Wireless MEMS-Based Accelerometer Sensor Boards for Structural Vibration Monitoring: A Review

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***Abstract*—Monitoring and analysing the integrity of structures and machinery is important for economic, operational, and mission critical reasons. In recent years, there has been growing interest in performing Structural Health Monitoring (SHM) by monitoring structural dynamic response via Micro Electro-Mechanical System (MEMS) accelerometers. In addition, the possibility of embedding these devices within a Wireless Sensor Network (WSN) and allowing measured data to be wirelessly transmitted has contributed to the development of many new applications not possible just a few years ago. These sensors, for use in SHM applications, need to detect low-amplitude and low frequency vibrations, operations which are not always feasible with the conventional low-cost sensor boards. Since the late 1990s, several accelerometer board prototypes have been proposed for achieving accurate vibration monitoring. This paper presents a summary review of the systems developed in the ten years following 2006 with particular emphasis on the sensing characteristics, performances, and applications of the designed sensor boards for microvibration detection and analysis.**

***Index Terms*— Acceleration measurement, MEMS sensors, structural health monitoring application, Wireless Sensor Network.**

I. Introduction

CIVIL and mechanical engineering structures such as bridges, buildings, and aerospace systems continue to be used despite aging, deterioration, and operation past design life. For instance, in 2013 one out of nine of the United States bridges were rated as structurally deficient, with an average age of 42 years [1]. Therefore, it is likely that the damage accumulation limit for many of these structures is getting closer and will be exceeded in the near future. Thus, the ability to monitor the condition of such systems is important for both an economic and a life-safety standpoint. The process of continuously monitoring the integrity and the response of a structure is referred to as Structural Health Monitoring (SHM) [2]. It allows detecting damages at an early stage, tracking their evolution, and helping to reduce the costs and downtime associated with the repair of hazardous conditions prior to a failure. The progresses achieved in Micro Electro-Mechanical Systems (MEMS) technologies and wireless data transmission, have extended the sensing capability on structures. As a result, the integration of sensors and improved transmission capabilities have opened the door for new structural monitoring applications using novel approaches such as the use of Wireless Sensors Networks (WSNs) for the realization of low-cost monitoring systems [3, 4]. Currently, structural instrumentation using MEMS-based sensors provides low cost installation, low invasive effects, and equivalent performance to that of their macro-scale counterparts [5]. Wireless transmission, by reducing installation time and efforts, resolves many issues intrinsic to wire-based instrumentation. Such issues include: a) wire impedance and signal quality, b) mounting ease, and c) scalability and remote tasking abilities. The first issue is related to limitations due to cable length, which cannot exceed a few meters of extension and requires the installation of signal amplifiers. Furthermore, the triboelectric noise produced by the wire itself, which creates problems when low-amplitude signals are of concern. Finally, the wires may mass load or interfere with the functions of the structure being tested. The avoidance of the stated issues makes WSNs extremely appealing, as vibrations ranging from 10^1 m·s^{-2} (severe shaking) to 10^{-2} m·s^{-2} (microvibration) need to be detected on large-scale structures having natural frequencies in the range of 10^{-1} to 10^1 Hz [6].

The idea of operating many MEMS sensors within a WSN was initially introduced by researchers at the turn of the new millennium [7] and several authors remarked the potential benefits of this technology over traditional SHM systems [8-10]. Nevertheless, issues were highlighted when these systems were used for vibration monitoring of large-sized civil structures [11]. These issues included a lack of accuracy on a wide range of low-frequency accelerations, difficulty in handling large amounts of data, and limitations in high-speed data sampling and high duty-cycle [12]. As a matter of fact, the first systems installed low-cost, high-noise density sensors and Analog-to-Digital Converters (ADCs) lacking of resolution for microvibration monitoring as well as sensing instability due to unregulated battery voltage [13, 14].

In the last few years after resolving sensor accuracy issues at low frequency and amplitude vibrations, these systems have proved their reliability for performing microvibration measurements and SHM analyses. This paper provides a summary of the state-of-the-art of wireless, MEMS-based

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systems for vibration monitoring and discusses the future research issues in this field. The paper is organized as follows: Section II describes the general features of the wireless sensor boards for SHM. Section III presents a detailed overview of the systems developed in the last ten years, with particular emphasis on sensing characteristics that might influence measurement precision (i.e. sensor noise-density, sensitivity, bandwidth, and conversion accuracy). Finally, potential paths for future development are briefly outlined in Section IV followed by conclusions in Section V.

II. Characteristics of a SHM Wireless Sensor Board

As shown in Figure 1, a WSN typically consist of two components: a battery powered transmitter board and a receiver board connected to a server or computer. Transmitter boards are made of four principal sub-components: a sensing interface, a signal conditioning section, a computational core, and a radio transceiver for wireless communication [15]. Receiver boards are similar to transmitters, but with an opposite functionality. They receive the transmitted signal and down-convert it by reconstructing the original information before transferring it to a central analyzer for post-processing queries.

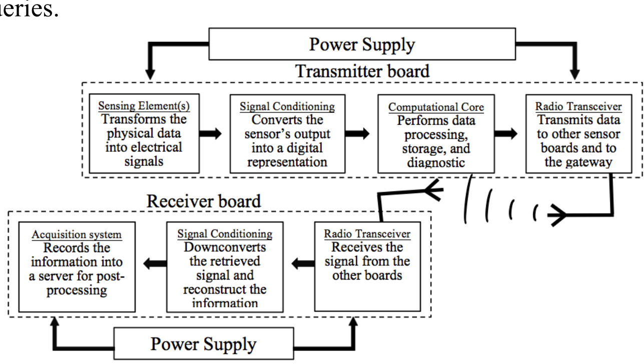

Fig. 1. Functional diagram of a sensing node's transmitter and receiver board

The sensing element is the core of the board and transforms the measured physical parameter into a proportional electrical signal. Some commonly used sensors for SHM applications include accelerometers, strain gages, temperature sensors, and anemometers. Many boards embed more than one type of sensing element [16], while others install only one sensor focusing on the measurement of a single physical quantity for accuracy and power-saving reasons [17]. In this paper wide emphasis is given to those parameters such as sensor noise-density (ND), sensitivity, sensing range, and bandwidth (BW), which determine the measurement resolution. In particular, the ND is the square root of the power spectral density of the noise output. The sensitivity is the ratio of change in input (e.g. acceleration) to change in the output signal (e.g. voltage) and defines the ideal relationship between acceleration and output. The sensing range defines the maximum amplitude the accelerometer can detect, while the BW is the frequency range that the sensor operates in. As a result, the accelerometer nominal resolution (i.e. the smallest detectable increment in acceleration) connects the ND and BW by a non-linear equation. Depending on the application the accelerometer is used in, different resolutions are required. For instance, ambient vibration monitoring with a resolution below $0.98 \cdot 10^{-3}$ $m \cdot s^{-2}$ (i.e. a fraction of mg) is desirable, while a resolution on the order of $9.86 \cdot 10^{-3}$ $m \cdot s^{-2}$ (i.e. mg) is sufficient for general-purpose vibration detection and modal parameter extraction [6]. Table I summarizes the parameters optimum values for microvibration detection.

TABLE I
Sensor Boards Design Parameters and optimal values range

Parameter	Description	Optimal value
Noise-density ($m \cdot s^{-2} \cdot Hz^{-0.5}$)	Noise output power spectral density	$< 0.49 \cdot 10^{-3}$
Sensitivity ($mV \cdot m^{-1} \cdot s^{2}$)	Physical input – electrical output ratio	>100
Sensing range ($m \cdot s^{-2}$)	Detectable amplitude range	±14.71
Bandwidth (Hz)	Detectable frequency range	0.10 - 50
Resolution ($m \cdot s^{-2}$)	Smallest detectable acceleration	$0.98 \cdot 10^{-3}$

The signal conditioning section is responsible for converting the sensor's analog output into a digital representation that can be processed by digital electronics. Usually, this operation is performed using an ADC. This section also includes elements for amplification, linearization, compensation, and filtering purposes. As a result, the board resolution also depends on the ADC effective number of bits and full-scale measurement range in Volts, together with the accelerometer's sensitivity. For many SHM applications a 16-bit ADC is enough for detecting microvibration; nevertheless, higher values are sometimes preferable or other conversion systems desirable [18].

The computational core is the principal difference between a WSN sensor board and its wire-based counterpart. The presence of a Micro-Controller Unit (MCU) allows for on-board data processing and background checks on the board's measuring cycles. A MCU size determines its processing speed and power consumption. High-resolution MCUs, suitable for resolving microvibration, may take up to 25% of the board's total power consumption [19]; therefore, researchers have developed systems with off-board computational sections. The computational core also embeds a memory for measured data storage and for loading diagnostic algorithms. Many different memory sizes and employed algorithms are commercially available, which tailor towards the particular monitoring activity to be performed [20, 21].

To finish, radio frequency (RF) communication allows each single board to interact with the other nodes of the WSN and to transmit the recorded data. For this reason, communication emerges as an additional issue that needs to be addressed as an effective network is designed. This is particularly true as high-speed data sampling, high fidelity sensing, high transmission rate, and large amounts of data are often involved in SHM systems. RF communication becomes a real challenge on large-sized structures made of concrete or steel components.

Two main network topologies are used for communication: the single-hop (also called star topology) and the multi-hop [22]. The star topology is a simple method in which all sensor boards transmit data solely to the gateway, which acts as a central server. This method supports high sampling rates, large data size, precise node-to-node synchronization, and limited data loss as the routing of data packets only needs a queue for all of the nodes to transmit directly to the base station [23]. On the down side, this solution is spatially limited by the radio range and cannot span long distances. The multi-hop is more complex and versatile involving intermediary nodes that transfer data and commands between two nodes that are not in the direct radio range. In practice each intermediate node behaves as a receiver and as a transmitter for retrieving the signal to the central server. As focus moves to full-scale implementation, the need for multi-hop communication is required for solving the problems associated with large-scale sensor deployment. Multi-hop communication involves both the knowledge of the most effective routing path between nodes and gateway but also a correct delivery of the data. For this reason, the design of this network is a non-trivial task [24]. Due to the increase of communicated data, interference that can produce data loss and time synchronization problems (e.g. jitter, delay, throughput, etc.) may occur among the nodes [25]. Many protocols have been proposed for WSN [22]; however, not many of them are specifically suited for SHM applications [26]. One of the most used protocol is the cluster-head type (used for improving sensing accuracy and reducing power consumption), one example of which will be described in Section III. B.

III. Description Of The Accelerometer Sensor Boards

In this section, the main wireless MEMS-based accelerometer sensor boards proposed for structural vibration monitoring are chronologically listed and divided by sensor boards within (i) single-hop networks and (ii) multi-hop networks. Table II summarizes their main characteristics and offers a brief comparison, while a description of the specific applications is provided in Table III. It should be pointed out that the review highlights the state-of-the-art of the last ten years. For a complete summary before 2005, interested readers can refer to papers by Lynch et al. [15, 27].

A. Sensor Boards Based on Single-Hop Networks

In 2008 Whelan et al. proposed the Wireless Sensor Solution (WSS) based on the Tmote Sky platform integrating a 16-bit MSP430F1611 MCU and a ChipCon 2420 for RF transmission [28]. The WSS, powered by a set of 3 rechargeable AA batteries, was equipped with a strain transducer and a two-axis LIS2L02AL accelerometer manufactured by ST Microelectronics [29] having a resolution of $2.63 \cdot 10^{-3}$ $m \cdot s^{-2}$ when operated at 50Hz bandwidth. The system was completed using a signal conditioning section embedding a programmable gain amplifier to maximize the features of the 12-bit ADC. By amplifying the signal prior to conversion, an ADC resolution that is below the noise floor of the accelerometer could be obtained. The total power consumption of the sensor board in active mode was equal to 185.7 mW (i.e. 79.4 mW for the acceleration-monitoring section and 106.3 mW for the strain-monitoring unit). The WSS was tested through laboratory tests and field deployments [30, 31]. The latters included the use of 20-node and 30-node star topology WSNs over two reinforced concrete bridges for a two-day monitoring period. During the test, ambient vibrations were sampled at 128 Hz and transmitted in real-time to the network coordinator over 11 tests each of which had duration of three minutes. The results showed the capability of the system to detect vibrations having amplitude as low as $19.61 \cdot 10^{-3}$ $m \cdot s^{-2}$. The measurements were also used for evaluating the first natural frequency of the bridge, equivalent to 9.50 Hz [32], while data recorded on the second bridge were used for computing the bridge's mode shapes, starting at 8.07 Hz [33].

In 2010, starting from a previous design proposed by Lynch et al. [34], Park et al. developed the Acceleration-based Smart Sensor Node (Acc-SSN). A SD-1221L accelerometer was selected as the sensing element providing a resolution of $0.62 \cdot 10^{-3}$ $m \cdot s^{-2}$. The conditioning section was modified with an amplifier, a 0.1 Hz cutoff-frequency high pass-filter, a 100 Hz cutoff-frequency anti-aliasing filter, and a 16-bit ADS8341 ADC manufactured by Texas Instruments, Inc. with a resolution of $0.45 \cdot 10^{-3}$ $m \cdot s^{-2}$. The computational core relied on an ATmega128 MCU for operation schedule, system control, and autoregressive model computation, while it used a 2.4GHz XBee wireless radio for RF transmission [35]. Due to the increased computational capabilities compared to the previous version, the MCU power consumption was equal to 114 mW, bigger than the ADC-sensor unit power requirements (42 mW), but still smaller than the RF communication power consumption (nearly 300 mW). The Acc-SSN was tested deploying a seven-nodes WSN over a six-meter long, lab-scaled, pre-stressed concrete slab excited using an electro-magnetic shaker and performing a back-to-back comparison with wire-based accelerometers. No long-term monitoring evidences were shown in the research, rather data recorded with both typologies of sensors were used for validating the global and local damage detection method selected by the authors. Operating in single-hop architecture, the system relied on the comparison of the cross-spectral densities computed at a captain senor node (selected in order to reduce noise effect) and the other six sensor nodes spread on the structure. Results proved the capability of the Acc-SSN in measuring vibrations having an average amplitude of about $196.12 \cdot 10^{-3}$ $m \cdot s^{-2}$ and in detecting the structure's first mode frequency at 25 Hz [35].

In 2012 Chae et al. developed the u-Node, a WSN system integrating different types of sensors (i.e. two accelerometers, a strain gauge, a thermometer, and a wind gauge) and using a ZigBee module for RF transmission purposes [36]. The board installed an Atmel 128L MCU for data processing, and was powered using a ±5 V power supply and a solar cell for energy harvesting. The u-Node's conditioning section consisted of a 16-bit AD7708 ADC manufactured by Analog Device, able to guarantee a resolution of $0.37 \cdot 10^{-3}$ $m \cdot s^{-2}$. The installed accelerometers were an ES-U2 (a force-balanced type manufactured by Kinemetrics Inc.) and an AC310-002 (a MEMS-based type manufactured by NewConsTech Inc. [37]). The AC310-002, due to its nominal ND ($0.13 \cdot 10^{-3}$ $m \cdot s^{-2} \cdot Hz^{-0.5}$) and BW (300 Hz), was the controlling factor for the overall measurement providing a resolution of $2.79 \cdot 10^{-3}$ $m \cdot s^{-2}$. Depending on the type of sensor used, the single node could work both in a single-hop or a multi-hop configuration. For dynamic sensors, the RF module performed better in a star typology configuration due to the high volume of transmitted data. The prototype was validated by a three-month deployment on the Yongjong Grand Bridge, a suspension bridge in Korea. The sensors were installed in the stiffening truss structure and in the suspension hanger cables. For proving the reliability of the wireless communication, data for all 45 sensors deployed were logged for one week, showing a transmission rate within a 90% range. Results showed that the u-Node could detect accelerations with an average amplitude of $196.12{\cdot}10^{-3}$ $m{\cdot}s^{-2}$ and evaluate the cable's fundamental frequency using the off-board FFT as low as 3.00 Hz.

In 2014 Sabato et al. proposed the Acceleration Evaluator (ALE), a sensor board specifically developed for microvibration detection [38]. It embedded a very low ND ($0.003{\cdot}10^{-3}m{\cdot}s^{-2}{\cdot}Hz^{-0.5}$) single axes SiFlex 1600SN.A accelerometer manufactured by Colibrys Inc. [39], a DC-to-DC converter used as a voltage stabilizer, and a voltage buffer amplifier for low-amplitude vibrations magnification. The transmitter board used a 2.4 GHz transmitter in a single-hop configuration for data transmission to a remote receiver powered by a ±12 V battery. The main difference between ALE and other systems is the use of a Voltage-to-Frequency (V/F) converter instead of a conventional ADC. The absence of on-board computational unit allows for achieving more accurate measurements. To preserve the selected accelerometer's resolution performance ($0.14{\cdot}10^{-3}$ $m{\cdot}s^{-2}$ for a 1500 Hz BW), a 24-bit ADC having a resolution of $5.84{\cdot}10^{-6}$ $m{\cdot}s^{-2}$ should be used, which was considered too power demanding for a low-power system (i.e. up to 100 mA compared to the 8 mA required by the V/F). ALE was designed for converting the sensor output analog signals to FM signals using the V/F converter. This conversion also improved the robustness of the transmission against the electrical noise because of the modulation characteristics [18]. The system was validated in laboratory tests measuring vibrations having average amplitude of $9.81{\cdot}10^{-3}$ $m{\cdot}s^{-2}$ and frequency of 0.2 Hz. A comparison of the results with those obtained using a wired accelerometer, showed a maximum difference of 2% in the two sets of data [40]. It was used for extracting the natural frequency of a pre-stressed concrete pedestrian bridge from the ambient vibration recorded during a five-hour period (3.08 Hz) [41]. Furthermore, ALE was employed for determining the behavior of a stone pinnacle during an earthquake with a peak ground acceleration of 1.56 $m{\cdot}s^{-2}$ and a first fundamental frequency equal to 0.77 Hz [42].

B. Sensor Boards Based on Multi-Hop Networks

Starting from the results obtained in a previous study [17] Pakzad et al. in 2008 developed a novel sensor board interfaced with the MicaZ sensor platform to overcome the drawbacks of previous versions [43]. They modified the MicaZ board by adding two SD-1221 single-axis low noise accelerometers manufactured by Silicon Design [44] in addition to the ADXL202 dual axis accelerometer by Analog Devices [45]. The new sensors, due to their low ND (i.e. $0.05{\cdot}10^{-3}$ $m{\cdot}s^{-2}{\cdot}Hz^{-0.5}$), were used for resolving low-amplitude ambient vibration produced by traffic and wind loading. The updated board installed a 16-bit ADC (resolution $0.22{\cdot}10^{-3}$ $m{\cdot}s^{-2}$) and used an ATmega128 MCU and a 2.4 GHz radio for RF transmission. The sensor board power consumption (240 mW) was almost double than that of the sensor platform (118 mW), but this compensates for the decision of using a simpler hardware design. Due to hardware modification, the accelerometer resolution ($1.24{\cdot}10^{-3}$ $m{\cdot}s^{-2}$) was the limiting factor to the measurement accuracy. For this reason, the SD-1221 sensing range and BW were reduced from ±19.61 $m{\cdot}s^{-2}$ to ±0.98 $m{\cdot}s^{-2}$ and from 400 to 25 Hz respectively. It allowed achieving a sensor's resolution of $0.31{\cdot}10^{-3}$ $m{\cdot}s^{-2}$, close enough to that of the ADC. The board was validated by developing a 64-node WSN on the Golden Gate Bridge, showing it was capable of detecting vibrations having an average amplitude of about $49.03{\cdot}10^{-3}$ $m{\cdot}s^{-2}$ and defining the bridge's natural frequencies in the low-frequency range starting at 0.11 Hz [3, 46]. The system was first deployed for four months. Nearly two months passed before the batteries required replacement, proving the capability of performing prolonged continuous monitoring activities. Monitoring over an extended period of time allowed for a statistical analysis of the bridge's modal properties, proving a high resolution and confidence in the identified vibration modes [47].

In 2008, Cho et al. updated the existing version of the Wang et al.'s WiMMS sensor board [48, 49] capable of 16-bit data collection on four simultaneous channels using a low-power (less than 20 mA) MCU. They substituted the previously embedded sensor with a CXL02LF1Z accelerometer manufactured by Crossbow Inc. [50] and deployed a 21-node WSN [51]. The network was designed for operating with a hierarchical topology consisting of a manager node (acting as gateway of the WSN to the base station), two cluster head nodes, and several leaf nodes. Leaf nodes were used for sampling data, while the cluster head provided reference signals to the leaf, post processing analyses (e.g. modal identification and damage localization), and organizes the communication with the sub-nodes and other cluster heads. Due to the sensor ND ($1.37{\cdot}10^{-3}$ $m{\cdot}s^{-2}{\cdot}Hz^{-0.5}$) and BW (50 Hz), the achievable resolution was $12.28{\cdot}10^{-3}$ $m{\cdot}s^{-2}$, lower than the resolution of the embedded 16-bit ADC ($0.37{\cdot}10^{-3}$ $m{\cdot}s^{-2}$). The developed WSN was implemented for evaluating the performances of a distributed modal identification method. The efficiency of the method was estimated by extracting the structural dynamic modal parameters of a balcony in a historic theater and on a stay cable from real-time recorded accelerations in a single-day test [52, 53]. The system proved the capacity to evaluate natural frequencies as low as 2.72 Hz and 6.79 Hz for the balcony and cable stay, respectively, validating the modal identification algorithms. To cope with low-resolution issues, in 2010 Swartz et al. improved the board sensing capabilities by installing a CXL01LF1Z accelerometer (ND equal to $0.69{\cdot}10^{-3}$ $m{\cdot}s^{-2}{\cdot}Hz^{-0.5}$), a customized signal conditioning section having a 0.03 - 25 Hz band-pass antialiasing filter, and an amplifier for small amplitude vibrations magnification [54]. The board resolution improved to $4.34{\cdot}10^{-3}$ $m{\cdot}s^{-2}$, but was still the limiting factor of the measurement. The system was tested in conjunction with a board embedding a strain gauge, for recording accelerations on wind turbines and computing their modal frequencies and operational deflection shapes. Recorded accelerations were on average equal to $98.06{\cdot}10^{-3}$ $m{\cdot}s^{-2}$, while the smallest evaluated frequency was 0.64 Hz.

TABLE II
SUMMARY OF THE PROPOSED WIRELESS MEMS-BASED ACCELEROMETER SENSOR BOARDS BETWEEN 2006 AND 2016 (LIMITING FACTOR HIGHLIGHTED IN BOLD)

Study (-)	Accelerometer (-)	Noise-Density ($10^{-3} m \cdot s^{-2} \cdot Hz^{-0.5}$)	Sensitivity ($mV \cdot m^{-1} \cdot s^{2}$)	Sensing Range ($m \cdot s^{-2}$)	BW (Hz)	Acc. Res. ($10^{-3} m \cdot s^{-2}$)	ADC (bit)	ADC Res. ($10^{-3} m \cdot s^{-2}$)	Transmission (-)
Pakzad [24]	SD-1221	0.05	203.96	±0.98	0.1 - 25	**0.31**	16	0.22	Multi-hop
Cho [51]	CXL02LF	1.37	101.98	±19.61	0 - 50	**12.28**	16	0.75	Multi-hop
Swartz [54]	CXL01LF	0.69	203.96	±9.81	0.03 - 25	**4.34**	16	0.37	Multi-hop
Park [35]	SD-1221L	0.05	203.96	±19.61	0.1 - 100	**0.62**	16	0.45	Single-hop
Nagayama [61]	LIS3L02DQ	1.03	67.30	±19.61	0 - 56	**9.75**	-	-	Multi-hop
Rice [63]	LIS3L02AS4	0.49	67.30	±19.61	0 - 50	**4.39**	16	0.68	Multi-hop
Jo [66]	SD-1221L	0.05	203.96	±1.96	0 - 15	0.24	16	**0.37**	Multi-hop
Whelan [28]	LIS2L02AL	0.29	67.30	±19.61	0 - 50	2.63	12	**10.88**	Single-hop
Meyer [55]	LIS2L06AL	0.88	22.43	±58.84	0 - 100	11.16	12	**32.65**	Multi-hop
Bocca [59]	LIS3L02DQ	1.03	67.30	±19.61	0 - 56	**9.75**	16	0.68	Single-hop
Chae [36]	AC310-002	0.13	203.96	±19.61	0 - 300	**2.79**	16	0.37	Single-hop
Hu [72]	SD-1221	0.05	203.96	±0.98	0 - 50	0.44	12	**4.31**	Multi-hop
Sabato [38]	SF1600	0.003	122.37	±29.42	0 - 1500	**0.14**	-	-	Single-hop
Kohler [73]	SF1500	0.003	122.37	±29.42	0.1 - 1500	**0.14**	24	0.003	Multi-hop

TABLE III
SUMMARY OF THE VALIDATION TESTS PERFORMED ON EACH WIRELESS MEMS-BASED ACCELEROMETER SENSOR BOARD AND MINIMUM VALUES MEASURED

Study (-)	Test (-)	Application (-)	Min. Acc. ($10^{-3} m \cdot s^{-2}$)	Min. Freq. (Hz)
Pakzad [46]	Golden Gate Brg. monitoring	Amplitude detection and natural frequency evaluation	49.03	0.11
Cho [51]	Theater balcony monitoring	Natural frequency evaluation and modal identification	Not Provided	2.72
Cho [51]	Cable stay	Natural frequency evaluation	Not Provided	6.79
Swartz [54]	Wind turbine	Amplitude detection, modal and deflection shape identification	98.06	0.64
Park [35]	Pre-stressed concrete slab	Natural frequency evaluation and damage detection method validation	196.12	25.00
Rice [63]	Shaking-table	Sensor board characterization	490.3	1.00
Rice [64]	Stawamus Chief pedestrian Brg.	Amplitude detection and natural frequency evaluation	9.81	2.45
Rice [65]	Jindo Brg.	Amplitude detection and transmission protocol evaluation	9.81	0.44
Jo [67]	Truss structure	Sensor board characterization	4.90	10.00
Jo [68]	Jindo Brg.	Amplitude detection and natural frequency evaluation	98.06	0.44
Whelan [32]	Wright Road Brg,	Amplitude detection and modal identification	19.61	9.50
Whelan [33]	Big Sucker Brook Brg.	Amplitude detection and modal identification	19.61	8.07
Meyer [57]	Stork Brg.	Natural frequency evaluation	196.12	3.75
Bocca [59]	Wooden truss structure	Modal parameters extraction	980.60	4.40
Chae [36]	Yongjong Grand Brg.	Natural frequency evaluation and cable tension	196.12	3.00
Hu [72]	Zhengdian Highway Brg.	Amplitude detection and natural frequency evaluation	19.61	7.90
Sabato [40]	Shaking-table	Sensor board characterization	9.81	0.20
Sabato [41]	Streicker Brg.	Amplitude detection and natural frequency evaluation	9.81	3.08
Sabato [42]	Stone pinnacle	Amplitude detection and natural frequency evaluation	49.03	0.77
Kohler [73]	Shaking-table	Sensor board characterization	98.06	1.00
Kohler [73]	Robert A. Millikan Library	Amplitude detection and natural frequency evaluation	1.96	1.20
Kohler [73]	1100 Wilshire Blvd. Bld.	Natural frequency evaluation	Not Provided	0.25

In 2009 Meyer et al. proposed another prototype based on the Tmote Sky platform [55] by equipping the sensor board with sensors for temperature and humidity measurements and a LIS2L06AL MEMS-based accelerometer manufactured by ST Microelectronics [56]. Due to the accelerometer ND ($0.88 \cdot 10^{-3}$ $m \cdot s^{-2} \cdot Hz^{-0.5}$) and BW (100 Hz), the accelerometer resolution was equal to $11.16 \cdot 10^{-3}$ $m \cdot s^{-2}$, further lowered when the analog signal output was processed using a 12-bit ADC ($32.65 \cdot 10^{-3}$ $m \cdot s^{-2}$). The prototype was implemented within a seven-node WSN with a routing topology that was periodically adapted by assessing the link quality between adjacent nodes and choosing the most reliable one for transmission. The system was tested over a period of nearly one year and a half on a cable-stayed bridge by monitoring the bridge deck vibrations and measuring the cable tension force. Despite the relatively high amplitude of the ambient vibrations (i.e. on average $196.12 \cdot 10^{-3}$ $m \cdot s^{-2}$), the system experienced some difficulties in measuring the accelerations accurately. Recorded data were used for estimating the cables' natural frequencies and upload their values every two minutes. Results showed that the accuracy of the estimated values was within 5-10% of that evaluated from data recorded using a wire-based system [57]. The study also focused on determining the sensor board's power consumption (i.e. 65 mW for the RF transmitter compared to the 5 mW required by the sensor-ADC), showing that the most influential contribution to power consumption was the duty-cycle and not the computational stage. Therefore, operating with lower duty-cycles (i.e. below 7%), the lifetime of the node could be extended to nearly six months.

Bocca at al. in 2009 proposed ISMO, a wireless sensor node based on the Sensinode U100 Micro.2420 platform [58], before proposing an updated version in 2011 introducing a time-synchronized WSN to process acceleration data locally and in real time [59]. The prototype's computational core consisted of a MSP430 MCU manufactured by Texas Instruments and a 12-bit DAC, while RF transmission was performed using ChipCon CC2420 transceiver. The sensor board installed a three-axis LIS3LV02DQ accelerometer having a resolution equal to $9.75 \cdot 10^{-3}$ $m \cdot s^{-2}$ [60], a temperature, and a humidity sensor, for correlating the effect of the environmental condition to the modal properties of the structure being tested. The board was powered using a ±3 V power supply and had a total power consumption of nearly 300 mW. The accelerometer output signal fed a 16-bit ADC having a resolution equal to $0.68 \cdot 10^{-3}$ $m \cdot s^{-2}$, showing that the embedded sensor was the measurements' controlling factor. The ISMO efficacy was evaluated with ten-minute long shaking tests on a lab-scale wooden bridge excited using a random signal having average amplitude of about $980.60 \cdot 10^{-3}$ $m \cdot s^{-2}$. Off-board analyses between the WSN and a wired system showed an error of nearly 1% in the computation of the first structural mode (4.40 Hz) and nearly 7% in its damping ratio value [59]. Also, analytical evaluation showed that the expected lifetime of the WSN did not depend on the number of daily activations of the node, but on the packet loss ratio.

From 2007 to 2011, researchers at the University of Illinois, Urbana-Champaign worked on developing a sensor board for high-resolution SHM measurements. The system was based on the Intel's Imote2 platform incorporating a variable processing speed PXA27x MCU and a ChipCon 2420 RF transmitter. In the first study Nagayama et al. used the commercially available ITS440 sensor board showing some intrinsic limitations for microvibration sensing [61]. The sensor board included light, temperature, relative humidity sensors, and a three-axis LIS3L02DQ digital accelerometer manufactured by ST Microelectronics [60]. Because of its features (e.g. built-in 12-bit DAC with pre-selectable cut-off frequencies and low-accuracy sampling rate), it could not guarantee enough resolution for SHM applications. For this reason, in 2009 Rice et al. developed the Structural Health Monitoring Accelerometer (SHM-A) sensor board installing a LIS3L02AS4 analog accelerometer manufactured by ST Microelectronics [62], operated with a 50 Hz cutoff frequency (resolution of $4.39 \cdot 10^{-3}$ $m \cdot s^{-2}$) and powered using ±3.3 V power supply [63]. Also, modifications were made on the conditioning section by customizing a Quickfilter QF4A512 with a four-channels 16-bit ADC with selectable gains. It featured flexible and highly accurate user-selectable sampling rates, individually programmable digital Finite Impulse Response (FIR) filters, and provided a resolution equal to $0.68 \cdot 10^{-3}$ $m \cdot s^{-2}$. Tests performed on the sensor platform showed power consumption equal to 196 mW, mostly due to the installed ADC. Instead, the power consumption of the whole SHM-A increased with the sampling rate and the number of channels selected (i.e. from 495 mW to nearly 700 mW at ±4.5 V), demonstrating the effect of on-board computational analyses on current consumption. The system was validated through a shaker table test against a wire-based accelerometer [63] and used for short-term structural testing on the Stawamus Chief Pedestrian Bridge. 22 experiments, 60-second long each were performed for evaluating the behavior of the sensor board in cold environments. Tests were performed to measure the bridge's natural frequencies and to validate the safety of the bridge's design as it was coupled with strong winds. Test results proved the capability of the sensor board in measuring acceleration as low as $9.81 \cdot 10^{-3}$ $m \cdot s^{-2}$ and the bridge's flapping mode at 2.45 Hz [64]. Finally, the prototype was evaluated with a 70-node WSN deployment on the Jindo Bridge, a cable-stayed bridge in South Korea, for measuring vibrations due to traffic and wind load [65]. The monitoring activity was performed for nearly two months sampling data for 30 seconds every day and using small solar panels connected to the sensor boards for energy harvesting. The accelerometer resolution was the controlling factor in the overall measurement noise floor, meaning that the SHM-A board had excellent resolution for general-purpose applications, but not enough for microvibration monitoring. In 2010, Jo et al. updated the resolution by developing the SHM-H sensor board for measuring low-level ambient vibrations [66]. The core of the system was the same as the SHM-A board, but a SD-1221L accelerometer [44] was used, and the board was powered using a low-dropout linear regulator for supplying a stable ±5 V. Considering the sensor's specification, the resolution of the board was equal to $4.34 \cdot 10^{-3}$ $m \cdot s^{-2}$. For this reason the accelerometer range was limited from ±19.61 $m \cdot s^{-2}$ to ±1.96 $m \cdot s^{-2}$ and the BW from 400 to 15 Hz for achieving a resolution of $0.24 \cdot 10^{-3}$ $m \cdot s^{-2}$, matching that of the installed ADC. The prototype was tested for estimating the board noise floor during shaker table tests over a lab-scale truss structure [67]. Results from these tests showed the possibility to measure vibrations having an average amplitude of about $4.90 \cdot 10^{-3}$ $m \cdot s^{-2}$. Also, it was used within a 70-node WSN for another one-year-long monitoring of the Jindo Bridge [68-71]. To improve measurements quality, the SHM-H was used as cluster head (i.e. reference sensors) in the tree-typology network realized. The bridge monitoring activity, a continuation of the one described in [65], validated the full-scale deployment and long-term operation feasibility and was used for implementing novel autonomous cable tension monitoring applications.

Hu et al. in 2013 validated a sensor board for measuring acceleration and strain using a customized S-Mote WSN platform [72]. The system core was based on a MSP430F1611 MCU by Texas Instruments, on a 12-bit ADC as the signal-conditioning element, with a ChipCon CC2420 for RF transmission, and was powered by a ±3.6 V lithium battery. The sensing element selected was a SD-1221L MEMS-based accelerometer [44], whose sensing range and BW were reduced to ±0.98 $m \cdot s^{-2}$ and 50 Hz for achieving a nominal resolution of $0.44 \cdot 10^{-3}$ $m \cdot s^{-2}$, higher than the resolution of the embedded ADC ($4.31 \cdot 10^{-3}$ $m \cdot s^{-2}$). The power consumption analysis of the board showed that the RF usage was the main factor in the board's power consumption (nearly 75% of 680 mW). Therefore, a duty-cycle approach was adopted reducing the active sampling time to one hour per day. One peculiarity of the board was a sophisticated conditioning section capable of amplifying the sensor's output signal in the range 0.4 mV – 0.1 V by a factor of 500 using two stages (i.e. 50x amplifier, high-pass filter, 10x amplifier) to ensure data collection of weak signals as well. In their study, Hu et al. validated the system with a 250 second measurement performed on the Zhengdian Highway Bridge, a pre-stressed concrete bridge in Wuhan, China using the road traffic as excitation. The data sampled by the accelerometers deployed at one-quarter of the three central spans proved the system's capacity of measuring vibration having an average amplitude of $19.61 \cdot 10^{-3}$ $m \cdot s^{-2}$. Records were then used for extracting the bridge natural frequencies below 20 Hz by computing an off-board FFT based on a proposed modal identification method.

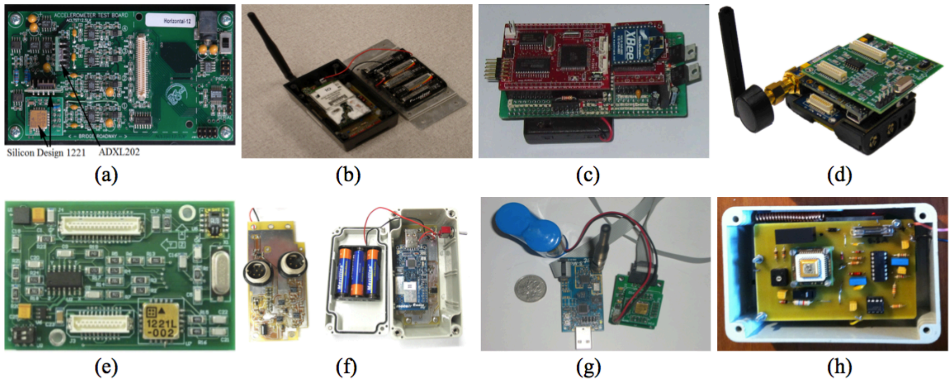

Fig. 2. Some of the proposed wireless MEMS-based accelerometer sensor boards: a) Pakzad et al. [24]; b) WiMMS by Wang et al. [48]; c) Acc-SSN by Park et al. [35]; d) SHM-A by Rice et al. [63]; e) SHM-H by Jo et al. [67]; f) WSS by Whelan et al. [28]; g) S-Mote by Hu et al. [36]; h) ALE by Sabato et al. [38].

In 2015 Kohler et al. finished testing ShakeNet, a vibration sensing system made of tens of wireless nodes to collect structural vibration measurements [73]. The system was designed for overcoming the Crossbow's MDA-400 shortcomings, as low-frequency vibrations had to be recorded. For this reason the ShakeBox was equipped with a low-power 24-bit ADC, an analog modulator, a digital filter, three Si-Flex1500 [39] single-axis accelerometers manufactured by Colibrys Inc., an Imote2 for computational purposes, and it used the Tenet programmable wireless sensing software algorithm. The total power consumption of the unit was nearly 750 mW. The accelerometer, due to its very low noise floor ($0.003 \cdot 10^{-3}$ $m \cdot s^{-2} \cdot Hz^{-0.5}$) had a resolution of $0.14 \cdot 10^{-3}$ $m \cdot s^{-2}$ when it was used with a full BW of 1500 Hz. The resolution of the 24-bit ADC was equal to $0.003 \cdot 10^{-3}$ $m \cdot s^{-2}$, enough for resolving low-amplitude vibrations. The system was validated with shaker-table tests using sinusoidal excitation ranging from 0.1 to 90 Hz ten seconds to two minutes long and comparing results in time and frequency domains with those recorded using wired accelerometers. Analysis of absolute amplitudes showed that the difference between the two signals were always within a 10% tolerance. In addition, the ShakeNet was tested recording the ambient vibrations of the Millikan Library, a nine-story reinforced concrete building on the CalTech campus, on the Vincent Thomas Bridge in San Pedro, CA, and on the building at 1100 Wilshire Boulevard in downtown Los Angeles, a 15-story reinforced concrete building that holds a 21-story steel moment-frame. During the Millikan Library test, the system performance was compared to that of permanently installed accelerometers during several forced vibration tests lasting on average 30 minutes each. A difference in the recorded amplitudes of about 10-20% was observed, and most likely due to the lack of robust physical coupling of the ShakeNet with the floor slab [74]. The bridge was monitored by a 20-node WSN to measure ambient vibration for one day, exhibiting frequencies of bridge vibration in agreement with previous studies [75]. The building was monitored by a 30-node WSN for three days. Despite several faults in the data transmission, this test was useful for evaluating the system lifetime under realistic deployment conditions. During this test the building's modal frequencies were identified starting at 0.25 Hz.

IV. Research Challenges

In recent years, more effective networks have been successfully installed on different structures, and recorded data has been used for evaluating modal frequencies, damage indices, and other types of structural monitoring parameters. Nevertheless, there is room for improvement. More work is needed to permit this technology to fulfill the requirements for SHM of large-scale structures, especially when these systems are used as nodes within a WSN. Several efforts have been made for developing more accurate and energy-saving algorithms for independent processing tasks [21]. Nevertheless, the main challenges researchers are now facing is turning the sensor boards from pure data acquiring devices into intelligent systems, making the WSN more powerful and efficient [76, 77]. In particular it means that the power supply, data transmission reliability, and network bandwidth are still problems, which need to be addressed for improving the network's efficiency. Battery life is the main problem as it provides a finite source of energy, which is too short for performing long-term monitoring. Since no other reliable power sources are available, some possible solutions researchers are working on consist of developing strategies for maximizing the operating time of the sensors. Time sensors are placed in sleep mode, performance of more effective computational algorithms on board to reduce the amount of transmitted data, and implementation of energy harvesting techniques from ambient energy sources are possible solutions as well [78]. Also, transmission reliability plays a key role in the realization of a stable WSN, as delay due to time synchronization or failure in some of the nodes may affect quality of results [25]. At this point it should be highlighted that a trade-off between full data transmission and limited data retrieving has to be found. A large amount of data will result in network congestion and higher power consumption, while a smaller data amount may reduce the accuracy of the recorded information. For such reasons many researches have been now focused on the construction of scalable networks, on developing control algorithms for improving the performances of the network itself, and reducing the amount of transmitted information [79]. Building self-calibrating sensors for reducing measurement errors, and implementing self-healing techniques for resolving issues due to erroneous behaviors in long-term monitoring [80] are other investigated solutions.

V. Conclusions

In this paper, the development of sensor boards installing MEMS-based accelerometers for structural vibration monitoring has been analyzed and surveyed. The survey focuses on the sensing aspect of the developed boards including a detailed description of the SHM applications they were employed in. This technology, initially proposed in the late 1990s, has continued developing, producing a number of technical solutions for its application within WSNs. The first boards developed employed low-resolution and high-noise-density MEMS sensors coupled together with low-resolution ADCs, but technological development made it possible using more sophisticated sensing elements and conditioning devices. Nowadays, modifications applied to the board's sensing interface and signal conditioning have shown how this technology is mature enough for performing SHM-oriented monitoring and supporting SHM analysis. High-resolution monitoring is achieved employing low-noise sensors and reducing their sensing range for increasing measurement accuracy and matching that of the embedded ADC (e.g. SHM-H). Other researchers tried to use very-low noise sensors and to adopt alternative conversion systems (e.g. ALE); while others developed boards embedding both very low-noise sensor and very-high resolution ADCs (e.g. ShakeNet). The current state-of-the-art MEMS sensors have proven that a measurement accuracy equivalent to that achievable using traditional wire-based Integral Electronics Piezoelectric (IEPE) accelerometers is now possible when microvibration (i.e. amplitude in the order of 10^{-2} $m\cdot s^{-2}$ and frequency in the order of 10^{-1} Hz) is recorded. A decrease in production costs and improvement in MEMS technology also allowed using increasingly effective hardware, such as lower noise-floor sensors (e.g. $0.003\cdot10^{-3}$ $m\cdot s^{-2}\cdot Hz^{-0.5}$) and higher resolution ADCs (e.g. 16 or 24-bit). Beside the hardware architecture, even the designed computational core and embedded software for performing engineering analysis have proven their reliability, both when computations are performed on-board and off-board. From a hardware standpoint this technology is almost completely efficient; the next step for being considered a valid commercial alternative to traditional wire-based SHM systems concerns the reliability of the network itself.

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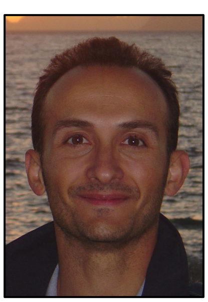

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