

An Overview of WSN in Structural Health Monitoring in Civil Structures

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Abstract – *The potency of structural health monitoring (SHM) using wireless sensor networks (WSNs) to reduce the costs associated with the implementation and maintenance of SHM systems has inspired researchers' interest. SHM systems have been used to monitor critical infrastructure including bridges, highrise buildings, and stadiums, and they have the ability to extend the life of structures while also improving public safety. WSNs for SHM encounter specific network design problems due to their high data collection rate. This paper provides a detailed overview of WSN, SHM using WSNs, difficulties using smart sensors for SHM applications. The challenges, desirable properties, and approaches of SHM systems are also outlined in this paper.*

Key Word – *Structural Health Monitoring, Civil Structures.*

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1. INTRODUCTION

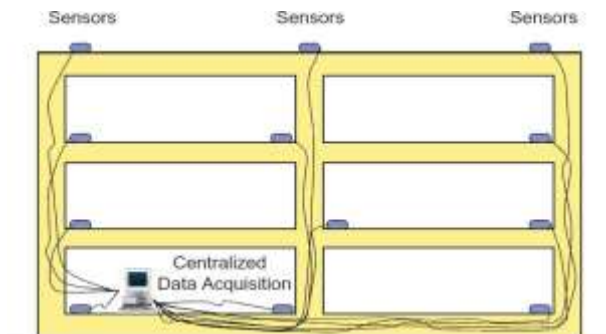
Civil engineering systems, such as bridges and buildings, have become increasingly important in our daily lives. The majority of India's existing civil engineering systems have been in use for several years. These systems tend to deteriorate as soon as they are used, which may be due to ageing or damage caused by day-to-day activities. As a result, determining the state of these structures is more important than ever before in order to provide the required maintenance and repair. Furthermore, assessing the state of civil engineering structures following natural disasters such as earthquakes, floods, and cyclones, as well as man-made disasters such as explosions, is important. These critical/important civil engineering systems must be evaluated and repaired as soon as possible in order to be safe to use. Civil construction failures, such as bridge or building collapses, often result in a large number of casualties as well as social and economic problems.

Structural Health Monitoring (SHM) is a rapidly expanding area that offers a forum for continuous evaluation of civil engineering systems in order to ensure their protection and serviceability (Yong Gao & Spencer 2008). By carrying out the required maintenance/repair work based on the inputs obtained through SHM, the structure's service life can be extended, preventing any failure. As a result,

most developed countries are rising their budgets for evaluating the state of their main civil infrastructures. The SHM system provides a way to lower the cost of maintenance, repair, and retrofitting a structure over its lifetime. In the broadest sense, damage to civil engineering structures is caused by changes in material performance, connections, boundary conditions, etc., due to deterioration. For example, the detrimental effects of material ageing on structural performance and overloading usually result in loads that differ significantly from design loads, thereby reducing the structure's safety and even leading to its failure. Damage to civil engineering structures can be caused by several causes, such as corrosion, repeated loads of fatigue, ageing, etc. In bridge structures, loads due to vehicle movement, over-loaded vehicles and wind can cause damage. Excessive loads caused by cyclones, hurricanes, and earthquakes, on the other hand, can cause structural damage. Damage to civil engineering systems can be divided into two types: linear and nonlinear. In the case of linear damage, the structure behaves elastically even after the damage has occurred, while in the case of non-linear damage, the structure behaves non-linearly once the damage has occurred.

Several SHM techniques have been formulated over the last few decades. However, applying them to civil infrastructures causes a few difficulties. To

evaluate the structure's efficiency, most current SHM techniques include calculating the magnitude of loads that will be applied to it. However, in many situations, measuring the loads that are applied to the structure (bridges) or, alternatively, creating such loading in the structures to obtain responses is difficult. Because of this challenge, current SHM techniques for assessing the health of civil engineering systems that involve load measurement have been limited. For structural health monitoring and assessment, techniques that use ambient vibrations in the structure caused by loadings have become more popular. However, further research is needed to improve health evaluation techniques that use the vibration of structures in the ambient environment. Another issue with implementing the current SHM strategy is that harm is a local phenomenon. As compared to sensors located farther away from the damage, sensors located near the damage report the highest responses. As a result, sensors must be widely spread within a system to effectively detect the location of damage. Because of the difficulties in routing the cables from the sensor locations to the central data acquisition system, using a traditional wired sensor system to measure the health of a structure by installing a large number of sensors would be difficult. Figure 1.1 depicts a structural health monitoring device with wired sensors. Since the cables are easily damaged, the cabling needed to link the sensors instrumented for monitoring large civil engineering structures to the central data acquisition system is more complicated and difficult to handle.

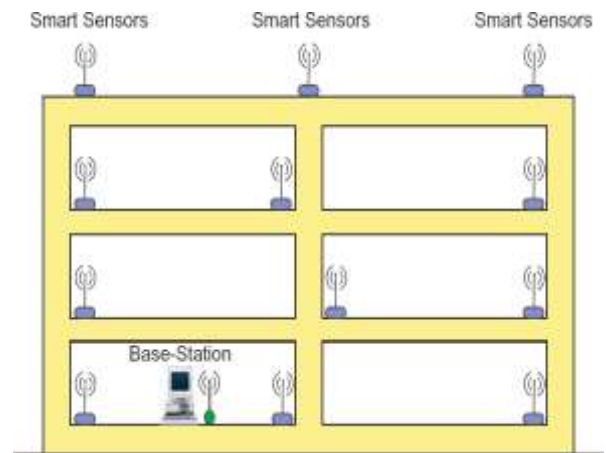


(Source: Spencer et. al. 2004)

Figure 1.1 Graphic representation of the wired structural health monitoring

The recent advances in the field of smart wireless sensors have led to SHM use many sensors. The essential part of a stylish wireless sensor is the microprocessor that reproduces the concentrator level calculations and brings the sensor to life. Programs can be developed and uploaded to the sensor's microprocessor, by which the smart sensors can record data locally at the node level, perform few computations at the node level, make decisions, extract only valuable information, send results to the control system, etc. As a result, a few computations can be performed at the node level to detect damage. Unwanted data, such as signal noise, may

be removed at the node level, minimizing the amount of data that must be transmitted to the central station, which is not possible for a traditional sensor device. Wireless data transfer is possible with smart wireless sensors that have wireless transmission capabilities. In Figure 1.2 a diagram of the system shown structural wireless monitoring.



(Source: Spencer et. al. 2004)

Figure 1.2 Graphic description of wireless structural health monitoring

Smart wireless sensor technology offers a distributed computing environment that can be used to develop efficient SHM strategies using damage detection algorithms. As a result, the performance of SHM can be improved by deploying a large number of low-cost smart wireless sensors and using their computational and communication capabilities. These smart wireless sensors provide critical data that can be used to detect, locate, and assess structural damage caused by heavy loads and environmental degradation. The data collected by these smart wireless sensors allows for a better understanding of the structural system's physical state.

2. WIRELESS SENSOR NETWORKS

In the last decade, enormous progress has been made in the area of structural health monitoring all over the world. In particular, the application of latest technology, involving a variety of sensors such as strain gauges, vibrating wire sensors, optical fibre sensors, Micro Electro Mechanical Systems (MEMS), Wireless Sensor Networks (WSN), vision-based measurement systems, data acquisition cards, and computer-based data analysis, has increased in particular. As opposed to the widely used traditional approaches for infrastructure control, this is a significant development. To fix the issues with conventional wired structural health monitoring, research has been conducted on the production of WSNs for structural health monitoring systems using smart sensors. Several benefits of wireless sensor

networks over conventional wired health monitoring schemes include:

Wireless connectivity: removes the need for expensive and vulnerable to failure cables to link remote sites to the monitoring station.

Fast deployment and flexible topology: Since the sensor network does not need any fixed infrastructure and forms its own network (an ad-hoc network), it can be set up easily. Similarly, the number and location of monitoring sites can be modified dynamically without re-configuring the network.

Low maintenance and operating costs: sensor nodes need very little on-site maintenance because they consume very little power, are durable, and can be reprogrammed and calibrated from a remote location.

A wireless sensor network involves a sensor, computational hardware and communication hardware. For monitoring purposes, a wireless sensor system can be mounted in a structure. A sensor network has four basic components:

- (1) An array of different kinds of sensors
- (2) A wireless node for communication between sensors and the base station
- (3) A local base station for data collection from the wireless nodes
- (4) A control station for post-processing data from various base stations

The best benefit of WSN in structural health monitoring is that sensing and computation can be done at the sensor node itself. Since SHM collects a large amount of data, data compression and synthesis algorithms are critical for data management. WSN is a multidisciplinary research field that includes communication and networking, signal processing, data management, user-friendly system architectures, power management algorithms, and platform technology (hardware and software, such as operating systems).

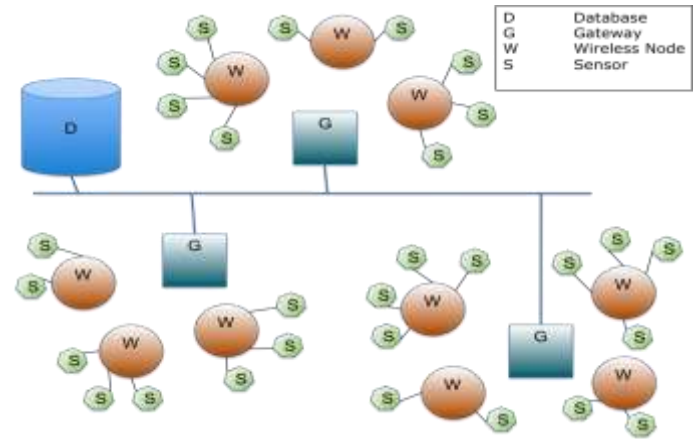


Figure 1.3 wireless sensor network

3. WSN ARCHITECTURE

Wireless Sensor Networks (WSNs) are dense wireless networks of compact, low-cost, low-power, distributed autonomous sensors that collect and relay environmental data to allow more accurate monitoring and control of physical environments from remote. In general, each sensor in a network is assumed to have certain constraints in terms of energy source, power, memory, and computational capabilities.

Each spatially dispersed sensor node interacts with one another in a WSN to forward their sensed data to a central processing unit/sink or to perform local coordination such as data fusion. The sink nodes have access to infrastructure networks such as the Internet, which the end user uses to retrieve the sensed data [QinghuaWang]. The most advanced networks are bi-directional, allowing sensor behavior to be controlled [Darpan, (April 2012)].

Figure 1 depicts two types of network topologies. Sensor nodes may form either a flat network topology, in which sensor nodes often act as routers, transferring data to a sink through multi-hop routing, or a hierarchical network topology, in which more efficient fixed or mobile relays collect and route sensor data to a sink. Seismic (by proximity to target), magnetic, thermal, visual (a line of sight to the target), infrared, acoustic (by propagation like a wave with potential bending), or radar are some of the sensor's mechanisms. Self-identification and self-diagnosis are also capabilities of smart sensors. Figure 1 demonstrates the basic topology architecture of a WSN.

The ideal wireless sensor network is said to be scalable, fault-tolerant, low-power, smart and software-programmable, efficient, capable of quick data acquisition, long-term reliable and accurate, low-cost, and maintenance-free [Neha.2012]

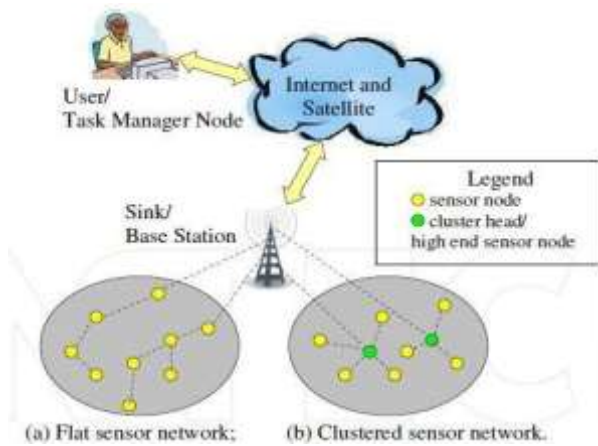


Figure 1.4: Typical network architecture for wireless sensors

4. ARCHITECTURE OF SENSOR NODES

A sensor network consists of the following components: a set of sensor nodes spread across a sensor field, a sink that communicates with the task manager through the Internet with users. A sensor network's basic component is a collection of sensor nodes. Due to the great promise and potential of applications shown by various wireless remote sensor networks [Akyildiz (2002); Arici & Altunbasak (2004); Mainwaring et. al.(2002); Delin (2001); Schwiebert et. al (2001); Korhonen et. al.(2003)], several researchers are currently working on developing pervasive sensor nodes. As shown in Fig. 1, a sensor node is made up of four basic components. A sensing unit, a processing unit, a communication unit, and a power unit are the four components.

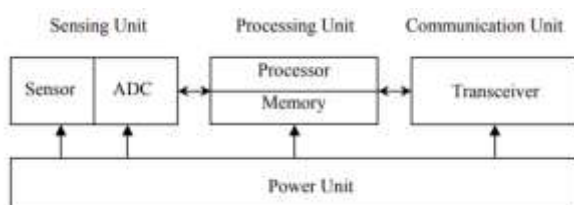


Figure 1.5: The components of a sensor node

Sensing units typically consist of application-specific sensors and ADCs (analog to digital converters), which digitalize the analog signals provided by the sensors when they detect a specific phenomenon. In certain situations, you'll even need an actuator.

Sensors, as the very front end linking our physical world to the computational world and the Internet, play an obvious role in a sensor network. Despite the fact that MEMS technology has advanced steadily in recent decades, there is still a lot of room for smart front end sensor growth. Among them, various chemical and biochemical sensors, such as sensors to detect toxic or explosive traces in public areas, sensors for diagnostic analysis, and sensors used in extreme conditions, remain one of the most

challenging sensor classes to explore and develop. New sensing principles, materials, and sensor designs must be developed and implemented. An embedded operating system, a microcontroller, and a storage component are typically associated with the processing device. It takes care of data processing, analyzes raw sensing data, and responds to individual user requests. It also manages connectivity and carries out a number of application-specific activities. For processing components, energy and cost are two major constraints. For particular tasks, nodes can have various types of processors. A video sensor node, for example, can require a more powerful processor than a standard temperature sensor. Another important consideration for an embedded system is a small embedded operating system, such as Berkeley's TinyOS. Aside from basic process and resource management capabilities, it may also provide software tailoring and real-time management capabilities, as well as support for embedded middleware, network protocols, and embedded databases.

The sensor node is connected to the network by the transceiver. Typically, each sensor node has the ability to send and receive data from other nodes as well as the sink. The task manager can communicate with the latter through the Internet (or satellite), and information is transmitted to the end user. The most power-hungry part of the node is the transceiver. Thus, in this material, the analysis of multi-hop communications and complex power-saving modes of operation, such as having several separate sleep states, is critical. The power unit provides power to all of the node's operating components. Because of the power unit's limited capacity, such as the battery's limited lifespan, the development of the power unit and the design of a sensor network's power-saving working mode remain two of the most significant technological issues. A solar battery may be used in some cases. A sensor node can also include application-specific functional subunits including a position finder, mobilizer, power generator, and other special-purpose sensors. Depending on the needs of the application, the type or number of such subunits can vary. It's an interesting area that should be explored continuously.

5. WSN IN STRUCTURAL HEALTH MONITORING

Structural health assessment techniques can be broadly classified into local and global techniques. Local techniques aims at finding highly localized damages in a structure. These techniques include ultrasonic, thermal, X-ray, magnetic or optical imaging techniques, but this type of inspection requires a significant amount of time, skilled manpower and disruption of the normal operation of the structure. Global assessment techniques assess the state of the structure by breaking down

its response to external excitation. The excitation can be environmental (wind loads, vehicle development in spans) or limited (using a vibrating shaker). In both cases, modular limits, such as characteristic frequencies, damping ratios, and modal shapes, are evaluated to distinguish between damage such as expansion, scour, erosion, etc.

As part of structural health monitoring applications, researchers have been developing and testing wireless sensor networks in recent years, where distributed sensors record the vibration responses in structures. Potential damage can, therefore, be localised and its extent can be estimated in real time. WSN is designed to address the constraints of existing SHM methods that rely on regular visual inspections or costly wired data acquisition systems. Salient features of WSN for Structural Health Monitoring applications are:

- WSN is a framework for structural health monitoring applications that incorporates recent developments in sensor technology, such as MEMS, wireless communication, and information technologies.
- WSN includes distributed sensor processing, which includes a central control station that can receive data from multiple sensor clusters instrumented in multiple systems in multiple geographic locations.
- Smart wireless sensor nodes with robust components and power management features can collect health monitoring parameters such as strain and vibration in real time on-site.

The wireless modules or mote are the essential elements of the WSN since they have the suitable equipment and the programmable memory where the customer can transfer the created application code. In recent times, a wide range of platforms have been established, particularly Mica2, Sunspot, Imote2 and Wasp mote, for different types of applications such as environmental monitoring, monitoring of carbon dioxide, traffic monitoring, etc. In essence, Motes has hardware components such as Microprocessors/Microcontrollers, Micro-Electro-Mechanical Systems (MEMS) sensor modules and communication devices (also called transceivers). Wireless sensor nodes provide with user-friendly operating systems to help with node operations. The user can develop application codes and upload them to the sensor node's memory for it to run properly using these operating systems.

6. CHALLENGES OF THE WSN IN STRUCTURAL HEALTH MONITORING

Some of the challenges in updating wireless sensor arrays in SHM are

- Sensor nodes must be distributed widely in order to obtain a broader perspective of structural behavior.
- Depending on the range of wireless communication, the topology of a sensor network varies frequently.
- Sensor nodes have power limitations, which is a significant major obstacle for long-term structural health monitoring.
- Since SHM requires the processing of large quantities of data, the sensor node's computational and memory capacities are also important.

Sensor networks use source-node processing, while a hierarchical processing architecture is used for others. Nodes also use computing capabilities locally to perform simple computations instead of sending the raw data to the nodes responsible for the data fusion, and then only distribute a subset of the data and/or partially processed data. In energy supply and radio channel transmission bandwidth, sensor nodes are nearly invariably limited. Energy awareness is required at all layers of a communications protocol stack to meet these challenges. Continuous and autonomous monitoring, and effective power management, are two important implementation problems in WSN designs. The solution is to set up a network that is only partially active during non-critical structural responses but completely active when higher response levels are measured. Power management isn't a major problem in a conventional wired sensor system. The sensors should be working at all times and should be able to be interrogated to obtain data at any time. In comparison to wired systems, power management techniques are one of the most important aspects of an effective WSN implementation. A solution to these problems is also being studied in order to achieve significant energy savings in sensor network applications.

7. RESEARCH EFFORT TOWARDS SHM USING SMART SENSORS

Some SHM applications with light sensors have been considered using scale models. The detected obligations include making information with a single wireless node, gathering information synchronized with other nodes, the preparation of information on board, etc. (2002, 2003) installed information management in a sophisticated sensor unit. A mica knot was fitted to measure the acceleration of a wave responses on both sides of its flown junction and then determine the relational coefficient of the responses to identify free vibration. Lynch et al. (2002) performed a Fast Fourier Change (FFT) to know the response of the five-step production

model in the replay room. Nitta et al. (2005) ran an AR model on the Mica2 and provisionally verified its legitimacy using a three-story building model. These investigations quickly showed the importance of high-performance sensor systems for SHM applications using simplified models.

Large-scale installations and expansions have also been the subject of skillful sensor research. Straser and Kiremidjian (1998) and Lynch et al. (2003) estimated the lateral reactions of the Alamosa canyon bridge to approve the presentation of their sensors. Galbreath et al. (2003) monitored a highway link on the LaPlatte River in Vermont using Microstrain's wireless strain sensor unit (Microstrain Inc. 2007). Aoki et al. (2003) estimated the response acceleration of a light pole on the Tokyo Rainbow Bridge in Japan. The information was sent to a safe over a WLAN. Chung et al. (2004) presented a DuraNode sensor unit at a Walker Connect at the University of California at Irvine. The information collected wirelessly was divided on a PC to obtain the initial three vibration modes. Ou et al. (2005) introduced eight mica nodes in the Di Wang tower in China. Lynch et al. (2005) introduced 15 units of light sensors on the Geumdang Bridge in Korea to measure the vibration response to stress. The FFT was freely applied to the estimation signals at the conscious sensor nodes and the results of the Fourier shift were reported to the base station. In the field of geotechnical research, Chen et al. (2005) suggested the use of a wireless MEMS-based vertical seismic cluster sensor called Terra-Scope. These exploration efforts have shown that glowing sensors can assess the acceleration of a large civilian infrastructure, but the nature of the information has not really been analyzed.

Thanks to research facilities and basic large-scale applications, the benefits of sensor settling time were realized. Straser and Kiremidjian (1998) reported that the installation of the wireless system at Alamosa Canyon Bridge took 30 minutes, which was much faster than the connection-based system. Lynch et al. (2003) upgraded shiny sensor units on a similar scaffold, and installation time was only a fraction of the opportunity to introduce the connection-based system.

Many researchers have also explored another way to use SHM to address innovations in wireless communication. Information is retrieved using a traditional wired security system and then returned to a remote safe via telephone, WLAN, or other wireless communication (Oshima et al. 2000; Mufti 2003; Karbhari et al. 2003). In any case, this system does not have the scattered built-in microprocessors, nor does it have the wiring costs to configure the sensors. Different methods should be used when the goal is a densely instrumented measurement.

8. DIFFICULTIES USING SMART SENSORS FOR SHM APPLICATIONS

Although many researchers have demonstrated the use of ingenious sensors for SHM applications, none of them have implemented an undeniable SHM system. Civil architects generally face challenges when upgrading SHM applications into expert sensors. For example, many of the systems on display cannot be used in many ways for countless active sensors. Some sophisticated sensors may not be able to obtain reliable estimation information due to sensor failures, timing errors, unfortunate information, etc. The important points are summarized here from the point of view of the SHM application.

1) Sensor equipment

Although only some types of sensors have been upgraded to sophisticated sensors, these sensors do not cover the wide range of sensors that civil engineers regularly need. For example, almost all experienced sensors have used a strain sensor, while strain is one of the important physical quantities by which underlying conditions can be assessed. Velocity or retraction sensors haven't seen any expert sensor app. At the moment when civil specialists cannot find the suitable sensors in the light sensor tables, it is necessary to change the sensor sheets. The open source steps make it easy to rebuild the sensor sheets. Although accelerometers are one of the most widely used sensors, their suitability for civil engineering applications is unclear. Customers cannot accept that MEMS accelerometer attributes are similar to traditional accelerometers. The increase in the speed of the vibrating tables or the response of the structural model was recorded with sharp sensors to observe the presentation of their accelerometers (Straser and Kiremidjian 1998; Lynch et al. 2002; Arici and Mosalam 2003; Casciati et al. 2003; Kurata et al. 2004; Ruiz-Sandoval 2004; Hou et al. 2005).

Limited affectability and high levels of motion are some of the timing issues with MEMS accelerometers. As the thickness of the speed of sound increases from one of the traditional piezoelectric accelerometers, PCB 393B04 (PCB Piezoelectronics, Inc. 2007), it is 0.04 μg that of the MEMS accelerometer used in many ADXL201 models (Analog Devices, Inc. 2007) is 200 $\mu\text{g}/\sqrt{\text{Hz}}$. The accelerometer on the Imote2 LIS3L02DQ sensor board (STMicroelectronics 2007) has a noise level of 50 $\mu\text{g}/\sqrt{\text{Hz}}$. This shaker tray is considered low enough for a high throughput scale test with a shaker or pathogen table. In any case, the relevance of estimating environmental vibrations of structures should be further investigated. Ruiz-Sandoval (2004) and Ruiz-Sandoval et al. (2006) used a high-sensitivity, low-motion accelerometer, SD1221 (Silicon Designs,

Inc. 2007). This MEMS-type accelerometer has a stirring force of $5 \mu\text{g}$ /. Ruiz-Sandoval (2004) has shown that this accelerometer is suitable for SHM applications. Customers must know the detection attributes of smart sensors.

The properties of the accelerometer must be carefully verified, especially in the low-repetition area, as this repetition involves significant vibration methods of civil infrastructure. The regular frequencies of tall structures, towers or long extensions can be as low as 0.1 Hz. Regarding the frequency of vibrations, the increase in speed during the run with few repetitions is small, which demonstrates the importance of a tall target and the ability to influence a recognition system. Ruiz-Sandoval (2004) and Ruiz-Sandoval et al. (2006) approached their sensor board with an extraordinary focus on the low repetition level. Despite the fact that many smart accelerometric sensors have been proposed, only a predetermined number of acceleration sensor blades can accurately measure low vibrations.

In addition to the sensor itself, the Analog-to-Digital Converter (ADC), the Anti-Aliasing (AA) channel, and the voltage regulator also affect the type of estimation signals. An ADC with a low target value devalues the estimated indicators with large quantification errors. For example, the Mica2 ADC only has a 10-part lens, which limits the dynamic range of the sensors. The configuration of the low pass channels is critical to detecting unassigned computer controlled flags. The flexible sensor voltage should be controlled so that current drawn by the microprocessor, radio, or flashing memory does not disrupt current flow to the sense segments. These segments must be consciously planned. Another thing is that it is not possible to extract reduced auxiliary information in hypothesis signs. Since these issues affect signal quality, brilliant sensor customers simply cannot accept that the detection attributes of a sensor node match those of a sensor segment.

In fact, even a large group of sophisticated sensors is certainly not an information-rich access point for SHM if the required physical quantities cannot be accurately estimated by each bright sensor. The development of sensor boards for SHM applications continues to be a major exploration problem, as does the fit of these sensor boards.

2) Total data

General information for SHM applications often encounters three related problems: 1) information size is excessive, 2) information can be lost during wireless communication, and 3) communication expansion is limited. Each of these problems is summarized below. Ultimately, smart sensors should not collect much information, while SHM applications use information obtained from various sensors with

high frequency inspection. The first smart sensor applications, such as monitoring the natural environment, only processed a limited amount of information about a rare place. Once again, SHM applications regularly receive several thousand houses of information, each of which is expressed as two- or four-byte information. Test frequencies greater than 100 Hz and inspection times greater than a moment are very normal. Given the need to process large amounts of information, SHM applications with smart sensors can be divided into two groups, neither of which has completely abused the sensor's capacity.

Smart sensors, like traditional wired sensors, are used in the primary collection, with all the preparation information collected in a uniform area (see Figure 1.6). Then, built-in SHM algorithms are applied to this information. This methodology takes into account the application of a large number of traditional SHM algorithms, which were examined. In all cases, as the number of alarmed sensors increases, the estimated information to be collected will exceed half the transmission capacity of the network, regardless of whether Grand Slam or Bounce communication is used.

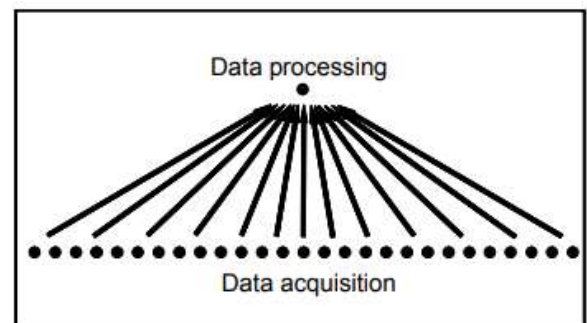


Figure 1.6: Central focus of purchasing information

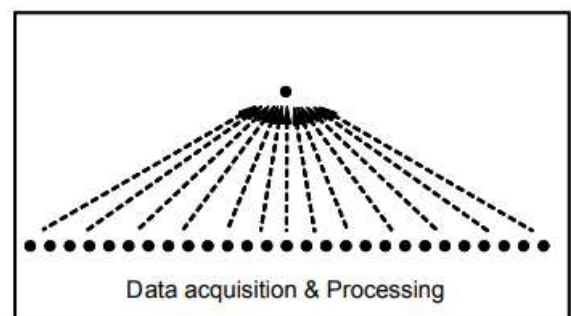


Figure 1.7: Independent approach to information processing.

However, as the number of smart sensors rises, the volume of measurement data that needs to be obtained centrally exceeds network capacity, regardless of whether homerun or hopping connectivity is used. The lack of scalability of this

strategy is a significant flaw. A tiered network is one solution to achieve scalability.

Chintalapudi, et al. (2006) used low-level nodes and high-performance high-level nodes. When the higher-level nodes have sufficient power, the power consumption is directed to the lower-level nodes. The multilevel networking approach is only relevant when powerful nodes are configured and the graceful force against these nodes is pragmatic.

Post-registration requires each alarmed sensor to measure and process information autonomously without exchanging information between neighboring nodes, as shown in Figure 1.7 (Sohn et al. 2002; Lynch et al. 2005; Nitta et al. 2005). Since only the information processing efficiency is returned to the base station, the communication required can be minimal. Therefore, this method can be adapted to countless bright sensors. In any case, the free sensor node approach does not use the information that can be accessed from neighboring nodes. All spatial information is ignored. For example, information on fashion modules cannot be recorded or used in this methodology. Information from different types of sensors associated with independent nodes cannot be combined. The inability to process attached spatial information in this way limits its adequacy.

Gao (2005) proposed a Distributed Computing Strategy (DCS) for SHM, which provides a customizable methodology that can be used to consolidate spatial information. With respect to the Damage Locating Vectors (DLV) strategy (Bernal 2002), this DCS approach should not be halfway between the collection and examination of the estimation information. Rather, the DCS shares information between neighboring nodes to use spatial information. Because this neighbor information communicates with limited numbers of neighboring nodes, the total amount of information that is sent over the network is kept low. Therefore, this SHM system can be adapted to countless sensors that are sent densely over huge structures. Although DCS does not require measurements on all DOFs, the representation of the strategy improves with the estimated amount of DOF. PC review and test approval on a rebuilt wireless network showed DCS to be a promising SHM conspiracy. However, this method has not yet been updated and tentatively tested for experienced sensors.

For SHM applications, data loss during wireless communication is also a concern. Unless missing packets are resent, wireless communication suffers from packet loss. Data loss was recorded by Kurata et al. (2004) during shake table experiments. Many civil engineering systems that use smart sensors struggle to fix the question of data loss. Some clearly neglect missing data, while others, by accident, receive all packets during experiments. SHM methods developed so far, on the other hand,

suggest that data obtained at sensors is usable for data processing at the base station. The effect of missing data on structural research has not been extensively analyzed. To solve this dilemma, Mechitov et al. (2004) used a dependable communication protocol. The transmission speed is slower than contact without acknowledgment because acknowledgment packets are sent regularly. SHM technologies using smart sensors are expected to progress when secure connectivity networks capable of transmitting vast volumes of data become available.

Smart sensors have a contact spectrum that is normally shorter than the scale of civil infrastructure. Multihop connectivity is used for gathering data or transmitting commands to smart sensor nodes on systems. Prior to multihop contact, a routing route must typically be determined (Mechitov et al., 2004). If a communication route between two randomly chosen nodes is required, each sensor node must create a very large table to store routing paths. Routing could be aided by application-specific connectivity skills, such as data collection and distribution to a sink node. Multihop communication may begin after paths have been discovered. The routing path, packet layout, overhead information, and other considerations must all be carefully considered..

3) Time synchronization

Structures that are automatically evaluated presume the data is coordinated, which is not always the case for smart sensor networks. Several synchronization protocols have been proposed. They provide synchronization precision of tens of microseconds in certain instances. The effect of SHM on time synchronization accuracy, on the other hand, has not been explored. Civil engineers may incorrectly assume that a time synchronization error of less than a millisecond is appropriate since normal frequencies of structures used in analyses are normally below 10 Hz. Prior to deployment, SHM techniques must be checked for time synchronization error.

4) Limited computational capability

Any SHM programs use numerical operations that require a lot of computing power and memory. This group contains approaches that include the manipulation of large matrices, such as ERA. Since smart sensors have limited battery space, these approaches are either difficult to incorporate or have limited performance (Chintalapudi et al., 2006; Nagayama et al., 2004).

5) Power

When it comes to civil infrastructure monitoring, electricity use is a big deal. Structure monitoring could have better access to power sources than

other smart sensor applications (such as habitat monitoring). Buildings have electrical sources, and many long bridges have power for light poles and other uses. However, wiring electricity to a huge range of sensors takes a long time and raises installation costs, negating one of the smart sensor's key benefits. Furthermore, the location of sensor placement on a structure is not necessarily similar to a power source. It's likely the usable power would need to be transferred to a compatible voltage and frequency. Any systems are powerless. As a consequence, the availability of a power supply cannot be assumed. Smart sensors with batteries are advantageous and, in many situations, the only alternative.

It's likely that smart sensors' batteries won't be quickly replaced until they've been installed on civil networks. Any nodes could be installed in inaccessible locations. The replacement of batteries in smart sensors is not a standard repair operation. SHM devices, on the other hand, use more electricity than other wireless sensor applications, limiting battery life. So far, no permanent battery-powered smart sensor solutions for SHM have been introduced. Many researchers are trying to find a solution to this problem; one interesting method is power harvesting.

9. SOME CHALLENGES, DESIRABLE PROPERTIES, AND APPROACHES OF SHM SYSTEMS WITH SMART SENSOR

Characteristics must first be developed for a SHM system using smart sensors. Many researchers have been working on a SHM that uses smart sensors through a variety of methods. Some researchers only use the ability to communicate wirelessly, while others stress the use of the embedded microprocessor. Assumptions often differ widely about the type of power source. The desirable features for a SHM strategy implemented on a smart sensor network are set out herein and serve as guidance for this review.

The challenges, desirable properties, and approaches of SHM systems are summarized in Tables 1 and 2. The following section describes the adaptability of the sensor sheets, which favors the accessibility of the corresponding sensors.

Table 1 SHM difficulties with smart sensors and approaches.

Difficulty	Approach
Sensor hardware	- The Imote2 sensor board, which has a triaxial accelerometer, is employed. The performance of the accelerometer is compared with reference sensors. - Sensor board customizability is demonstrated.
Data aggregation	- Model-based data aggregation is proposed. - DCS for SHM allows distributed data processing, eliminating the need for centrally collecting a large amount of data.
Time synchronization	Synchronized sensing middleware service is proposed.
Limited computational capability	- Computational tasks are distributed by employing model-based data aggregation and DCS for SHM. - The Imote2 has a relatively fast microprocessor as well as large RAM.
Power	- Power consumption is kept moderate by employing DCS for SHM and model-based data aggregation. - CPU clock frequency is switched depending on tasks to perform. - Power harvesting is not addressed in this research.

Table 2: Desirable Characteristics and Approaches

Desirable characteristic	Approach
<i>Scalable resource aware system</i>	
Scalability	DCS for SHM and model-based data aggregation offers scalability
Power awareness	- RF and flash memory usage are kept moderate through DCS for SHM and model-based data aggregation, as well as implementation ingenuity. - The homogeneous hardware configuration of the network potentially offers reassignment of roles based on available power.
Bandwidth awareness	- RF communication is managed by manager node and cluster heads. - Reliable communication protocols, which wait for longer intervals in a congested communication network, are developed.
Memory awareness	SHM system is designed so that request on memory usage does not exceed the currently available memory size of the Imote2, 256 kB.
Computational power awareness	- Computational tasks are distributed by employing DCS for SHM and model-based data aggregation. - The frequency scalable processor on the Imote2 is utilized to make efficient use of computational power.
Modal operation	- Smart sensors get ready to enter sleep mode. - TinyOS which support modal operation is employed.
<i>Autonomous distributed embedded computing</i>	
Model-based data aggregation	Model-based data aggregation is proposed and implemented.
Collaborative distributed data processing	DCS for SHM and model-based data aggregation realize collaborative distributed data processing.

Desirable characteristic	Approach
Autonomous initial configuration and maintenance	• Not realized in this thesis.
Fault tolerant system	
Message packet loss tolerance	• Reliable communication protocols are proposed.
Node failure tolerance	• The homogeneous hardware configuration of the network potentially addresses the node failure.
Byzantine error tolerance	• Not realized in this thesis.
Desirable algorithmic characteristics specific to SHM for civil infrastructure	
Multi-scale information	• Not realized in this thesis.
Collaboration in local sensor communities	• DCS for SHM and model-based data aggregation offers this collaboration.
Redundancy	• DCS for SHM gives redundancy through overlapping clusters.
Multiple functions	• Baseline measurement and continuous SHM of a structure are implemented on smart sensors. • Rare event monitoring, traffic monitoring, local weather monitoring etc. are not realized.

Desirable characteristic	Approach
Desirable platform characteristics specific to SHM for civil infrastructure	
Appropriate sensor availability	• The Imote2 sensor board, which has a triaxial accelerometer, is employed. The performance of the accelerometer is compared with reference sensors. • Sensor board customizability is demonstrated.
Sufficient RAM, flash memory, and RF bandwidth	• The Imote2 has relatively large RAM and flash memory. • The Imote2 has a ZigBee compliant RF component. The throughput is larger than RF components on other smart sensor platforms such as Mica2.
Environmentally hardened	• Not realized in this thesis.
Open source OS and interface	• TinyOS is employed.

10. CONCLUSION

Structural Health Monitoring (SHM) techniques attempt to efficiently identify, locate, and evaluate damage caused by extreme loading events and progressive environmental degradation by measuring structural response. The structural response is a representation of both the structural state and the excitation force. SHM strategies are expected to reveal structural position, such as the presence of damage, by analyzing response data. SHM has seen a lot of study in mechanical, aerospace, and maritime applications, as well as civil engineering. When it comes to deploying wireless sensor networks (WSNs) for structural health monitoring (SHM), sensor placement is important. Existing civil engineering approaches do not take WSN constraints like communication load, network connectivity, or fault tolerance seriously. This paper provided a theoretical study of WSN-based SHM systems. Background information on structural health monitoring was addressed here. The rapid growth of wireless sensor network (WSN) technology provides us with a novel approach to real-time data acquisition, transmission, and processing.

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