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Next generation wireless smart sensors toward sustainable civil infrastructure

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Abstract

This paper presents the recent development of a next-generation wireless smart sensor (WSS) platform to enable a more accurate, inexpensive, and greatly simplified method of instrumenting structures for structural health monitoring. The modular hardware platform features a 24-bit high-precision, analog-to-digital converter with eight differential channels of analog input, and programmable antialiasing filters. The node can measure: (i) three-axes of acceleration for global response monitoring (ii) strain for local response monitoring, (iii) temperature, and (iv) high-level voltage signals from external sensors, providing the multi-scale sensed information needed for advanced structural health monitoring (SHM). Communication with a power-optimized ZigBee radio can be achieved at distances of up to 1 km. An extensible, actor-based software framework facilitates the creation of distributed SHM applications. The framework employs a service-oriented architecture (SOA) approach and provides a suite of modular, reusable, and extensible middleware services suitable for WSS applications. This platform addresses critical SHM needs, enabling tightly synchronized sensing, addressing data loss, and efficiently implementing the demanding numerical algorithms required for system identification and damage detection on sensor nodes with limited resources.

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1. Introduction

Structural health monitoring (SHM), combining various sensing technologies with data acquisition and processing capability, plays a pivotal role in assessing the condition of structures. The ability to continuously monitor the integrity

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of structures in real-time can provide for increased safety to the public, particularly for the aging structures in widespread use today. The ability to detect damage at an early stage can reduce the costs and down-time associated with repair of critical damage. Observing and/or predicting the onset of dangerous structural behavior, such as flutter in bridges, can allow for advance warning of such behavior and commencement of mitigating control or removal of the structure from service for the protection of human life. In addition to monitoring long-term degradation, assessment of structural integrity after catastrophic events, such as earthquakes, hurricanes, tornados, or fires, is vital. These assessments can be a significant expense (both in time and money), as was seen after the 1994 Northridge earthquake with the sheer number of buildings that needed to have the moment-resisting connections inspected. Additionally, structures internally, but not obviously, damaged in an earthquake may be in great danger of collapse during aftershocks; structural integrity assessment can help to identify such structures to enable evacuation of building occupants and contents prior to aftershocks. Furthermore, after natural disasters, it is imperative that emergency facilities and evacuation routes, including bridges and highways, be assessed for safety. Addressing these issues is the goal of SHM.

Visual inspection has been the common practice in inspecting and monitoring the condition of civil infrastructures. However, cost often prohibits the use of visual inspection to infrequent occurrences. Wired sensor-based monitoring systems have long been the most common supplement to inspections; however, realizations of such wired systems are limited by the high cost of instrumentation and maintenance due to cabling; scalability is the main issues that limits the use of wired based system in larger and more complex structures. For instance, the total cost of the monitoring system on the Bill Emerson Memorial Bridge in Cape Girardeau, Missouri was approximately \$1.3 million for 86 accelerometers, which makes the average installed cost per sensor a little more than \$15,000; this cost is not atypical of today's wired SHM systems [1].

Wireless smart sensors are an attractive alternative, differing from traditional wired sensors in a number of significant ways. For example, each WSS node communicates wirelessly, eliminating the need for costly cabling. Moreover, each node has an on-board microprocessor that can be used for digital signal processing, self-diagnosis, self-calibration, self-identification, and self-adaptation functions. Sensor can be easily deployed, moved, and replaced after initial instrumentation of the system.

Researchers have made continuous efforts to develop a series of wireless or smart sensor platforms to facilitate structural health monitoring [2]. Wireless sensors have been commercially available for over a decade; however, only a limited number of full-scale implementations have been realized, primarily due to the lack of critical hardware and software elements. One example of full-scale deployment was a wireless sensor network implemented on the Golden Gate Bridge in 2008, which had issues with scalability of the network; it took approximately 10 hours to collect 80 seconds of data (sampled at 1000 Hz) from 56 sensor nodes to a central location [3]. On the hardware side, the developed sensor node was only able to measure acceleration data out of available measurands such as strain and wind data that are necessary for integrated structural health monitoring of the bridge. To address these issues, researchers at the University of Illinois built upon the Imote2 platform, overcoming numerous hardware and software hurdles. These developments were showcased in a US-Korea-Japan collaboration that deployed the world's largest wireless smart sensor network to monitor the 2nd Jindo Bridge in South Korea [4, 5]. Unfortunately, the Imote2 is no longer in production.

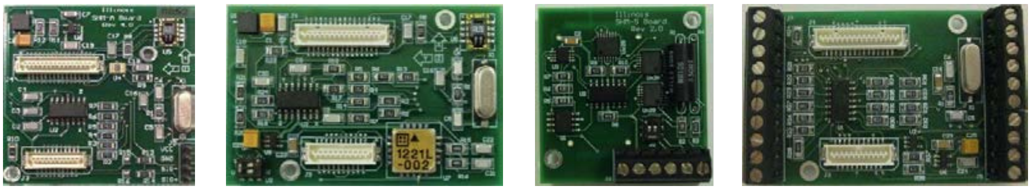
This paper presents the recent development of the Xnode, a next-generation wireless smart sensor (WSS) platform to enable a more accurate, inexpensive, and greatly simplified method of instrumenting structures for structural health monitoring. This platform addresses critical SHM needs, enabling tightly synchronized sensing, addressing data loss, and efficiently implementing the demanding numerical algorithms required for system identification and damage detection on sensor nodes with limited resources.

2. Experience and lessons learned from the 2nd Jindo Bridge deployment

This section briefly summarizes the 2nd Jindo Bridge deployment and discusses the key lessons learned from that experience. First the necessary hardware and software developments are discussed. Subsequently, the full-scale deployment and results are presented. In-depth reports of the deployment and the design of the hardware and software framework are found in Refs. [4, 5].

2.1. Hardware Development

A wireless sensor platform designed for data-intensive applications, Intel's Imote2, was selected for this effort, due to its high-performance Xscale processor (PXA27x) ranging from 13 to 416 MHz and relatively large memory size of 32 MB FLASH, and 32 MB SDRAM; such large RAM enables the on-board computations and serves as storage of long-term measurements. Sensing with the Imote2 is facilitated by sensor board(s) stacked on the Imote2 via two board-to-board connectors. To measure various responses such as acceleration, strain and wind speed to accurately identify structural condition of the bridge, several types of sensor boards were developed (see Fig. 1); the SHM-A board and SHM-H boards were developed to measure acceleration and high-precision acceleration response of the bridge; SHM-S board was developed to measure strain response; SHM-DAQ board was developed to measure analog sensor signal and connected to anemometer to acquire wind information at the bridge site.



(a) SHM-A (b) SHM-H (c) SHM-S (d) SHM-DAQ

Fig. 1. Developed sensor boards: (a) 3-axis acceleration, (b) high-precision acceleration, (c) strain, (d) analog data acquisition.

2.2. Software Development

The Illinois Structural Health Monitoring Project (ISHMP) Services Toolsuite, developed through collaboration between researchers in Smart Structures Technology Laboratory and Open Systems Laboratory at University of Illinois at Urbana-Champaign, is the software foundation for the Imote2-based remote sensing functionality deployed at the 2nd Jindo Bridge. With the Toolsuite, these powerful nodes can achieve highly-synchronized data collection, aggregation, synthesis, and decision-making in real time. The distributed application coordinated scheduled and event-triggered data acquisition, power management, and network monitoring and maintenance functionalities. Because SHM applications for WSSNs require complex programming, ranging from network functionality to embedded algorithm implementation, software development in this environment is very difficult, exacerbated by the fact that many different sensor platforms exist with their own special-purpose operating systems and applications. The service-oriented architecture of the Illinois SHM Toolsuite is based on the actor model [9] to support concurrency and distribution. This facilitates application development by enabling the composition of middleware services and application code to be selected to fulfill the specific requirements of a particular deployment.

2.3. Full-scale deployment and results

The first autonomous, full-scale wireless bridge monitoring system was initially installed on the second Jindo Bridge in South Korea in 2009 through a joint effort among the University of Illinois at Urbana-Champaign, the Korea Advanced Institute of Science and Technology (KAIST), and the University of Tokyo. The 2nd Jindo Bridge is a cable-stayed bridge connecting the Korean peninsula and the Jindo Island. The bridge consists of steel box girder with a center span of 344 m and 60 parallel wire strand cables (see Fig. 2).

The monitoring system comprised 113 WSS nodes measuring a total of 659 channels of data by 2010, resulting in the world's largest wireless smart sensor network for dynamic bridge SHM. The SHM-A sensor board was used on 100 nodes. A SHM-H board, which enables measurement of accelerations as low as 0.05mg, was used for 10 nodes. The remaining three nodes were connected to 3D ultrasonic anemometers to measure and collect wirelessly the speed and direction of wind on the bridge. Wireless strain measurements were also available using the SHM-S sensor board. All 113 nodes were self–powered using solar or wind energy harvesting. Should any anomalies in the measured data be detected during the autonomous system operation, the base-station computers automatically email the research team so that appropriate action can be taken.

Fig. 2. Jindo Bridge, Jindo, South Korea.

The monitoring system can estimate the bridge's various physical states. For example, as depicted in Fig. 3, the modal properties such as natural frequencies, mode shapes, and modal damping ratios can be extracted from the measured accelerations and used to refine the numerical model to determine structural performance and find possible damage locations. Cable tension force, one of the most important integrity measures for cable-stayed bridges, is estimated automatically using a vibration-based method.

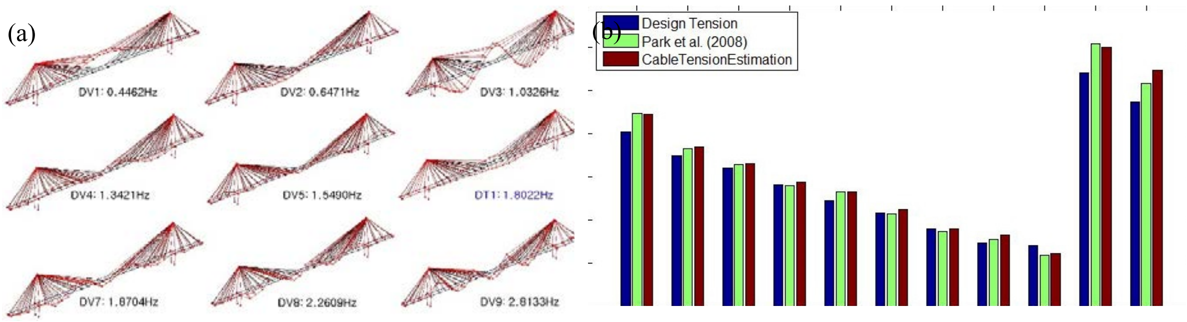


Fig. 3. Monitoring results: (a) mode shapes and natural frequencies; (b) cable tension estimation.

The Imote2 wireless sensor platform, coupled with the various SHM sensor boards developed at the University of Illinois and powered by the Illinois SHM Toolsuite software, has been a significant enabler of research on wireless sensor-based structural health monitoring. The hardware and software platforms, developed in part for the 2nd Jindo Bridge deployment, have been later utilized by over 70 research groups in 15 countries.

2.4. Lessons learned

The experience of deploying a large network of wireless sensor for monitoring cable-stayed bridge taught the research team several important lessons:

1. *Fidelity of data acquisition.* The data acquisition capability is limited by the analog-to-digital converter's (ADC) minimum resolution, available sampling rate, and measurement synchronization. Measuring low-level

ambient vibrations using existing wireless smart sensors can be particularly challenging, so a high-resolution ADC is required (e.g., 24-bit). Another issue is sampling rate. SHM can often be categorized in to consist of two types of responses: static and dynamic. Static responses vary slowly in time, requiring low-sampling rates (e.g.,1 Hz); temperature, humidity, light, crack depth, compass orientation, etc. are in the domain of static measurements. On the other hand, dynamic measurement require sampling at a high rate (e.g., 100 Hz). Examples of dynamic responses are acceleration, strain, wind velocity, tilt etc. The sampling rate for dynamic responses must be at least twice the largest frequency of interest. To ensure signal integrity, high-quality anti-aliasing filters must be used for dynamic measurements. Moreover, the measurements must be tightly synchronized, which is a difficult task, as each wireless sensor has its own local clock. For example, a 1 ms synchronization error between two measured acceleration responses will result in 3.6 degree error in the phase angle at 10 Hz and 36 degree error at 100 Hz [6], which can be identified falsely as damage.

2. *Reliable Communication.* Many issues intrinsic to the wireless sensor must be addressed to ensure reliable communication. Wireless communication is not reliable unless lost packets are properly transmitted and tracked. The performance of wireless communication is not only affected by the distance between nodes, but also network environment. For example, when multiple nodes are trying to send packets at the same time, the packets collide and are lost during communication. Packet loss may degrade measurement signals because it interferes with acquiring accurate data acquisition.

3. *Power Management.* Power management is not an issue in a traditional wired sensor implementation; the sensors can remain active at all times and thus have the ability to be interrogated at any time to acquire data. Unlike such wired systems, one of the most critical features of a successful wireless sensor deployment is the implementation of careful power management. Energy saving can be implemented by imposing duty cycle (i.e., sleep and wake) allows the sensor network to sleep most of the time. In SHM for civil infrastructures, energy harvesting through a solar panel and wind power can be employed to extend the operational life of wireless sensor network. Energy saving and harvesting should be balanced to achieve long-term full-scale deployment.

4. *Data Management.* The management of data collected from a WSS network is critical, given that each sensor node acquires large amounts of data. For example, four channels of 16-bit data are collected at 100 Hz for an hour take 3MB of memory. If tens or hundreds of sensor nodes have to send the data to the base station, data inundation can occur. Note that the time for data acquisition and transmission is heavily dependent on the sampling rate, measurement time, size of network, number of bits on ADC and channels. Data aggregation that processes raw measurement into useful information (e.g., acceleration into displacement/cable tension) is necessary to manage such data challenges.

These lessons inform the development of the next-generation WSSN platform for civil infrastructure monitoring.

3. Design of the next-generation wireless smart sensor platform

This section describes the design and development of the Xnode Smart Sensor. The section first introduces overall design philosophy and then describes hardware and software framework enabling its implementation.

3.1 Design philosophy

The primary motivation for developing a next generation wireless sensor system was to provide powerful hardware and a robust software framework for both campaign-style and long-term SHM. The hardware must have high-resolution (24 bit) and high sampling rate (>10 kHz) data acquisition, a power microprocessor suitable for high data throughput applications and data aggregation, and an RF transceiver that allows for long-range (up to 1 km) and reliable communication. In terms of the software framework, a middleware service-oriented framework that supports network and application scalability (e.g., data collection protocol, time synchronization, etc.), software packages that incorporate libraries for hardware and data processing (e.g., sensor driver, numerical tools, SHM algorithm, etc.), and a user-friendly interface are required. For the next-generation sensor to be deployed on full-scale structures, autonomous network operation, a maintenance-friendly environment such as over-the-air programming, automatic report generation of faults, and power management should be considered.

Aligning with these requirements, the Xnode has been developed as a next-generation wireless platform for structural monitoring applications. Table 1 show the comparison of the Xnode with other wireless sensor platforms in terms of hardware.

Table 1. Comparison of selected wireless sensor platforms [7].

Platform	Maximum Processor Frequency	Expandable Data Storage	Radio Range	ADC Resolution (bits)	Number of Sensing Channels	Sampling Rate	Energy Harvesting
WaspMote [13]	14	2GB	7 km	-	7	-	X
Microstrain [14]	N/A	-	2 km	16	7	1kHz	X
iMote2 [12]	416	-	300 m	-	-	-	-
Martlet [10, 11]	80	32GB	>500 m	12	9	3kHz	X
Xnode	204	4GB	1 km	24	8	16kHz	X

3.1. Xnode hardware

The Xnode consists of three boards which are the process board, radio/power (RP) board and the sensor board. The processor board, the mini4357 developed by Embest Technology, features an LPC4357 microcontroller from NXP that operates with ARM Cortex M0/M4 microcontroller at frequencies up to 204MHz, which can be used to execute on-board computation and data acquisition. The non-volatile memory available on the mini4357 is 32 MB of SDRAM, in which is used for temporary data storage and processing. The mini4357 has various general purpose input/output (GPIO) pins and interfaces such as serial peripheral interface (SPI) and inter-integrated circuit (I2C).

To extend the data storage size for high sampling application, the SD card can be plugged into the RP board that provides extensible storage space of several GB. The RP board includes a power management circuit that controls charging from wall power and solar panels. The radio transceiver in the RP board is a 2.4 GHz radio for low-power wireless communication (Atmel AT86RF233). The communication reaches up to 1km line-of-sight with maximum transfer rates of 250 kbps.

The sensor board shown in Fig. 4 employs a 24-bit ADC (Texas Instruments ADS131E8) which has 8 channels allowing maximum sampling rate up to 16 kHz. In terms of sensing, the 3-axis analog accelerometer (LIS344ALH) takes 3 channels, leaving up to 5 channels available for external analog sensors. Built-in strain circuitry is provided to accommodate up to 3 channels of strain sensing; the measured electrical signal is easily converted into strain through embedded shunt calibration.

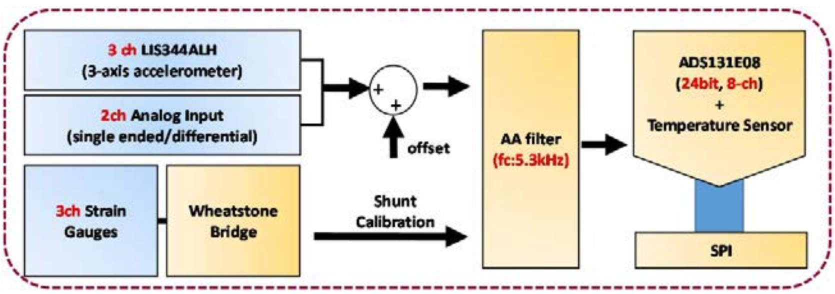


Fig. 4. Schematic for the Xnode sensor board.

The MEMS accelerometer has selectable range setup for ±2g and ±6g with noise density of 50 ug/$\sqrt{\text{Hz}}$. The analog input is added with signal offset such that the resulting signal stays within 0-3.3V range. Strain gauges are connected to the sensor board through external connector, and the resulting differential signal is directly fed through the ADC. All analog signals are AA filtered to reject undesirable high-frequency component. The ADC transfer 8-ch of data through SPI communication with LPC4357.

The developed hardware is stacked together to comprise an integrated sensor node. The sensor node is packaged in an IP67 environmentally hardened enclosure (see Fig. 5). Through the connectors on either side of the enclosure, solar panel, wall-power, and external sensors can be easily plugged.

Preliminary Initial testing shows that the 24-bit ADC can achieve a dynamic range of 140 dB (ENOB: 21.1).

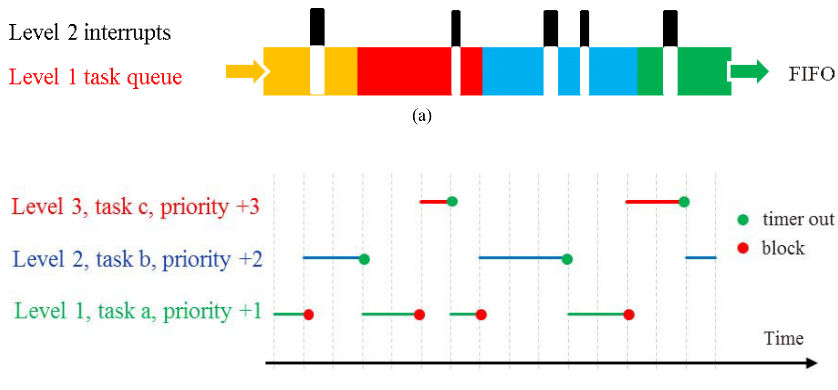
(a) (b)

Fig. 5. Xnode Smart Sensor: (a) stacked modular boards; (b) weather-proof enclosure.

3.2. Xnode software

The emergence of wireless smart sensor platforms with powerful computational capabilities has enabled wireless SHM applications; however, as the demands of wireless SHM systems increase, certain properties of event-driven operating systems for these sensor nodes, such as the TinyOS operating system of the Imote2, have begun to impose limitations on the development of SHM systems. The problematic characteristics include static resource allocation, single-application focus, lack of real-time scheduling support, and dependence on a non-standard programming language. To address these limitations, the Xnode has been developed based on a real-time operating system (FreeRTOS), commonly used for industrial control systems and similar applications.

One key benefit of the Xnode software platform is the more flexible application framework. Moving to this new platform enables several benefits for users compared to the Imote2 (TinyOS-based system), mainly due to the availability of a real-time scheduler. FreeRTOS provides a priority-based preemptive scheduler, as well as inter-task communication and coordination tools (e.g., queues, mutexes, and semaphores). It can efficiently address the limitations of event-driven operating systems on low-power microprocessors. In particular, long-running, low-priority tasks can no longer block important function such as sensor sampling and radio communication (see Fig. 6).



(b)

Fig. 6. Comparison of task scheduling behavior in (a) TinyOS and (b) FreeRTOS [8].

The Xnode retains the successful SOA-based middleware functionality of the Illinois SHM Toolsuite, allowing the rapid development of application functionality based on composing the available middleware modules for fundamental WSSN functionalities (synchronized sensing, reliable communication, time synchronization, power management, etc.), as well as application-level services specific to SHM (cable tension estimation, system identification, modal analysis, etc.). Fig. 7 shows the outline of the implementation of the RemoteSensing application providing synchronized distributed data acquisition over the WSSN.

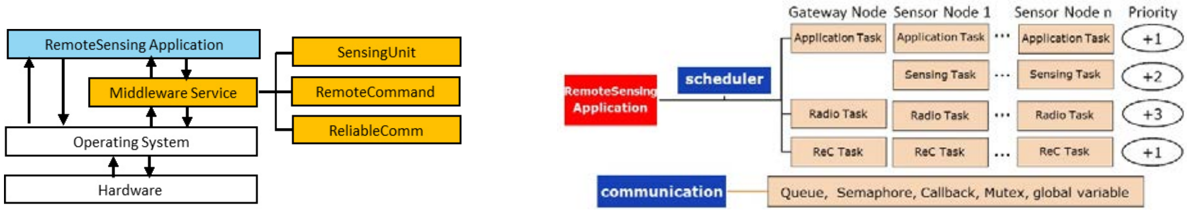


Fig. 7. Outline of the RemoteSensing application structure and its implementation in FreeRTOS [8].

Based on the experience of the Jindo Bridge deployment in the Imote2/TinyOS-based environment, the Xnode platform takes effort to be more open and standardized for easier development and interoperation with other software and hardware platforms. The standard C language is used for application development, in place of a custom nesC variant, which allows for much simpler portability of applications with the Xnode platform. Many libraries and numerical algorithms implemented in C can be used directly, without modification, in the Xnode code. Additionally, the radio communication is based on the IPv6 protocol stack, widely adopted by the Internet of Things (IoT) community, opening the door to potential integration of heterogeneous devices inside a single WSSN.

4. Discussion

As a wireless sensor platform, the Xnode Smart Sensor is clearly differentiated from other available platforms in its capabilities and intended uses. Similar to the Imote2, the Xnode supports high-fidelity, high-sampling rate applications requiring precise synchronization among hundreds of sensor channels. Combined with the Illinois SHM Toolsuite, the Xnode is a research enabler across a range of civil engineering applications and use cases that are currently difficult to implement due to insufficient resolution of available ADCs, lack of software support, and/or the complexity of implementing low-power distributed embedded systems.

With the emergence of IoT technologies, the availability of more standardized hardware, network protocols, and software interfaces promise that the near future will bring the possibility of heterogeneous WSSNs, combining different sensor platforms in a single deployment. Such deployments will be able to take advantage of the unique features of different WSS platforms, such as power efficiency, processing capability, ADC resolution, and sensor selection on an as-needed basis to fit the requirements of a particular monitoring deployment. The Xnode takes the first steps on this path by utilizing a standardized network protocol stack and providing open APIs to its middleware services.

The unique high-fidelity synchronized distributed sensing capabilities of the Xnode also provide a cost-effective alternative to wired data acquisition systems for structural health monitoring. Previous wireless platforms lacked either ADC resolution, communication range, or network scalability to serve as a viable replacement for wired systems. Considering that a large portion of the wired monitoring system cost results from the cabling between the sensors and the data acquisition system, wireless sensors are an attractive alternative, especially for large civil structures, offering the potential for low-cost, continuous, and reliable SHM.

5. Conclusion

This paper discussed the motivation and primary design philosophy for the development of a next-generation wireless smart sensor platform intended for high-fidelity dynamic structural health monitoring applications. Various hardware and software issues are taken into account based on the lessons learned from recent efforts to develop, stabilize, and operate full-scale wireless smart sensor networks for SHM of civil infrastructure. High-fidelity, multi-scale responses can now be captured by the Xnode Smart Sensor platform with a synchronized, distributed data acquisition application that can also be extended to perform in-network data processing and analysis. The Xnode takes steps to increase the standardization of the WSSN environment for SHM applications, which up to now has been fragmented and reliant on systems focused solely on a single platform or even a single deployment. However, much work remains to be done to integrate and standardize the various WSSN-based solutions developed by the community.

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