Multi-scale wireless sensor networks for structural health monitoring

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ABSTRACT: With growing interest in wireless sensor networks and their application to Structural Health Monitoring in Civil Engineering, many important issues including network lifetime and stability, damage detection reliability, and overall effectiveness when using low-cost sensors must be realistically addressed. In response, a multi-scale wireless sensor network is introduced in this study, integrating data from a heterogeneous sensor array for a more robust and effective approach to damage detection. This approach extends the role of the sensor network from simply a means for communication to a technology that can be engineered to improve structural assessment through the interaction of sub-networks fusing data from distributed, heterogeneous sensor arrays. As a secondary benefit, the multi-scale network concept introduced here helps to improve power efficiency, minimize packet loss and latency and eliminate synchronization issues through the use of a decentralized analysis scheme and the activation of sub-networks only in the vicinity of suspected damage.

1 INTRODUCTION

Given the present burdens associated with inspection and maintenance of Civil Infrastructure Systems (CIS), the development of effective, automated damage diagnosis techniques, including the sensor technologies that support them, has become a major research need. Most research in these areas of "intelligent" structural assessment and evaluation retain the traditional architecture of a centralized data acquisition hub wired to tens or even hundreds of sensors, posing significant installation and maintenance costs. As such, researchers at various institutions have taken advantage of ever-evolving wireless communications technologies to propose untethered systems for CIS, some of which are summarized in Spencer (2003). Even in this wireless format, many of these applications emulate the hub-spoke architecture of traditional wired systems and thus serve merely as an exercise in wireless communications and should be distinguished from wireless embedded sensor networks characterized by local processing capabilities that minimize the amount of data transmitted in a single- or multi-hop strategy to extend the lifetime and robustness of the network. An example of the latter, based on the initial wireless sensor development by Straser & Kiremidjian (1998), was introduced by Lynch et al. (2003) and validated on the Alamosa Canyon Bridge. The multi-hop WISDEN system (Caffrey et al. 2004), which uses the small MICA Motes developed at the University of California at Berkeley (Hill et al. 2000), provides yet another example. In these applications, by avoiding the transmission of lengthy time histories, battery life of the wireless nodes can be extended, while the issues of strict time synchronization and loss intolerance are marginalized.

While such developments in wireless sensor networks have demonstrated their potential to provide continuous structural response data to quantitatively assess structural health, many important issues including network lifetime and stability, damage detection reliability, and overall effectiveness when using low-cost sensors must be realistically addressed. In response to these needs, the concept of a multi-scale wireless sensor network is introduced in this study, integrating data from a heterogeneous sensor array for a more robust and effective approach to decentralized damage detection. This approach extends the role of the sensor network from simply a means for communication to a technology that can be engineered to improve structural assessment through the interaction of sub-networks fusing data from distributed, heterogeneous sensor arrays. As a secondary benefit, the multi-scale network concept introduced here helps to improve power efficiency, minimize packet loss and latency and eliminate synchronization issues through the use of a decentralized analysis scheme and the activation of sub-networks only in the vicinity of suspected damage. This paper introduces the network concept, hardware design and decentralized approach to damage detection.

1.1 *Proposed Response*

Current wireless sensor networks and even future ones using power scavenging technologies must be power efficient not only in their hardware and software, but also in their overall network architecture -- yet another reason to fully exploit on-board computational capabilities. This study utilizes the capability for decentralized data analysis, while extending the concept of wireless embedded sensor networks to a multi-scale format to introduce several benefits:

1 improved damage detection (reduction of false positives and negatives) and localization capabilities through the fusion of data from different types of spatially distributed sensors,
2 compensation for limitations of low cost sensors through the aggregation of sensor outputs at various scales and locations, and
3 improved power efficiency and network performance through the use of a decentralized analysis scheme and network architecture utilizing only sub-networks in the vicinity of suspected damage.

One feature of this effort is the use of spatially distributed and fundamentally different sensors reporting structural quantities at different scales. As damage is inherently a local phenomenon, a localized approach to sensing and detection is advantageous. For example, strain provides important information about structural health specific to critical members. Common damage states, particularly those associated with corrosion, loss of stability in braces/ribs and fractures, all result in increased local stress concentrations. For this reason, the authors augment the commonly-measured acceleration data with strain data to enhance detection capability. As shown by Law et al. (2005), the use of strain and acceleration data in concert produces "more accurate results than using any of the two separately." As such, this study provides a damage detection approach that is inherently more robust, while improving the overall efficiency of the wireless network concept, since local networks are only activated when further verification is required.

2 NETWORK CONCEPT AND ARCHITECTURE

2.1 *Network Concept*

The overall multi-scale network concept was derived with the primary objective of enhancing damage detection capabilities, while conserving power and is generally demonstrated on the simply supported beam shown in Figure 1. The structure is first subdivided into zones to aid in the localization of damage. Each zone contains sensors capable of detecting two "scales" of response: accelerations (MESO- or m-nodes) that carry with them the complete modal character of the response at that location and strain gages (MICRO- or μ-nodes) that provide an indication of stress concentration/strain behavior at critical locations, including the underside of the deck, joints, transverse beams near the supports, braces/ribs, and near upper flanges of girders likely to corrode. Within each zone, accelerometers and strain gages share information across scales to aid in the damage detection process, forming a local network (MICRO- or μ-net). Meanwhile, accelerometers also share information across zones by interfacing with neighboring accelerometers to form a larger network (MESO- or m-net) to enhance reliability. All activities of the network are triggered by a central node (MACRO- or M-node), which receives information on damage states from the network and interfaces with the user.

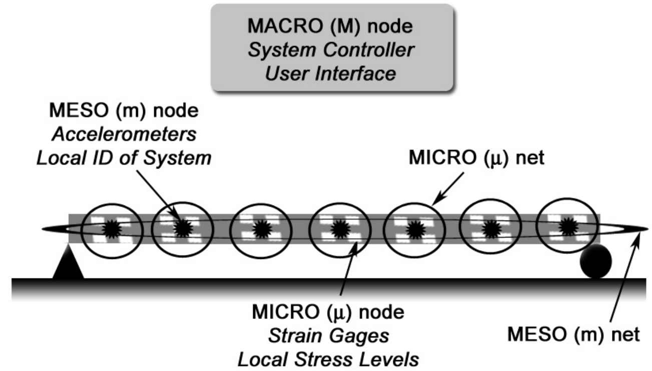

Figure 1. Schematic representation of multi-scale network architecture.

While each node of the m- and μ-nets should ideally be untethered, using wireless communications and on-board batteries, the preliminary design proposed here offers some compromise. The μ-nodes are wired locally to an m-node, forming μ-web to locally concentrate power and processing. Note that this represents a first approach to the multi-scale network concept, and future designs would have a completely wireless approach at all scales. Finally, the M-node would be equipped to receive wireless transmissions from the m-nodes and can be interfaced by a website to the end-user for reporting of results or for triggering.

Communications within the network are designed to maximize battery life at each of the m-nodes. The decentralized system identification approach and the utilization of μ-webs aid in this goal by minimizing the amount of data transmitted wirelessly, and thereby the power depleted. However, the very architecture of the network is also designed with power conservation in mind. Within the m-net, only one m-node remains active to serve as a sentinel in the case of extreme events. The role of sentinel is cycled throughout the m-net. All other nodes in the m-and μ-nets remain dormant until activated by one of two means: an alert from this sentinel or a command from the M-node. The M-node may initiate tests according to a regular schedule under a specified operational state, e.g., monthly during peak traffic flows, or when triggered by the end-user. As shown in Figure 2, the detection process begins with the activation of all nodes in the m-net. The m-nodes collect time histories and perform system identification locally, allowing a determination of potential damage. Nodes detecting damage remain alert and notify their nearest neighboring m-nodes so that findings may be compared within the m-net to help validate the authenticity of the damage suspicion. In this process, all nodes that do not participate in such local collaboration return to a hibernation state to conserve power. If damage is indeed confirmed within the m-net, the μ-net associated with the zone of damage is activated to begin taking strain data in parallel with the accelerations detected at the m-node, and this data is fused in a decentralized system identification approach to either corroborate or dismiss the initial damage claim. If the damage claim cannot be validated by the by the μ-node, the μ- and m-systems return to a hibernating state. If the damage claim is validated by the μ-net, its location within the μ-net is estimated and then reported back to the M-node through a multi-hop scheme. This information is then relayed to the end user.

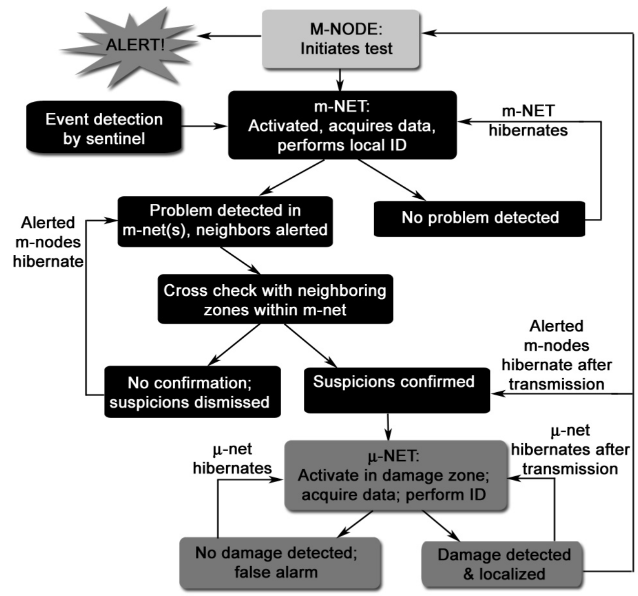

Figure 2. Schematic representation of operational structure of network.

2.2 *Network Architecture*

The goal of this task is to investigate and design reliable and energy-efficient protocols for data acquisition, processing, and transmission that are tailored to the Structural Health Monitoring (SHM) application and operate under various bounds such as maximum latency and minimum lifetime. Numerous issues need to be addressed in the implementation of a sensor network. For some of them, standard solutions found in the literature or derived from the authors' own experience are applicable; others require further investigation and study. For the SHM application, there are mainly two parts of the network protocol stack where fundamental research is needed: channel access and data acquisition. Since both depend strongly on the underlying communication channel, the peculiarities of the wireless channel are first addressed.

2.2.1 *The Wireless Channel*

Many wireless solutions have been proposed for SHM but virtually all of them consider the wireless connection merely as a convenient replacement for wires that would be expensive to deploy. Likewise, in the literature on wireless ad hoc and sensor networks, a disk abstraction is often used to model the wireless links, where two nodes are assumed to be connected in a wire-like fashion if their distance is smaller than the so-called transmission range. Hence the stochastic nature of the wireless channel is neglected completely, which results in inaccurate (usually overly optimistic) analysis and simulation results and, in turn, to inefficient protocols. While this has been pointed out and is easily demonstrated experimentally, little has been done in terms of analysis and practical implementations of channel-aware protocol design for wireless sensing systems.

In this study, the wireless channel is explicitly taken into account by (1) characterizing its properties in detail (including, e.g., small-scale fading), (2) exploiting its properties whenever possible (e.g., the broadcast nature that permits local data distribution at no additional energy expenditure). In the presence of (static) small-scale fading, physical proximity does not guarantee good links, and, in turn, relatively long links may still exhibit small path loss. With pedestrian or vehicular traffic on a bridge, the channel is also subject to dynamic small-scale fading and possibly shadowing. Such relatively slow fluctuations in the channel quality are problematic due to the lack of time diversity; thus the network needs to adapt and self-configure to such slow changes in the link quality. Opportunistic approaches (Venkataraman & Haenggi 2004) are promising and their feasibility is being explored in this project; however, they also raise fairness and latency concerns, and they often require knowledge of the channel state, which may be difficult to obtain. It needs to be emphasized that with clever design of the physical, channel access, and networking layers, spread spectrum techniques are not required. Thus, the narrowband transceiver in the proposed hardware platform is certainly capable of handling the data traffic reliably.

2.2.2 *Channel access*

In any multi-node or multi-user wireless system, a MAC (multiple-access) layer is needed that regulates the channel access. Channel access is an instance of a distributed resource allocation problem that includes space, time, bandwidth, and possibly power. In an energy-constrained network with event-driven traffic, this is a particularly critical issue, since many nodes will start sensing and transmitting simultaneously when an event occurs. The MAC scheme needs to be specifically designed for these phases of high traffic. While continuous traffic flows can be accommodated by reservation-based schemes (TDMA, FDMA, CDMA), such schemes with fixed assignment do not provide the flexibility called for by this application. Random access techniques with smart adaptive back-off or a negotiation or contention phase seem more promising, but standard solutions such as the CSMA-based MAC scheme in the IEEE 802.11 standard perform sub-optimally. In this study, the capability to distinguish between noise and interference as reasons for packet loss is explicitly exploited, since the protocols need to react differently depending on whether a packet is (1) lost due to noise (implying too little power at the transmitter or too large a distance) or (2) interference (implying that too many nodes are trying to access the channel). In case (1), either the transmit power needs to be increased or a different route needs to be found. In particular, simple retransmissions are very unlikely to succeed. In case (2), the MAC scheme has to adapt and resolve the collision; here, a simple back-off and retransmission may solve the problem.

If the M-node is able to reach all the lower-tier nodes, it is possible to use centralized scheduling schemes where the M-node assigns time slots or polls the m-nodes. In addition, the M-node could ensure tight synchronization among the nodes, which helps scheduling transmissions and sleep intervals. For the upstream link, however, some m-nodes will most likely be unable to reach the M-node directly, so they have to find multi-hop routes and use other nodes as relays to deliver their data. Since the network topology is fixed, routing is not the primary concern. There is, however, interdependence between routing and channel access. To avoid congestion or even instability, it must be ensured that the maximum offered traffic load does not exceed about 25% of the network capacity. The spatial correlation of the data needs to be exploited at the MAC layer, just as in the network layer, so that traffic load can be reduced accordingly.

2.2.3 *Data acquisition and local processing*

Significant energy and reliability gains can be expected from collaborative data acquisition and local preprocessing, since nearby μ- and m-nodes will sense correlated data and short-distance communication is inexpensive and robust. It is therefore sensible to investigate distributed detection and compression schemes at the local level (μ- and m-nodes).

The decentralized detection scheme presented in Chamberland & Veeravalli (2003) only focuses on binary detection problems (hypothesis testing) and need to be extended for the purposes of the SHM application. A key idea being pursued is based on the fact that temporal and spatial diversity can be traded off. Tight synchronization permits tradeoffs between temporal and spatial sampling. High temporal resolution is achieved if the nodes' sampling rates are identical but the sampling times have a relative offset. High spatial resolution is achieved when all nodes sample at the same time instants. So, depending on the size of a phenomenon, the application can ask for high temporal or spatial resolution or the m-nodes themselves can switch to higher temporal resolution if the sensed data within their clusters is very similar. Within the same framework, the quantization can also be dynamically adjusted.

Note that the architectural and networking issues are not independent and thus cannot be addressed in isolation. Rather, a so-called cross-layer (or “holistic”) approach is adopted, which is distinct from previous work in SHM. In particular, both the channel access scheme and the local processing algorithms need to be tied in with the sentinel structure described in the previous section: the MAC (and routing) layer needs to be aware which nodes are awake, and for local processing and data exchange, nodes need to be awoken.

The main objective of this task is to achieve longevity and reliability of the network by using innovative approaches to network protocol design and by collaborative processing at the nodes.

3 HARDWARE PLATFORM DESIGN

Though there have been a number of proprietary wireless platforms, as reviewed in (Spencer 2003), open hardware/software platform of the MICA Motes developed at the University of California at Berkeley is adopted here (Hill et al. 2000). This platform's capabilities have already been demonstrated for a variety of SHM and non-SHM applications (e.g., Fang et al., in press). In the present study, this platform, which has largely been used for vibration measurements by accelerometers, will be adapted for heterogeneous sensing by incorporating multiple strain measurements to form a μ-web, with the objectives of minimizing cost and installation effort. As this μ-web occupies a small region of the structure, there is minimal installation effort and cost. Thus, while the long term vision of a multi-scale wireless network concept would have a holistic wireless approach, the use of strain gages (μ-nodes) tethered to an m-node is viewed as an obvious first step in this network's evolution.

3.1 *Hardware Overview*

Figure 3 shows a NEMA4X-grade enclosure containing a remote bridge monitoring unit (RBMU). The RBMU consists of a sensor board, a MICA2 mote from Crossbow and a battery pack for power-

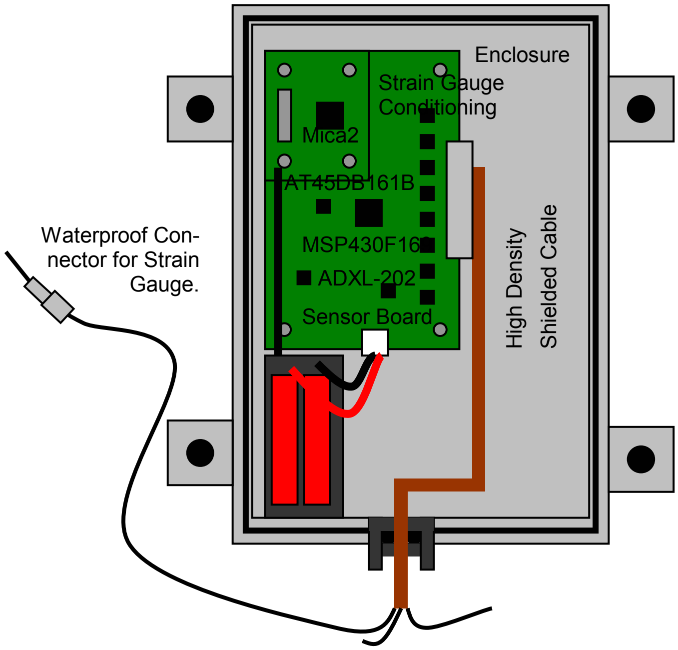

Figure 3. Rendering of m-node hardware for μ-web concept.

ing the sensor board and MICA2. The MICA2 will serve as the radio and handle any necessary ad-hoc routing algorithms. The Sensor Board will consist of signal conditioning electronics for the strain gages, the m-node's accelerometer, temperature and humidity sensors and a low cost ($9.00) 16-bit processor. The processor by Texas Instruments (MSPF430F1611) is supported by TinyOS and has over 10kBytes of RAM and a hardware multiplier for advanced signal processing. The MSP processor has an 8 channel 10μs 12-bit sampling A/D converter as well as a 2 channel 12-bit D/A converter for future applications. The processor also has access to an 8 pin 4 MB flash storage chip, the AT45DB161B, for additional data storage. Note this configuration can accommodate a second processor to expand the capabilities of the unit. The current validation program will verify whether or not this expansion is needed. Finally, the sensor board has waterproof external connectors, the enclosure has watertight seals and all external cables are shielded. The enclosure can be mounted to the bridge either via bolts or magnetic mounting tabs.

3.2 *Sensor Details*

Strains are measured by a three-wire quarter bridge circuit, whose outputs are amplified and filtered by a differential amplifier, INA338, to render a full-scale signal to the MSP430F1611 12-bit A/D. Given the trade-offs in accelerometer noise properties and cost, prototypes are being fabricated for a number of commercially available accelerometers, including those by Applied MEMS, the ADXL202E and ADXL213 by Analog Devices, and ICP Sensors by Honeywell. These are being evaluated experimentally to verify whether the proposed data fusion will offset reduced sensor accuracy. Roughly considering the capabilities of these various units, sensing bandwidth is limited to 20 Hz to minimize noise. In these configurations, the system can sample dynamic responses at up to 100 Hz with strains and accelerations within the limits roughly specified in Table 1.

Table 1. Strain and acceleration sensing limits.

Quantity	Resolution	Frequency Range	Operational Range
Strain	± 0.25 με	0-50 Hz	± 1000 με
Acceleration	0.2-0.4 mg	~0-20 Hz	± 1200 mg

4 DAMAGE DETECTION BY DATA FUSION

In light of the aforementioned network architecture requirements, a decentralized system identification scheme that utilizes the on-board capabilities of the motes is requisite. To avoid intrusion and minimize costs, such a scheme should utilize ambient excitation sources, e.g., traffic, wind, etc. Though preliminary research has demonstrated the merits of decentralized system identification for detection and localization, it has done so without considering the necessary trade-offs in resolution and noise thresholds to develop a low-cost, dense wireless sensor array on a complex system. One way to counteract the effects of this necessary reduction in hardware capability is in the network architecture itself, motivating this study's analysis of the potential compensation offered though the fusion of data from heterogeneous, spatially distributed sensor arrays.

The damage detection technique being used in this study is based upon the two-stage prediction model first proposed by Sohn & Farrar (2001). Details of the approach are available in that reference and are omitted for brevity. When implemented on a wireless platform with reduced quality sensors, the performance of this or any other damage detection technique will likely be affected. To compensate for these losses, the two-stage damage detection procedure is augmented by two levels of data fusion: through cross-checking within the m-net, which can be considered fusion at the network level (NetFusion), and confirmation at an m-node, where the system identification process itself aggregates measurements from distributed sensors (NodeFusion).

As shown by Law et al. (2005), the use of strain and acceleration data in concert produces "more accurate results than using any of the two separately." For this reason, the multi-scale network concept integrating strain gages is proposed here. Given the difficulty of quantifying initial stress states, a more practical strain metric considers the time-evolution of strain, provided there is a means to differentiate suspect behavior from environmental and operational effects.

In the context of this study, the μ-net is activated to confirm suspicion of damage at an m-node. As a result, time histories at n strategically placed strain gages are simultaneously captured at the m-node. These measurements, all in close proximity and under the same environmental and operational conditions, should show similar variations based on the evolution of the loading with time, provided they are not compromised in any way. Corroded, fractured or otherwise damaged elements would manifest a different dynamic character when compared to their intact counterparts. Based on this premise, damage can be detected not through comparison to a reference pool but through cross-referencing of the AR fit to normalized local strain time histories. A differential error matrix is formed containing the relative deviations of the AR coefficients of each strain measurement against the others. A statistical significance test is then performed on this matrix to identify if any strains within the μ-net show uncharacteristic response behavior. If so, the location is reported.

Finally, given the effect of environmental and operational variability, Sohn & Farrar (2001) proposed the construction of a reference pool to represent varying operational and environmental conditions. This must be performed at each m-node to insure that statistically significant errors in the ARX modeling are truly the result of damage. Since the system will operate primarily on a pre-determined schedule, the pool of operational states can be significantly reduced, while the environmental state can be more accurately identified by integrating outputs from the on-board temperature and humidity sensors.

5 SUMMARY AND ONGOING WORK

The field of SHM has naturally progressed toward wireless sensor networks to provide a quantitative and continuous metric of structural health. Recognizing the limitations imposed by reduced sensor quality and finite power supply, inherent to any practical wireless network, this study compensates by recasting the concept of network architecture to a multi-scale format with data fusion and spatially distributed, heterogeneous sensing to achieve improved reliability of damage detection and localization through the fusion of data from different, spatially distributed sensors. Further, through the adoption of a multi-scale network architecture that utilizes localized processing and mobilizes only those sensors in the vicinity of damage, this study seeks to improve power efficiency and performance.

The authors are currently performing experimental validations to examine implementation issues, e.g., the challenge of dealing with the limited availability of computational resources (8-bit microcontroller), management of available memory, including the usage of the external Flash memory in light of the need to conserve power, and reduced quality of sensors. Meanwhile, the overall network architecture is being validated on an integrated simulator, using Prowler, a MATLAB-based sensor networks simulator developed at Vanderbilt University (Simon et al. 2003). The system will be ultimately deployed on a 300-ft retired railroad bridge near the university.

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