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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].