Wireless Sensor Networks for Structural Health Monitoring: Challenges and Techniques

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Abstract
WSNs have been regarded as a substitute for traditional wire-based structural health monitoring (SHM) systems due to the low cost, easy deployment and high scalability. Despite of the existing deployments of WSNs on various structures, using WSNs for SHM is still a challenging task and many related issues are yet to be fully addressed or even clearly identified. Particularly, advantages and limitations of associated techniques to address some issues have not been well recognized. In this paper, we first review the existing WSN-based SHM systems and then identify five some challenging issues when WSNs are used to monitor structural conditions. These challenges, ranging from energy consumption, data delivery, to SHM algorithms and middleware framework, are mainly caused by the contradiction between the high requirements of SHM and resource-limited WSNs. Existing techniques to address these issues, along with their benefits and drawbacks, are also presented.

Key words: Wireless sensor networks, Structural health monitoring

1. Introduction

Structures like large dams, long-span cable-supported bridges, high-rise towers, tunnels etc. are critical components of the economic and industrial infrastructure. These structures are aging with years and are also subjected to possible unexpected severe environmental conditions and harsh loading scenarios. Therefore, it is important to monitor the integrity of these structures and detect and pinpoint the locations of any possible damage before it reaches a critical state. Correspondingly, a system that is able to provide such information is called SHM system [1] [2].

Recently, with the rapid advancement of key technologies such as sensors, microprocessors and wireless networks, wireless sensor network (WSN) has become an increasingly compelling platform for SHM applications. The most important property of the WSNs is the inclusion of smart sensor nodes with sensing, computation, and wireless communication units.

Compared with the traditional wire-based SHM systems, WSN-based SHM systems have significant advantages. First, wireless communication eradicates the need for wires and therefore represents a significant cost reduction and flexibility over a wire-based counterpart. The system deployment time is also dramatically reduced from months or years for a wired system to be days or even hours for a WSN-based counterpart. Second, because of the low cost of each sensor node, fine grain of monitoring can be achieved, which increases the quality of assessment. Third, a WSN-based SHM system can utilize the computational capability of wireless sensor nodes and realize autonomous and real-time monitoring without aggregating the raw data in the central station.

2. Applications of existing wire-based SHM systems

Although different kinds of WSN-based SHM systems have been designed for different SHM applications, the real implementations, particularly on large civil structures are still limited. In this section, some of the real implementations of WSN-based SHM systems, along with their achievements and limitations, are described.

The researchers has deployed 14 wireless sensor nodes on a bridge in Korea to monitor its response to speeding and overloaded trucks[3]. A laptop computer, with a compatible wireless radio attached, is used to collect bridge response data from the deployed wireless sensor nodes. A hub-spike architecture is adopted in the SHM system which means that the laptop is within the single communication range of all the wireless sensor nodes. Also, Fast Fourier transform (FFT) and peak picking techniques (PP) are implemented in each individual sensor node. However, the tested results showed that synchronization error among the 14 sensor nodes can be as large as 0.1s. Also, single-hop communication architecture may not be appropriate for large structures. Power consumption issue has not been carefully considered and the deployment is only for short-term purpose.

Berkeley researchers installed 64 MicaZ motes with their customized sensor board on the Golden Gate Bridge [4-5]. The deployed 64 sensor nodes constitute a network with 46 hops. These wireless sensor nodes were sampled at 1 kHz then averaged and down-sampled at 200Hz. To deliver the sampled data reliably through multi-hop wireless communication, they implemented a reliable communication protocol called 'Straw'. However, one limitation of the system is the bandwidth. It took over 12 hours to complete the transmission of the 20MB of data (1600 seconds of data, sampling at 50Hz on 64 sensor nodes) reliably back to a central station. The effective bandwidth achieved is only 3.5kbps, far below the 250kpbs theoretical bandwidth of MicaZ.

A WSN-based SHM system including a total of 70 Imote2 sensor nodes has been deployed on the Jindo Bridge[6-7]. The system also has the hub-spoke architecture but with two base stations. Correspondingly, the network was divided into two sub-networks, one with 37 nodes and the other with 33 nodes. The measured data shows a good agreement with data from the existing wired system. An autonomous monitoring is also realized by employing a threshold detection strategy and an energy-efficient sleeping mode (called 'SnoozeAlarm' in [6-7]) to extend the network lifetime. However, the single-hop communication network architecture is not appropriate for large structures. Also, when the deployed sensor nodes are in the 'SnoozeAlarm' mode, it takes 1~5 minutes to wake up the entire network. Therefore, the system does not support capturing critical data in short-term, transient events such as an earthquake.

Researchers from Italy and Sweden collaboratively designed a WSN-based SHM to monitor the structural response (e.g. deformation and vibration) of the Torre Aquila Tower, so as to preserve the integrity of the valuable artworks located inside [8]. Since this is a specific application and requires long-term deployment, customized wireless sensor nodes with dedicated communication software have been designed. The WSN-based SHM system installed in the tower consists of 16 sensor nodes, among them are the two fiber optical strain gauges, three accelerometers, and 11 temperature sensors. The system has been operating since for 4 months without changing battery, which is a good performance if compared with other WSN-based SHM systems. Also, the data loss ratio was estimated to be less than 0.01%. However, the scalability of the system is validated since only 16 sensors are adopted in the system. In addition, the long lifetime of the system is at the expense of long working interval: only three sensor nodes are equipped with accelerometers and they only work about 6 minutes every day.

3. The Challenges of WSN-based SHM

In this section, we identify four key challenges of WSN-based SHM.

3.1 Key Challenge 1: How to realize a long-term monitoring using WSNs using battery powered wireless sensor nodes

Limited power supply is one of the most critical issues of WSN-based SHM systems. Most of the wireless sensor nodes used in SHM are energy-consuming when working in a full load condition. Taking the Jindo bridge as an example, the maximum current draw of sensor nodes is 184 mA [6-7]. The battery can only support about 5 hours of continuous work. Considering the potential cost of the constant maintenance and battery replacement, particularly when the access of sensors is difficult, some measures need to be taken to extend the lifetime of the system.

Solutions proposed to solve this problem can be largely classified into three categories: sleep & wakeup, in-network processing, and energy harvesting.

Sleep &Wakeup

A common approach to achieving energy savings in wireless sensor networks is to put the sensor nodes into the sleep mode if they are not working. Almost all the types of wireless sensor nodes working in the sleep mode consume much less energy than in the working status. For example, in the wireless sensor node designed by UIUC, the current draw of the node is only 0.5mA at sleep mode while can reach more than about 150mA in full load working status such as sampling and data transmission[9].

The most widely adopted power saving strategy is that sensor nodes are working and sleeping in a pre-defined schedule [10-12]. When the internal timers fire, sensor nodes are awaken from sleep mode. Sensor nodes then perform their routing work, such as sampling, data processing, and transmission, possibly after a time synchronization procedure, and then go to sleep until the next round starts. The duration in the sleep mode can be fixed or adjusted. For a system operating in a very low duty cycle, its lifetimes can reach the order of a few months or even years. However, it should be noted that, schedule-based approach limits the ability of the application users to initiate network operations at random or in case the event of interest occurs.

To address the limitation of schedule-based wakeup, another strategy, event-triggered wakeup is proposed. Compared with the schedule-based wakeup, event-triggered wakeup can put the sensor nodes into sleep state as long as possible while wake them up immediately if required. Events here can be the changes in vibration, or external radio transmission. To use this strategy, each sensor node should be equipped with a special hardware component which is designed to sense the event of interest. The component itself should be low-powered or even powerless. Once the event is detected by the component, it will wake up the node to which it is connected, generally by generating an interruption.

One type of event is external radio transmission. Waking up sensor nodes using this strategy is generally called 'radio-triggered wakeup'. Change in vibration is another event for SHM since it is often quite desirable to have the data sampled when the structure is under relatively large vibration amplitude.

In-network Processing

One of the most energy consuming operations in a WSN is wireless data transmission. To overcome this, computation power on the wireless sensor node is used. Instead of streaming the sampled data directly to a central unit, the collected data are processed and only the processed information, which uses fewer bits than the original one, is transmitted. From this perspective, in-network processing can be an effective way to decrease the energy consumption.

In-network processing techniques used in WSN-based SHM can be largely divided into two categories: compression and SHM algorithms.

Compression techniques use fewer bits to express the original data and generally include procedures such as coding and decoding. Traditional data compression techniques, either lossless or lossy, can be directly used in WSN. In [13-14], Huffman coding, wavelet compression are implemented at each sensor node on the sampled vibration data. In addition, some WSN-tailored data compression techniques have also been proposed, such as the lifting scheme wavelet transform (LSWT) method [15] and the adaptive linear filtering compression (ALFC) algorithm [16].

Another category of in-network processing techniques is the SHM algorithms. Compared with compression, more domain knowledge of structural engineering is involved. The output of SHM algorithm is the highly compacted information directly associated with structural condition. How to design light-weight and effective SHM algorithm in WSN is a challenging problem and will be described in section 3.

Energy Harvesting

Besides sleep & wakeup scheduling and in-network processing, energy harvesting techniques have also been used in WSN-based SHM systems. For example, solar panels and rechargeable batteries have been chosen in many WSN-based SHM systems such as [10] [17] [18].

3.2 Key Challenge 2: How to implement light-weight, and effective SHM algorithms

Implementing SHM algorithms in wireless sensor nodes has at least two advantages. First, structural condition can be provided in a timely manner and without any additional central station. Second, transmitting the structural information requires much less energy even than transmitting compressed or filtered data. In terms of whether data-level cooperation is required, SHM algorithms can be classified as node-level SHM algorithms and collaborative SHM algorithms.

Node-level SHM algorithms

Some SHM algorithms are intrinsically distributed and are able to detect damage using data from individual sensor only. Examples among these node-level algorithms are the AR-ARX algorithm [19], the DLAC algorithm [20-21] and the CDED algorithm[22]. These algorithms can be directly embedded into each wireless sensor node. In this approach, each sensor node does local processing, and only the damage information, mainly corresponding to the areas where it is located, are transmitted back to the base station. In the base station, generally a decision-fusion technique is implemented, and a more reliable and accurate damage information is obtained. A typical node-level SHM system is illustrated in Fig.1.

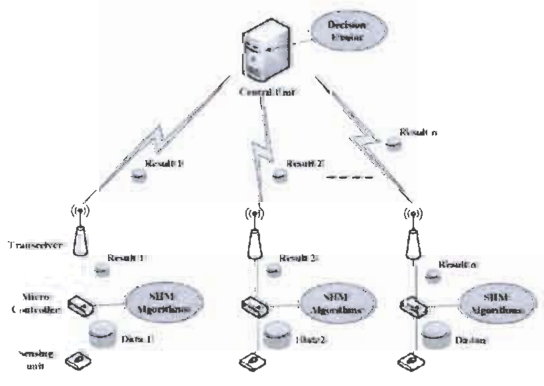

Fig. 1 Node-level SHM algorithms.

Implementing node-level SHM algorithms in a WSN is relatively simple and straightforward. Moreover, since no data-level communication is required, the wireless communication is kept as low as possible. However, it should be noted is that some of the node-level SHM algorithms are computationally intensive. Another significant drawback of node-level SHM algorithms is their in-effectiveness to detect structural damage. In this approach, each sensor node performs SHM algorithms based on its own measured data without any collaboration with others. Generally speaking, the SHM algorithms which use data from a single node cannot produce reliable and accurate identification result; even this result is only used to evaluate the local area corresponding to the sensor node. Without collaboration in the data level, individual sensor node lacks the ability to distinguish the actual damage from the input change and environment noise and therefore, is prone to generating false positive alarms (indication of damage when none is present). Not surprisingly, most of the classic SHM algorithms, such as finite element model updating methods[23], state space identification based algorithms[24], eigen realization algorithms (ERA)[25], are all centralized.

Collaborative SHM algorithms

Collaborative SHM algorithms are generally modified from the traditional centralized SHM algorithms. Since centralized SHM algorithms are effective to detect damage but generally will incur excessive wireless communication and computation, collaborative SHM algorithms try to find a way to reduce the wireless communication and computation while still try to achieve the original damage detection capability of centralized ones. In terms of how collaborative SHM algorithms are modified from centralized SHM algorithms, they can be classified as cluster-based SHM algorithms, model-based data aggregation, and networked computing.

A straightforward way to modify centralized SHM algorithm is through clustering. In this approach, the whole network is divided into a number of clusters. Sensor nodes within one cluster are generally within a single hop communication range of its cluster head (CH). CH in each cluster is responsible of collecting measurement from all the sensors in its cluster and performs classic centralized SHM algorithms. CHs can further communicate with each other to obtain more reliable damage information. The architecture of cluster-based SHM algorithms is illustrated in Fig. 2. Compared with the traditional centralized approach, the cluster-based approach limits the hops as well as the number of sensor nodes in each cluster, thus limiting the wireless communication as well as the intra-cluster computation. Compared with the node-level SHM algorithms illustrated in Fig. 1, this cluster-based architecture uses multiple sensor nodes to obtain local decision and therefore can obtain a more reliable and accurate damage identification result.

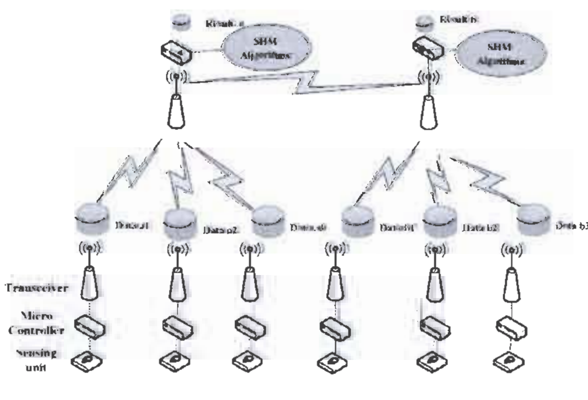

Fig. 2 Cluster-based SHM algorithms.

In cluster-based SHM algorithms, clustering itself is important. Different clustering strategies have different intra/inter-cluster wireless communication, computation, and even different capabilities to detect structural damage. How to find a clustering strategy which is optimal in one or some of these aspects is important as well as challenging.

Networked computing seems to be a promising approach to implement SHM algorithms in WSNs. Wireless sensor network can be viewed as a parallel computer with a number of processing nodes. The objective is then becomes how to perform arbitrary (and likely complex) computational tasks using a distributed network of wireless sensors, each with limited resources both in energy and in processing capability. To answer this problem, we first need to find an approach to decompose the complex computation tasks into smaller operations, each with its own input and output and collectively related through a certain dependency structure. We then need to distribute these smaller operations among individual smart sensor nodes so as to incur minimal energy consumption and delay. The research associated with the networked computing in WSN-based SHM has just started recently. Associated works can be found in [26-28].

3.3 Key Challenge 3: How to realize fast and reliable delivery of large amount of data

SHM generates large amount of data, they need to be delivered reliably and if possible, within a short period of time. However, this task is difficult because of the following reasons:

1. Unlicensed frequency bands have limited bandwidth.
2. Different layers of network protocols (OS, MAC, routing, network) further limit the actual bandwidth achieved.
3. Network size, environmental conditions also affect the bandwidth achieved.

Almost all types of smart sensor nodes use unlicensed frequency band to transmit the data. The theoretical bandwidth of unlicensed frequency band is generally limited. For example, widely used motes in WSN-based SHM such as MicaZ, Imote2, use 2.4GHz frequency band. The theoretical bandwidth of this frequency band is about 250kbps. Considering the high sampling frequency, this bandwidth is not adequate for many SHM applications. For instance, for a WSN-based SHM system including 40 sensor nodes, each generating 16-bit vibration data at 400 samples per second, the amount of data generated every second is 256k bits. This already exceeds the theoretical upper bound 250kbps.

Besides the limited bandwidth, network protocols at different layers further limit the actual bandwidth achieved. In TinyOS, a header will be added in each wireless packet and this overhead consumes significant amount of bandwidth, particularly when the packet size is relatively small. Although the header size is fixed in TinyOS, the relative header overhead can be decreased by increasing the packet size. It is found in [4] that doubling the packet size from 36 bytes to 72 bytes can increase the bandwidth by nearly 2 times (from 588B/s to 1172B/s). However, large packet size does not necessarily increase the bandwidth. For an environment where the packet loss rate is high, a larger packet size will decrease the effective bandwidth achieved. Besides the operating system, protocols in MAC, routing and network layers, also significantly decrease the actual bandwidth achieved. As a result, for wireless sensor nodes working in 2.4GHz, the maximum single hop data transmission speed is only about 80 kbps, less than one third of the theoretical upper bound.

Network size can be an obvious factor for effective bandwidth. A wireless network with smaller size generally has higher end-to-end throughput. As an illustration, the effective bandwidth in a 46-hop network is only 3kbps [4]. On the contrary, in [17], single-hop communication is adopted in which the corresponding bandwidth can achieve about 12kbps. Although a single-hop network can generally achieve much higher throughput, single-hop communication may not be practical for many SHM applications. The size of typical civil infrastructure is large, and the sensor nodes are frequently installed in obscured areas. These facts often make direct communication with the base station impractical.

Another type of factors that affect bandwidth can be attributed to the reliability of wireless link. Frequent packet-loss and re-transmission significantly reduce the effective wireless bandwidth achieved. Therefore, a WSN with reliable wireless link can have significantly higher bandwidth than the counterpart with poor wireless communication.

However, to establish reliable wireless links is not a trivial task, particularly in SHM. Civil structures under monitoring are usually made of concrete or steel components. Radio communication on and around these components is usually complicated due to radio wave reflection, absorption, and fading. In [29], three key factors that affect the link reliability have been identified. They are the quality of the antenna, the effect of spacing between the antenna and the wall, and a phenomenon known as fading. Correspondingly, higher-gain antennas located away from the wall were used which have been proven to be very helpful to increase the reliability. Similar suggestions about how to choose the antenna and antenna deployment can also be found in [30-31]. In [32], directional antennas are adopted to increase the transmission range as well as the reliability of wireless communication.

It also should be noted that in-network processing techniques can also be used here to improve the effective bandwidth achieved. The detailed description is omitted for brevity.

3.4 Key Challenge 4 : How to develop middleware framework for WSN-based SHM

The last point we wish to mention is associated with the middleware framework for WSN-based SHM applications. Traditionally, the development of a WSN-based SHM system needs to be carried out in a 'from-bottom-to-top' approach. Designers need to carefully choose or design the hardware (including appropriate processor board, sensor board, wireless communication module) and software (including system software, if necessary, and application software) which would satisfy the requirements. However, SHM application programmers, particularly civil engineers are generally not familiar with the operating system of WSN, and are unwilling to be exposed to the intricacies of WSNs like wireless communication and energy management, et, al. They wish to be only involved in the development of application software. Therefore, middleware framework which is able to provide programming abstractions is quite important. With the help of the middleware, SHM application programmers can focus on the SHM application logic without caring too much about the lower level implementation details.

However, developing middleware framework for WSN-based SHM system is not a trivial task. The main difficulty comes from the diversity of SHM applications. Different SHM applications have different requirements in terms of sampling frequency, communication range, synchronization accuracy, data delivery reliability, detection accuracy and energy strategy et al. A versatile middleware framework for WSN-based SHM should provide reusable services (e.g. synchronized sensing, reliable data delivery) and also should be able to configured or self-adaptive. Also, the way that different types of services are delivered, such as query-based, event-triggered or pub/sub-based, should also be carefully considered in the middleware framework.

To design a versatile middleware framework, we should first identify some common services that most of the SHM applications are required. Fig. 3 lists the common services required by most of the SHM applications. These services include:

1. Sampling service. This service mainly deals with techniques to realize synchronized sensing. The time synchronization protocols, along with the associated techniques such as re-sampling, time stamping are the supporting services for synchronized sensing.
2. Wakeup service. This service is used to provide different methods for fast and synchronized wakeup.
3. Data delivery service. Application users can use this service to realize reliable data/command delivery.

4. In-network processing service. Different in-network processing techniques, such as compression and various SHM algorithms are provided in this service for application users.
5. Other services for maintenance and debug. The services for maintenance include node failure detection and report, power management, network connectivity, etc. Some small but useful services for debugging include sensor test and radio test.

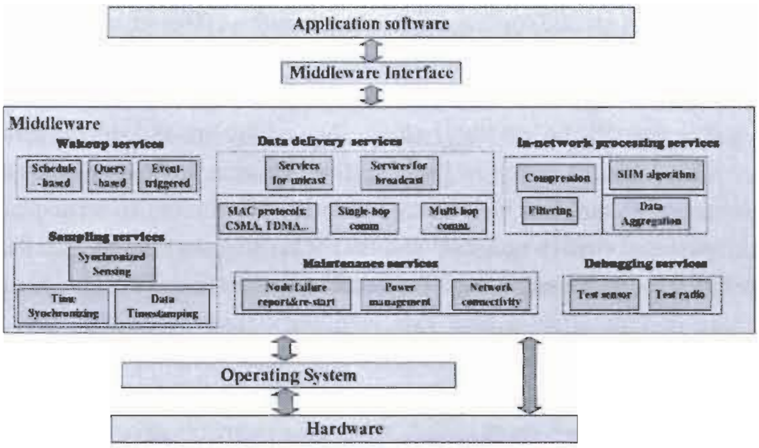

Fig. 3 Service-based middleware framework for WSN- based SHM.

This service-based middleware provides an application programming interface for application users. For different application, users can simply choose from these services and compose them together to constitute the service that is needed. For example, for a WSN-based SHM system which is used to realize automatic SHM, applications users can choose 'event-triggered wakeup' service, the appropriate SHM algorithms, along with services associated with basic network functionalities such as synchronized sensing and data delivery to realize this applications (see Fig. 4).

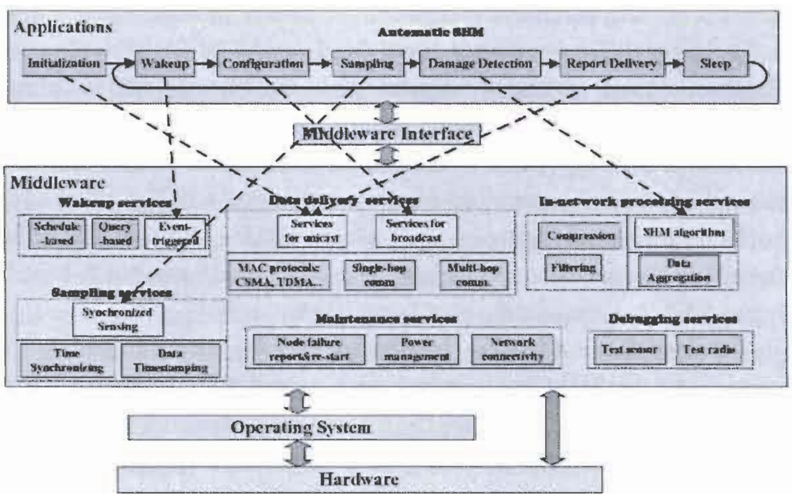

Fig. 4 Services chosen for automatic SHM

4. Conclusion

In this paper, we investigate a particular application of wireless sensor networks: structural health monitoring. Based on the existing WSN-based SHM systems, main challenges associated with WSN-based SHM are identified first and then the corresponding techniques are summarized. More depth investigation on these challenges should be carried out in the future.

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