecting this component are the resolution (number of bits) and the sampling frequency. These characteristics are highly important because they limit the quality of information sent to the computing core and from it to the rest of the system.

There are a wide range of ADCs on the market but for SHM applications the choice usually falls into those that have resolutions between 8-bits and 16-bits and sampling frequencies between 500 Hz and 500 kHz. In theory higher resolutions and sampling rates lead to a more accurate reading but in practise they will generate a lot of superfluous information. A resolution of 16-bits is more than enough to acquire signals that have changes of a few mV and a sampling rate of 500 kHz is sufficient to gather data that allows the understanding of the structure behaviour. It is also important to understand that an improvement of these characteristics means an increase of energy consumption which is a critical restriction in a wireless system.

Some smart sensors platforms support other types of sensors interface protocols usually I2C or SPI. These communication standards will subsequently be subject of further study.

2.2.2 Computing Core

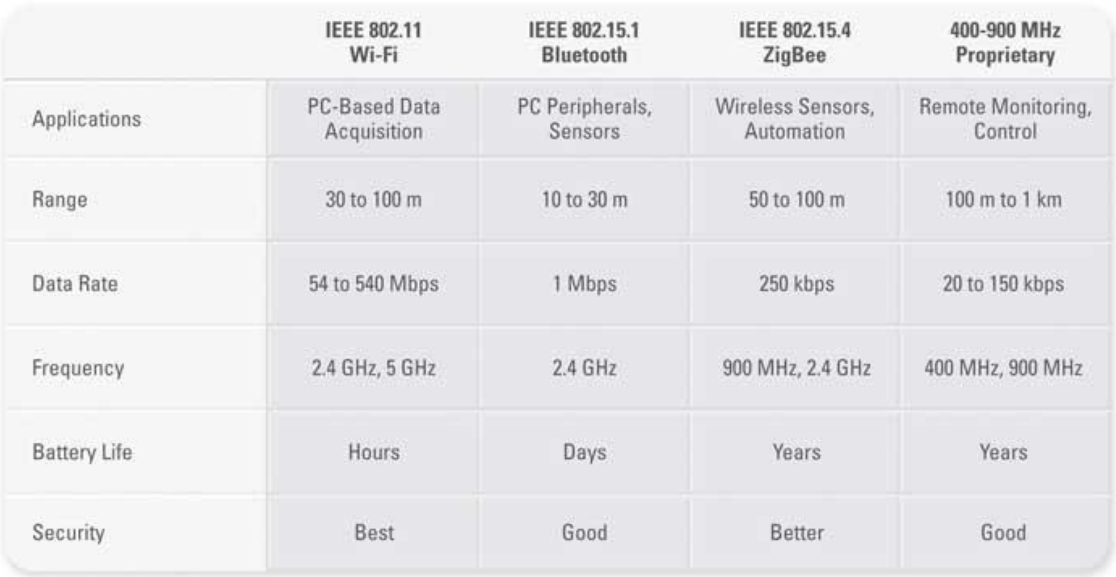
Once measurement data have been acquired by the sensing interface, the computational core takes responsibility of the data. This module has different roles according to the architecture of the overall system but normally it defines where the data is stored, how it is processed and also control the communication of this information. In order to perform these tasks the computing core is typically composed by a microcontroller. Usually the microcontroller has access to two types of storage, RAM (random access memory) where all the data required to process the information received is stored and ROM (read-only memory) used to store the firmware or other usual routines in the case of SHM damage detection algorithms. As RAM is easily expanded ROM is pretty much tied to the microcontroller chosen. There is wide variety of controllers that can be incorporated in these systems and one major classifier is the size of their internal data bus (in bits). In SHM the choice often falls between the 8-, 16-, or 32-bits microcontrollers. Another important element has to be taken in consideration the clock. The speed of the clock is a direct measurement on how fast the microprocessor is able to execute a given program. It is true that larger data buses and faster clocks enable a higher processing throughput however the improvement of these characteristics leads to an increase in power consumed.

2.2.3 Wireless Radio

In order to have the capability to interact with other wireless sensors and to transfer data to remote workstations, a wireless transceiver is an integral element of a smart sensor platform. This module should be able to transmit and receive data from other platforms, and like the computing core there is a wide variety of equipments in the market. Some of the main factors of choice are communication distance, radio frequency used and signal power. Wireless transceivers used in smart sensors usually operate in the ISM (Industrial Scientific and Medical) frequency bands, typically 900 MHz, 2.4 GHz and 5 GHz. Besides the physical limitations implied by the antenna's design and restricted power consumption the signal power, thus the communication distance is limited by legislation. The Federal Communications Commission (FCC) mandates the maximum power an antenna can output is 1W [13]. Some studies support that is more efficient to use various communication modules that transmit over shorter distances than a single module for long range transmissions [14].

Typically there are two types of wireless signals that can be sent upon a selected radio band. Narrow-band wireless transmission modulates all of the data upon a single carrier frequency. This strategy is prone to multipath effects and interference which diminish its performance. To enhance the reliability spread spectrum wireless transmission is preferred. Spread spectrum encodes data on a number of different frequencies within a frequency band which reduces the probability of interference. There are a number of methods for modulating data using this strategy the normally use are frequency-hopping spread spectrum (FHSS) and direct-sequence spread spectrum (DSSS) [15].

The need to integrate multiple platforms of different manufactures in one system led to the creation of specific standards for wireless communications. The Institute of Electrical Engineering (IEEE) has developed several protocols in the 2.4 GHz band. The 802.1x or Wi-Fi is mostly used on PC-based applications and allows high data rate transfer but on the downside the associated energy consumption is impractical for the use in smart sensors platforms. Bluetooth supported by the 802.15.1 standard is not as energy costly as Wi-Fi but as limit range that is sometimes too limited for SHM systems. Developed especially for sensor networks the 802.15.4 offers a good distance range keeping the power consumption to the minimum (Figure 2.5). Notice that all these standards only define the two lowest layers of the OSI model, Physical Layer (PHY) and Medium Access Layer (MAC) [16].



	IEEE 802.11 Wi-Fi	IEEE 802.15.1 Bluetooth	IEEE 802.15.4 ZigBee	400-900 MHz Proprietary
Applications	PC-Based Data Acquisition	PC Peripherals, Sensors	Wireless Sensors, Automation	Remote Monitoring, Control
Range	30 to 100 m	10 to 30 m	50 to 100 m	100 m to 1 km
Data Rate	54 to 540 Mbps	1 Mbps	250 kbps	20 to 150 kbps
Frequency	2.4 GHz, 5 GHz	2.4 GHz	900 MHz, 2.4 GHz	400 MHz, 900 MHz
Battery Life	Hours	Days	Years	Years
Security	Best	Good	Better	Good

Figure 2.5 - Wireless technologies survey [16]

In order to promote the use of wireless sensors some higher layers have been developed. The ZigBee Alliance has created a protocol based on the IEEE 802.15.4 standard which adds the Network Layer (NWK) and the Application Layer (APL) (Figure 2.6). Notice that ZigBee is an open protocol that anyone can have access to.

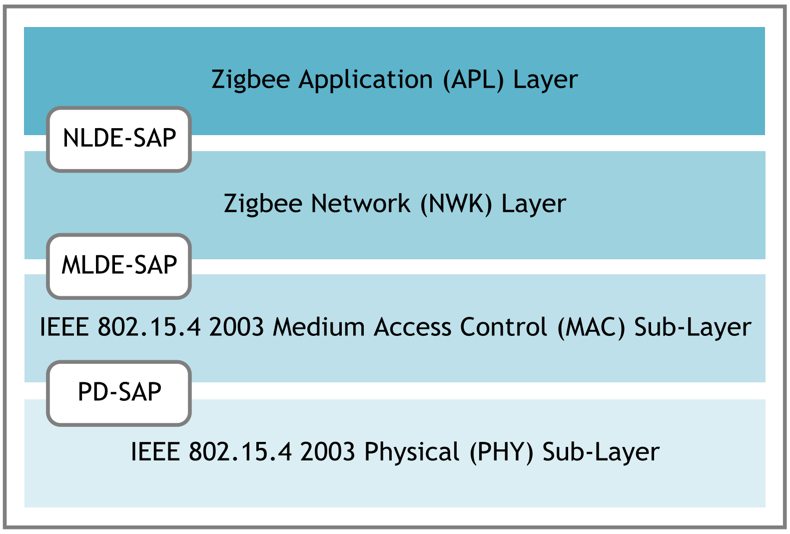


Figure 2.6 – The ZigBee stack

As it is based on the IEEE 802.15.4 lower layers this protocol uses the DSSS spread spectrum technique. In order to improve the robustness the IEEE standard also employ a technique usually known as frequency division access (FDMA). This means that it divides the 2.4 GHz band in 16 non-overlapping channels which are 5 MHz apart. As so ZigBee devices can comfortably coexist with other devices using the 2.4 GHz band.

One specific property of the ZigBee protocol, implemented by the Network Layer, is the definition of three node types. ZigBee Coordinators are used to form the network, the ZigBee Routers which can route packets and ZigBee End-Device, which can sleep and go into low-power modes. Using the sleep ability allows the system to save a lot of energy and is the major advantage of this protocol [17].

The ZigBee protocol is not the only one based on the IEEE 802.15.4 standard. One of the biggest competitors is the WirelessHART. This technology was developed in order to address some of the main concerns raised by the industry towards ZigBee. The first big difference is that WirelessHART defines only one type of node able to work as router or end-device, thus increasing the flexibility of the network. Also it uses time division multiple access (TDMA) to share the medium instead of the carrier sense multiple access with collision avoidance (CSMA/CA). The first one allows devices to increase their power savings because they only need to keep the radio on during the required timeslots. However this technique arises some problems the synchronism of the nodes [18].

These two protocols here discussed can support different network architectures like star, tree or mesh (Figure 2.7). However it is important to understand that one of the biggest advantages of having the network layer defined is that it enables the use of multi-hopping mesh architecture in an easy and interoperable way. The advantages of these different architectures will be discussed later in this chapter.

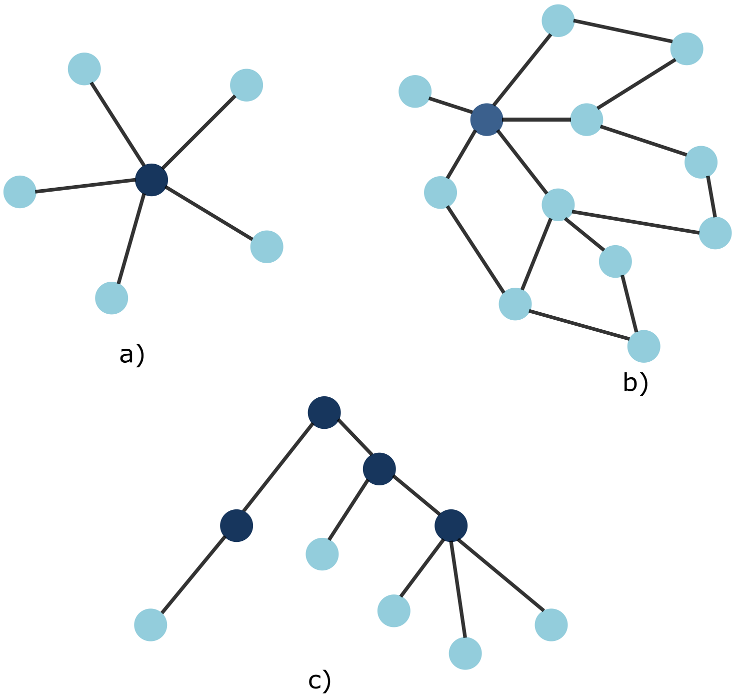


Figure 2.7 - Network architectures: a) Star topology, b) Mesh topology and c) Hierarchical tree topology

There are many more protocols developed on top of IEEE 802.15.4, it is even possible to only use the layers defined by this standard and built a solution from there. Wireless USB is another emerging technology for small and battery-operated devices. It uses the Ultra Wideband (UWB) which supports 480 Mbps over a distance of two meters. This protocol is not meant to function on a scale as large as ZigBee and it is more suitable for PC peripherals. Other solution developed by Zensys is the Z-Wave which is useful for home automation products. It operates in the 868 MHz band for Europe and the 908 MHz for the United States.

Usually this technology has a data rate of 9 kbps which is rather inferior compared to the 250 kbps offered by ZigBee [17].

All these protocols will be studied in a deeper manner throughout this document however the main focus will fall in the ZigBee and WirelessHART solutions due to their expressivity in the smart sensors domain.

2.2.4 Actuation Interface

The last subsystem shown in figure 2.4 is the actuation interface. It provides to a smart sensor the capability to interact directly with the structure where it is installed. Actuators and active sensors can both be commanded by this module which is usually composed by a digital-to-analogue converter (DAC). Actuators can be used to excite the structure in order to obtain better results but it is not always profitable energy wise. As to ADCs there are a lot of choices available in the market and it is necessary to understand the requirements of the actuators and the trade-off between functionality and power consumption [13].

2.2.5 Power Supply

Although not specified in figure 2.4 power supply is one of the major concerns of smart sensors design. In SHM systems does not make sense to communicate all the data wireless when there is still the need to equip the structure with cables to supply energy. Therefore most of the wireless smart sensor technologies are supplied by batteries or some kind of renewable energy source that can be produced on the local.

There are many types of batteries however the choice is usually lithium based batteries. Compared to the nickel-cadmium batteries lithium provides twice the energy density and allows more autonomy. They have a high cell voltage of 3.6 Volts which allows battery pack designs with only one cell. Their size and weight are also advantages compared to nickel-cadmium batteries and cause little harm when disposed. Despite its overall advantages, lithium has its flaws. It is fragile and needs a protection circuit to maintain safe operation, there are aging concerns when the battery is not in use and most of all it is expensive to produce.

The deep study of portable batteries is out of the scope for this research, yet a summary table is presented. Table 2.1 shows all the important characteristics that the designer has to have in account when choosing a battery.

Methods to increase the autonomy of wireless smart sensors are being developed. The use of renewable energies provided by photovoltaic panels, eolic generators or the utilization of the natural structure vibration are some of the examples [19].

	NiCd	**NiMH**	**Lead Acid**	**Li-ion**	**Li-ion polymer**	**Reusable Alkaline**
Gravimetric Energy Density(Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits in mW)	100 to 200 6V pack	200 to 300 6V pack	<100 12V pack	150 to 250 7.2V pack	200 to 300 7.2V pack	200 to 2000 6v pack
Cycle Life (to 80% of initial capacity)	1500	300 to 500	200 to 300	500 to 1000	300 to 500	50 (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20%	30%	5%	10%	~10%	0.3%
Cell Voltage (nominal)	1.25V	1.25V	2V	3.6V	3.6V	1.5V
Load Current (C-rate)						
- Peak	20C	5C	5C	>2C	>2C	0.5C
- Best result	1C	0.5C	0.2C	1C	1C	0.2C
Operating Temperature (discharge only)	-40 to 60ºC	-20 to 60ºC	-20 to 60ºC	-20 to 60ºC	0 to 60ºC	0 to 65ºC
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months	not req.	not req.	not req.
Typical Battery Cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle (US$)	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial Use Since	1950	1990	1970	1991	1999	1992

Table 2.1 - Characteristics of commonly used rechargeable batteries (adapted from [20])

Many solutions based on wireless smart sensors have been made next chapter will present some of the most notorious. Keeping in mind the goal of this dissertation all the technologies discussed are related to structural health monitoring.

2.3 Solutions based on wireless sensor networks

The academic community fast realized the need to reduce costs associated with wired structural monitoring systems. A wide variety of researchers from different institutions developed different prototypes of wireless sensor platforms. Latter partnerships were made and some companies start to invest in this emerging technology. Almost every single solution integrates the subsystems previous discussed, thus this subchapter will give only an overview of the different approaches in a chronological order.

2.3.1 Academic point of view

One of the first solutions presented date from 1998, Straser and Kiremidjian from Stanford University presented a system based on commercial off-the-shelf (COTS) components [21]. It uses a Motorola 68HC11 microprocessor, chosen for its large number of on-chip hardware peripherals and for the possibility of integrates high-level programming languages for embedding software. The wireless radio is a Proxim Proxlink MSU2 operating on the 902-928 MHz with a maximum range of 300 meters and a data rate of 19.2 kbps. Although the wireless sensor proposed does not give the proper attention to the power consumption it can be considered the first major step by the structural engineering community towards decentralized data processing and wireless SHM [13].

The next system comes from Lynch et al. [22] and was presented in 2001 (Table 2.2). Also from Stanford University, this solution emphasizes need of powerful decentralized data processing system. The 8-bit Atmel AVR AT90S8515 enhanced RISC (reduced instruction set computer) microcontroller was the choice for this platform. Representing the continuation of Straser and Kiremidjian work the idea was to increase the processing throughput without compromising the energy consumption.

Introducing a somewhat innovative concept Mitchell et al. (2002) [23] presented a solution based in a two-tier SHM architecture (Figure 2.8). The idea is to separate the monitoring system in wireless sensors and wireless data server (clusters). The communication between the sensors nodes and clusters is made with resource to the Ericsson Bluetooth wireless transceiver. It operates on the 2.4 GHz radio band and has a maximum reach of approximately 10 meters line of sight. In order to overcome this restriction a multihopping strategy is proposed. The Bluetooth radio consumes only 35 mW of electrical power. All the cluster nodes are equipped with a long-range radio which enables the transference of data between them. Furthermore this architecture allows the clusters to have powerful computing cores and it is also proposed the connection to the World Wide Web using cellular modems for long range communications [23].

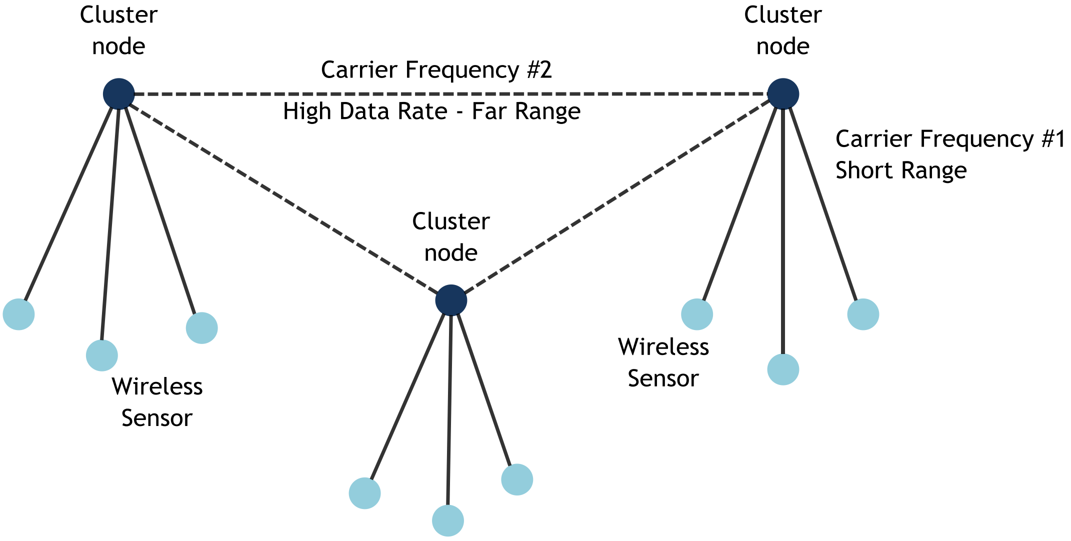


Figure 2.8 - Two-tier architecture proposed by Mitchell et al. (2002) [23]

	Straser and Kiremidjian (1998)	**Lynch et al. (2002)**	**Mitchell et al. (2002)**	**Kottapalli et al. (2003)**	**Lynch et al. (2004)**
DATA ACQUISTION SPECIFICATIONS					
A/D Channels	8	1		5	1
Sample Rate	240 Hz	100 kHz	20 MHz	20 MHz	100 kHz
A/D Resolution	16-bit	16-bit	8-bit	8-bit	16-bit
Digital Inputs	0	2		0	2
EMBEDDED COMPUTING SPECIFICATIONS					
Processor	Motorola 68HC11	Atmel AVR8815	Cygnal 8051	Microship PIC16F73	Atmel AT90S8515 AVR/ MPC555PowerPC
Bus Size	8-bit	8-bit	8-bit	8-bit	8-bit/32-bit
Clock Speed	2.1 MHz	4 MHz		20 MHz	4 MHz/20 MHz
Program Memory	16 kB	8 kB	2 kB	4 kB	8 kB/26 kB
Data Memory	32 kB	32 kB	128 kB	192 kB	512 kB/448 kB
WIRELESS CHANNEL SPECIFICATIONS					
Radio	Proxim Proxlink	Proxim RangeLan2	Ericsson Bluetooth	BlueChip RBF915	Proxim RangeLan2
Frequency Band	900 MHz	2.4 GHz	2.4 GHz	900 MHz	2.4 GHz
Wireless Standard			IEEE 802.15.1		
Spread Spectrum	Yes	Yes	Yes	Yes	Yes
Outdoor Range	300 m	300 m	10 m	500 m	300 m
Enclosed Range	150 m	150 m	10 m	200 m	150 m
Data Rate	19.2 kbps	1.6 Mbps		10 kbps	1.6 Mbps
FINAL ASSEMBLED UNIT ATTRIBUTES					
Dimensions	15x13x10 cm	10x10x5 cm	5x3.8x1.2 cm	10x5x1.5 cm	12x10x2 cm
Power Consumption			120 mW	100 mW	
Power Source	Battery (9v)	Battery (9V)	Battery	Battery (9V)	Battery (9V)

Table 2.2 - Summary of academic wireless sensing unit prototypes (1998 – 2003) (adapted from [13])

Kottapalli et al. (2003) [24] also used the two-tier network concept. The major accomplishment of their solution was to drastically reduce the power consumption. Wireless sensing units communicate with their corresponding site master using the BlueChip EVK915 which consumes only 36 mW when receiving and 150 mW when transmitting. Powered by alkaline AA batteries, this system can stand 18 months until the portable energy supply depletes [24].

	Aoki et al. (2003)	Mastroleon et al. (2004)	Sazonov et al. (2004)	Allen (2004) Farrar et al. (2005)	Wang et al. (2005)
DATA ACQUISITION SPECEFICATIONS					
A/D Channels		5	6	6	4
Sample Rate		480 Hz		200 kHz	100 kHz
A/D Resolution	10-bit	16-bit	12-bit	16-bit	16-bit
Digital Inputs		0	16		0
EMBEDDED COMPUTING SPECIFICATIONS					
Processor	RenesasH 8/4069F	Microchip PICmicro	Texas Instruments MSP430F1611	Intel Pentium/ Motorola	Atmel AVR ATMega128
Bus Size	8-bit	16-bit/8-bit	16-bit	16-bit	8-bit
Clock Speed	20 MHz			120/233 MHz	8 MHz
Program Memory	128 kB		16 MB	256 MB	128 kB
Data Memory	2 MB			Compact Flash	128 kB
WIRELESS CHANNEL SPECIFICATION					
Radio	Realtek RTL-8019AS	BlueChip RFB915B	Chipcon CC2420	Motorola neuRFon	Maxstream 9XCite
Frequency Band		900 MHz	2.4 GHz	2.4 GHz	900 MHz
Wireless Standard		IEEE 802.15.1	IEEE 802.15.4	IEEE 802.15.4	
Spread Spectrum		Yes	Yes	Yes	Yes
Outdoor Range	50 m	200-300 m	75 m	9.1 m	300 m
Enclosed Range	50 m			9.1 m	100 m
Data Rate		19.2 kbps	250 kbps	230 kbps	38.4 kbps
FINAL ASSEMBLED ATTRIBUTES					
Dimensions	30x6x8 cm	8x8x2 cm			10x6.5x4 cm
Power Consumption			120 mW	6 W	100 mW
Power Source					Five AA batteries (7.5V)

Table 2.3 - Summary of academic wireless sensing unit prototypes (2003 – 2005) (adapted from [13])

While these two last proposals focus on reducing the power consumption, Lynch et al. [25] presented an upgrade to their first system focusing on the processing power. This time a dual-processor configuration was proposed. It is known that microprocessors with high computational throughput consume more energy, so Lynch et al. [25] overcome this restriction using a two processor design where the low power 8-bit Atmel AVR AT90S8515 is utilized to overall unit control and real-time data acquisition, and the 32-bit Motorola MPC555 PowerPC is in charge of data processing. This second core is not always running allowing low power mode operations, actually it is only turned on when there is data ready to be analysed. It contains 448 kB of ROM and 26 kB of RAM, along with a floating-point arithmetic and logic unit (ALU) which permits the execution of demanding damage detection routines [13].

The next wireless sensing unit prototype called Remote Intelligent Monitoring System (RIMS) is proposed by Aoki et al. (2003) [26]. Designed for the purpose of bridge and infrastructures monitoring, each hardware component is chosen in order to reduce the energetic consumption and size of the platform. One important feature presented in this design is the addition of a dedicated three-axis microelectromechanical systems (MEMS) piezoresistive accelerometer (Microstone MA3-04). The study of sensors based on MEMS technology is part of the objectives of this dissertation and its discussion will be presented further ahead. It is important however to refer that these systems are low power consuming and really small (Figure 2.9).

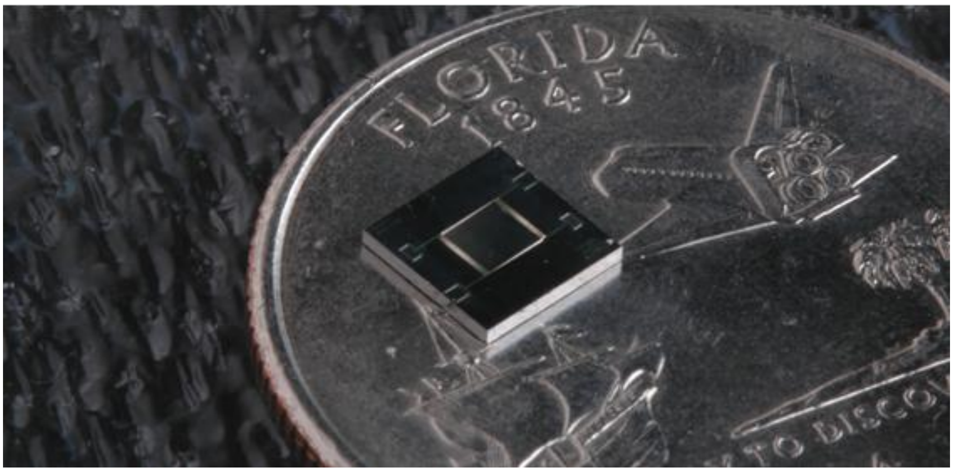


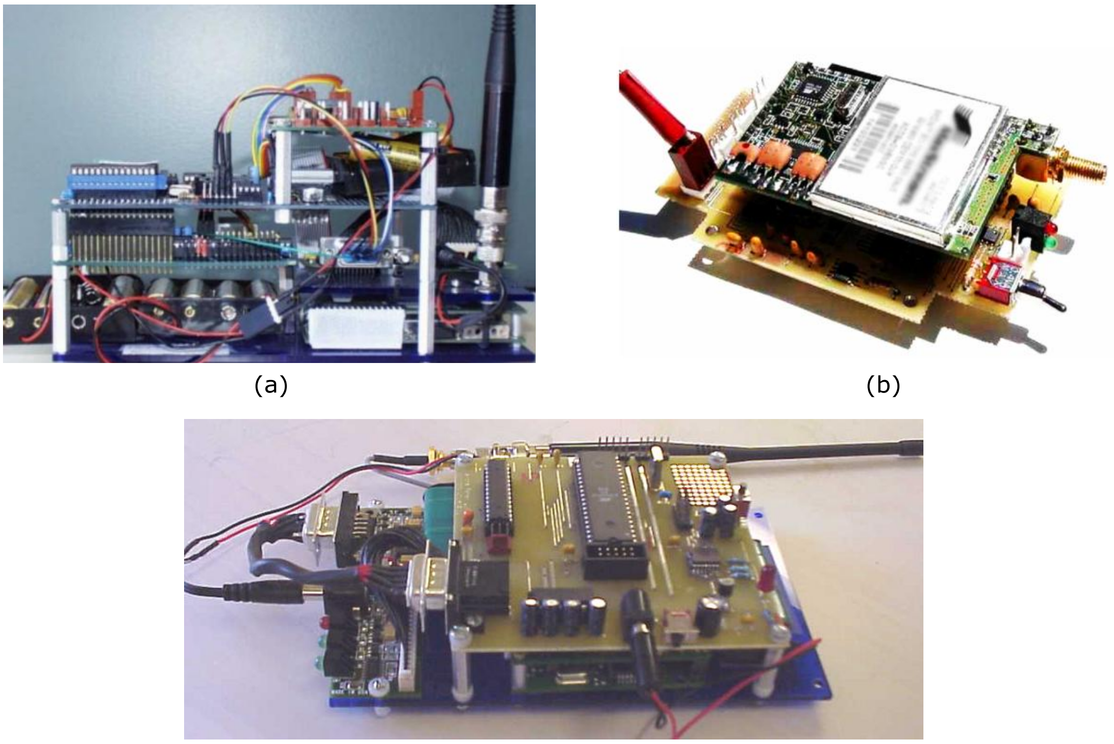
Figure 2.9 - The size of generic MEMS sensor

Extending upon the design proposed by Kottapalli et al. (2003) [24], Mastroleon et al. (2004) [27] have accomplished greater power efficiency by upgrading most of the unit's original components. The main change is the computational core which is changed by a PICmicro. Featuring a low power consumption and high computational performance this microcontroller is capable of achieving real-time processing and time synchronization by using multilevel priority interrupts and phase-locked loop (PLL) synchronization units [27]. Also the Mircrochip PICmicro enables the dynamic switch between six power modes, thus providing an ultralow power consumption platform.

The first prototype using the IEEE 802.15.4 standard was proposed by Sazonov et al. (2004) [28]. The wireless transceiver used is the Chipcon CC2420 which operates in the 2.4 GHz radio spectrum with a data rate of 250 kbps. It has a range of 10 to 70 meters, yet it only consumes 60 mW when receiving and 52 mW when transmitting.

The last design seeks to minimize power consumption simultaneous to maximizing functionality. With a different strategy in mind Allen (2004) [29] and Farrar et al. (2005) [30] proposed a system that emphasizes the computational power providing a wireless sensor design that was capable to perform a broad array of damage detection algorithms. In close collaboration with Motorola Labs they designed a platform that enables seamless interaction with DIAMMOND II, an existing damage detection package written in Java. It was selected a standard PC-104 SBC with a 133 MHz Pentium processor, 256 MB of RAM and a 512 MB Compact Flash (CF) card serving as hard drive. The interface with sensors integrates the DSP56858 digital signal processor (DSP) that is used to sample data from the Maxim ADCs. All these processing power led to a unit volume of 1750 cm^3 that consumes 6 W of power.

The last academic prototype here presented comes from Wang et al. (2005) [31]. Using the latest commercially available embedded system components they proposed a wireless sensing platform that has multitasking capabilities. This system is able to sample measurement data simultaneous to wirelessly transmitting data to other units. The most attractive feature is the wireless radio. The MaxStream 9XCite wireless modem operates on the 900 MHz band and is capable of data rates as high as 38.4 kbps. The communication range is 300 meters in line-of-sight and consumes 250 mW when transmitting and 150 mW receiving. Also MaxStream modem presents an idle mode that consumes only 5 mW making this unit really attractive to periodic monitoring systems.



(a) (b)

(c)

Figure 2.10 - Pictures of some wireless sensing units: (a) Unit from Straser et al. (1998) [21]; (b) Unit from Wang et al. (2005) [31]; (c) Unit from Lynch et al. (2003) [25]

2.3.2 Commercial solutions

A number of commercial wireless sensor platforms have emerged in the recent years that are well suitable for SHM applications. Using this type of solutions can be extremely advantageous because they feature an immediate out-of-the-box operation and good technical support. Many researchers use these commercial solutions to explore their theories and develop add-ons to make the unit more suitable for the application in question [13].

As for academic prototypes there is a way to big variety of commercial platforms to discuss them all in this chapter. An overview of the most common systems is made with special attention to the Mote wireless sensor platforms. The popularity of Motes is mostly due to the open source architecture both at hardware and software level. They were initially developed at the University of California-Berkeley and subsequently commercialized by Crossbow [32]. The first prototype developed is called WeC, was produced in 1999 and after commercialized as the Rene Mote by Crossbow. It integrates 8-bit Atmel AT90LS8535 AVR microcontroller which has an internal eight-channel, 10-bit ADC. In order to communicate with the other sensors it has a RF Monolithics TR 1000 wireless radio integrated. This transceiver employs amplitude modulation and operates on the 916 MHz frequency.

Rene Mote was after updated to produce the Rene2 platform which presents the same design with a new microcontroller. The choice recalled on the Atmel ATega163L that has a larger internal memory including 16 kB of ROM and 1kB of RAM. Some studies have been made using this platform to interface with two types of MEMS accelerometers, Analog Devices ADCL202 and Silicon Devices SD-1221. It was first concluded that two sensing channels cannot be sampled at the same time resulting in a relative 30 µs offset between samples. It was found that this offset has a negative impact on the embedded software used to calculate cross-correlation coefficients for sensor signals with high-frequency content. The internal memory featured was also a problem not allowing large buffers of sensor data to be stored. As result only on-the-fly data interrogation was possible to implement [33]. Other issues were raised related to the communications reliability when the single-channel RF Monolithics TR 1000 was tested [34].

In 2002 Crossbow released MICA Mote wireless sensor. The successor of the Rene2 is based on the 8-bit Atmel ATmega103L microcontroller which incorporates 128 kB of flash ROM and 4 kB of RAM. This unit was designed to work with the TinyOS embedded operating system. MICA still integrates the same wireless transceiver of its predecessor. Critical hardware issues that must be solved before these Motes can be used to SHM were addressed. Time synchronization across a large number of platforms is a big concern and tests identified errors of 7 ms with a MICA Motes solution [13].

The low reliability offered by the singe-channel RF Monolithics TR 1000 was other problem in need of attention. MICA2 was presented in 2003 and brought a new wireless radio with him. The Chipcon transceiver operates on the 900 MHz band and presents a frequency modulation (FM) with high noise immunity. The carrier frequency can be changed via software allowing FHSS encoding techniques. MICA2 was later upgraded to be in compliance with the IEEE 802.15.4 standard. A lot of studies using MICA2 Motes for SHM were made, there are still some issues that need to be addressed but all the researchers consent that wireless sensor solutions for structure monitoring is the path to follow [13].

	UC Berkeley-Crossbow WeC (1999)	UC Berkeley-Crossbow Rene (2000)	UC Berkeley-Crossbow MICA (2002)	UC Berkeley-Crossbow MICA2 (2003)	Intel iMote Kling (2003)
DATA ACQUISITION SPECEFICATIONS					
A/D Channels	8	8	8	8	
Sample Rate	1 kHz	1 kHz	1 kHz	1 kHz	
A/D Resolution	10-bit	10-bit	10-bit	10-bit	
Digital Inputs					
EMBEDDED COMPUTING SPECIFICATIONS					
Processor	Atmel AT90LS8535	Atmel Atmega163L	Atmel ATmega103L	Atmel ATmega128L	Zeevo ARM7TDMI
Bus Size	8-bit	8-bit	8-bit	8-bit	32-bit
Clock Speed	4 MHz	4 MHz	4 MHz	7.383 MHz	12 MHz
Program Memory	8 kB	16 kB	128 kB	128 kB	64 kB
Data Memory	32 kB	32 kB	512 kB	512 kB	512 kB
WIRELESS CHANNEL SPECIFICATION					
Radio	TR 1000	TR 1000	TR 1000	Chipcon CC1000	Wireless BT Zeevo
Frequency Band	868/916 MHz	868/916 MHz	868/916 MHz	315, 433, or 868/916 MHz	2.4 GHz
Wireless Standard					IEEE 802.15.1
Spread Spectrum	No	No	No	Yes (Software)	Yes
Outdoor Range					
Enclosed Range					
Data Rate	10 kbps	10 kbps	40 kbps	38.4 kbps	600 kbps
FINAL ASSEMBLED ATTRIBUTES					
Dimensions	2.5x2.5x1.3 cm	8x8x2 cm			10x6.5x4 cm
Power Consumption	575 mAh	2850 mAh	2850 mAh	1000 mAh	100 mW
Power Source	Coin Cell	Battery (3V)	Battery (3V)	Coin Cell	Battery

Table 2.4 - Summary of commercial wireless sensing unit prototypes (1999 – 2003) (adapted from [13])

A new generation of Mote platforms was introduced in 2003. It was the result of the collaboration between the University of California-Berkeley and the Intel Research Berkeley Laboratory. This new hardware conception was based proposes only a computational core and wireless transceiver. They recognized that specific sensing applications need specific sensing interface, thus iMote features a highly modular construction that allows separated sensing interfaces to be snapped onto its platform [13]. The iMote computational core is the 32-bit ARM7TDMI microcontroller running at 12 MHz, which provides four times greater computational power than the one integrated in the MICA Mote. It exhibits 64 kB of RAM for data storage and 512 kB of ROM for running TinyOS. The wireless communication module is the 2.4 GHz Zeevo Bluetooth radio which is integrated with the microcontroller in a single integrated circuit. In order to supplying energy to the mote it is used two Panasonic Lithium CR2 3V batteries. Studies by Spencer et al. (2004) [35] have reported the iMote as a powerful tool for future wireless SHM systems.

Following the MICA Mote concept TelosB was presented by Crossbow in 2005. The main update is the wireless module. It has an integrated transceiver that work in compliance with the IEEE 802.15.4 standard. As for the computational core the Texas Instruments MSP430 with a 16-bit bus is integrated. In regard to MICA unit this platform exhibits a powerful processor without increasing the power consumption [36]. Tmote Sky is the successor of Telos it was presented by Moteiv in 2005. It includes increased performance, functionality and expansion. With TinyOS support out-of-the, Tmote proportionate emerging wireless protocols and is integrated in the open source software movement [37]. Both these units have not yet been deeply studied for SHM applications. They are only referenced in this document for contextual reasons.

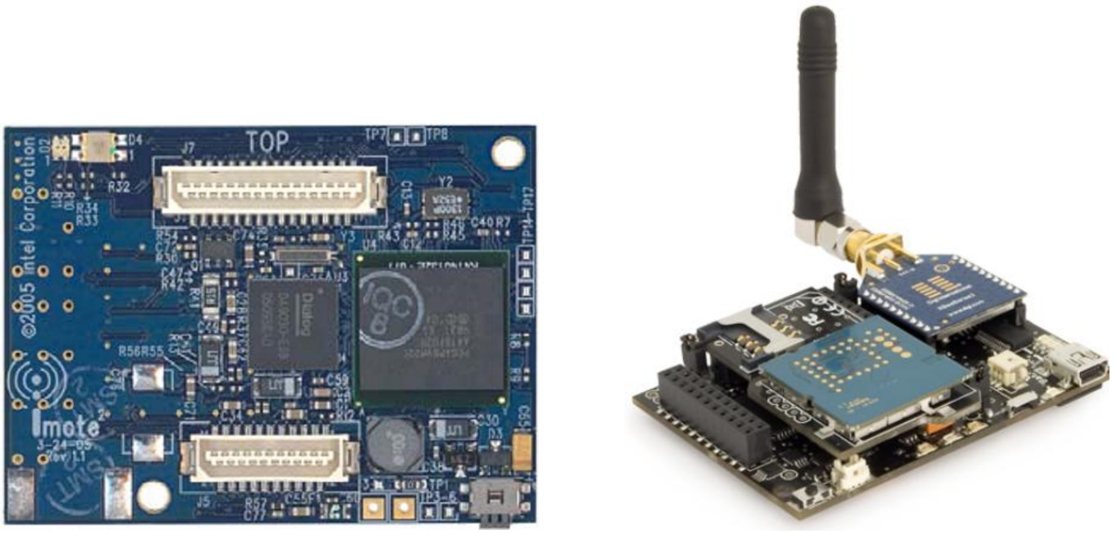
In 2007 Crossbow began selling the iMote2 (Figure 2.10). This platform is considered one of the most powerful solutions on the market. It integrates the Intel PXA271 XScale processor that can be configured to operate in different clock frequencies being the lowest 13 MHz and the highest 416 MHz. The ability to change the speed at which the computational core works is an important feature for energy optimization. This equipment supports several operating systems including TinyOS 1.1, TinyOS 2.0, SOS and Linux. iMote2 is considered one of the most advanced platforms on the wireless sensor field [38].

The last platform discussed in this overview is the Waspmote (Figure 2.10). It was presented by Libelium in 2009 and brought with him a lot of new features. The major characteristic is the 0.7 μA that it consumes when in sleeping mode. Also Libelium took the modular concept to a new level. Waspmote can be integrated with a lot of different wireless communication technologies. They offer a wide variety of XBee modules that support numerous standards like IEEE 802.15.4, IEEE 802.15.1 and ZigBee. Some tests showed an outdoor range of 12 Km using the 900 MHz radio and 7 km with the 2.4 GHz radio [39]. Also Libelium presents a lot of interface sensor units that can be snapped into the Waspmote without any hardware change [40].

As it was showed a variety of solutions are available to integrate wireless sensor networks (Table 2.2, 2.3, 2.4 and 2.5). At the same time that these platforms become more powerful at processing level and more autonomous they start to present a viable solution for structural health monitoring systems. The price of these devices is quite reduced compared to wired solutions, for example Crossbow sells the iMote2 for €100(US) a unit [41]. The reduced cost is also one of the reasons for the success of wireless sensor systems in the research community.

	UC Berkeley-Crossbow TelosB (2005)	**Moteiv Tmote Sky (2005)**	**Crossbow IMote2 (2007)**	**Libelium Waspmote (2009)**
DATA ACQUISITION SPECEFICATIONS				
A/D Channels	8	8		7
Sample Rate				15 kHz
A/D Resolution	12-bit			10-bit
Digital Inputs				
EMBEDDED COMPUTING SPECIFICATIONS				
Processor	TI MSP430	TI MSP430 F1611	Intel PXA271 XScale	Atmel ATmega1281
Bus Size	16-bit	16-bit	32-bit	8-bit
Clock Speed	4 MHz	32 kHz	13 MHz to 416 MHz	8 MHz
Program Memory	48 kB	16 kB	256 kB SRAM	8 kB SRAM and 4 kB EEPROM
Data Memory	10 kB	10 kB	32 MB SDRAM and 32 MB flash	128 kB flash
WIRELESS CHANNEL SPECIFICATION				
Radio	Integrated IEEE 802.15.4 radio	Chipcon CC2420	Chipcon CC2420	XBee modules
Frequency Band	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz, 900 MHz
Wireless Standard	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.4/ IEEE802.15.1
Spread Spectrum	Yes	Yes	Yes	Yes
Outdoor Range	75 to 100 m	125 m		7 km
Enclosed Range	20 to 30 m	50 m		
Data Rate	250 kbps	250 kbps	250 kbps	Depend on the radio
FINAL ASSEMBLED ATTRIBUTES				
Dimensions	6.5x3.1x6 cm		4.8x3.6x0.75 cm	7.35x5.1x1.3 cm
Power Consumption				
Power Source	2X AA batteries	2X AA batteries	3X AAA alkaline batteries	Lithium battery (3.3V)

Table 2.5 - Summary of commercial wireless sensing unit prototypes (2005 – 2009)



(a) (b)

Figure 2.11 - Wireless sensor platforms: (a) Intel IMote2.0; (b) Libelium Waspmote

2.4 Imbedded software and middleware

Systems based on wireless sensor networks do not rely only on hardware platforms. It is mandatory to have a good imbedded operating system and high quality middleware services in order to achieve good results. There are several software solutions already developed and this sub-chapter discuss some of them.

2.4.1 Imbedded operating systems

One of the most common used operating systems for SHM is TinyOS (www.tinyOS.net). It is open-source, has a large community and many successful implementations on wireless sensors. It utilizes a component-based architecture which is suitable for the use in smart sensors due to their extreme memory constraints.

This operating system employs non-blocking I/O which means that it has only one memory stack. TinyOS support two types of executions. Tasks work in a FIFO manner, the order they are implemented is the order that they follow. Hardware event handlers on the other hand can pre-empt the execution of a task [42]. Due to being an event-driven operating system it has limitations at temporal level. One of the known issues is the uncertainty of the delay when start sensing. This phenomenon has to be address in order to synchronize sensing is to be achieved [43].

Applications for TinyOS are written in nesC which is based on C-language. Although it is used widely for wireless sensor networks TinyOS is a challenging platform for non-programmers to develop network control and application software.

In the same line there is Mantis OS (Multimodal Networks of In-situ Sensors). It is a multithread embedded operating system for wireless sensor network platforms. It was developed for general purpose hardware and allows the performance of complex tasks even when they are time-sensitive [44].

Another operating system that has big impact is LiteOS. It is dedicated to sensor networks and was developed by the University of Illinois. The main feature of this operating system is the use of an object-oriented programming environment called LiteC which is based on C++ [45].

These are the main operating systems used for wireless sensor networks systems. Some hardware units can even handle some light version of Linux but the goal is always the same, provide a reliable base for developing applications on smart sensors.

2.4.2 Middleware Services

Before any damage detection routine can be implemented it is necessary to ensure certain features on the network itself. The existence of temporal synchronization inside the system is critical. It was already mentioned that tests with MICA Mote showed that interrogation algorithms present erroneous results when the data is not synchronized. Middleware services connect hardware to software and have to assure that the measurements made by the hardware components get to damage detection algorithms in the best conditions.

There are a lot of developments on time synchronization protocols and some of them will be studied in depth on the next chapters. One of the most complete overviews of these protocols is made by Sundararaman et al. (2005) [46].

2.5 Conclusion

The background studies here presented showed the importance of SHM systems. First it is discussed the structural health monitoring concept showing the main features and components. It is also mentioned the different types of tests performed in order to discover the condition of a structure.

Wireless sensor networks are given as a solution to reduce the initial costs of SHM systems. The concept of these platforms is presented and all the subsystems discussed. The state of art of smart sensor platforms is made in the sub-chapter 2.3. It is presented the distinction between academic and commercial solutions being discussed the most important devices.

After finishing this chapter it is possible to understand the advantages of using wireless sensor networks in SHM systems.

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