Wireless Structural Health Monitoring and the Civil Infrastructure Systems: Current State and Future Applications

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Abstract

Significant developments have taken place over the years with the first proof of concept of a wireless accelerometer accomplished in 1995. Since then, improvements of the initial system have been continuously taking place leading to the design of a more comprehensive system that includes a sensing unit that can accommodate multiple sensors, a wireless communications network that is reconfigurable for different applications, embedded algorithms for controlling the system and diagnosing problems and a decision support front –end that provides information and suggests follow-on actions to technical personnel and manages. In this paper we summarize the main components of these wireless structural health-monitoring systems with a specific focus on the development of the prototype decision support system. The development of damage-specific sensors as well as robust damage diagnosis algorithms is seen as imperative for future adaptation of such systems.. The paper concludes with a discussion on the current limitations of wireless monitoring systems and makes recommendations for future direction in order to advance the state of the art.

Keywords: structural health monitoring, sensing units, damage diagnosis, decision support

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1. Introduction

Wireless structural monitoring sensors were first introduced in 1995 [1] with a proof of concept conducted in parallel to a conventional cable-based system on a bridge in Alamosa Canyon, New Mexico. Since that experiment, there have been continuous improvements of the initial system by adding new features and updating it with newer more robust hardware and software components [2-5]. Currently, development of wireless structural monitoring sensing systems is being conducted throughout the world with variety of applications in mind. These developments are the result of clear recognition of the advantages of wireless communication over the legacy cable-based systems. One of the main advantages is the reduction in the overall cost of a monitoring system by as much as 30% due to elimination of communications cabling and installation, compact and less costly sensors, as well as increased transmission distance, bandwidth and overall reliability of the radios and wireless networks that can be used for wireless communication. A second advantage is the ease of installation. Another advantage is the scalability of the network system that can easily be increased in size with actual reduction in overall cost due to reduction on per unit cost and no additional cabling costs. Finally, the on-board computational feature of the sensing unit design provides for a rapid localized evaluation that can lead to a more direct damage diagnosis and prognosis.

Our most current wireless structural monitoring design incorporates a sensing unit, embedded damage diagnosis algorithms, wireless communications network, and a decision support system. In this paper we present a summary of the current system, the results of several laboratory tests, and discuss the challenges for wide practical applications. We conclude with some ideas for future directions in the development of wireless structural health monitoring.

2. Components of structural health monitoring system

Traditionally structural monitoring has consisted of a sensor, recording device and data reporting. These systems have functioned primarily with the objective to deliver data that can then be used subsequently for analysis of the structure and possibly for identification of damage. Our aim has been to design a comprehensive system that not only delivers data but provides information that is useful in making decision regarding the functionality and usability of the structure. Thus, our system consists of an intelligent sensing unit or sensing node, complex wireless communications network and a decision support system as identified in Figure 1.

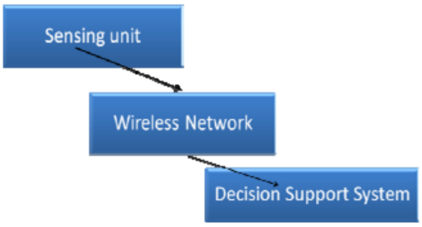


Fig. 1. Components of a comprehensive structure monitoring system..

In the following sections we briefly describe these components.

2.1. *Sensing Unit Design*

The sensing unit or node has the capability of accommodating multiple sensors such as different accelerometers, strain sensors, temperature and humidity sensors or other sensors as examples. The intelligence of the sensing node is provided through a dual microprocessor design. The first microprocessor serves and the monitor of the unit and performs basic functions such as puts the unit into sleep mode or wakes it up, it tells the sensors to start gathering data, it sends the data to a storage unit which typically resides within the unit. The second microprocessor has embedded algorithms that include signal filtering and cleansing and damage assessment. The sensing unit also houses the radio for wireless data transmission, communication with the central decision support system and downloading updates or new software residing on the microprocessors. The final component in the unit is the storage devise consisting of an SD card where all data and results of analysis are stored in a pre-defined database. Figure 2 shows the main components of the sensing unit or node.

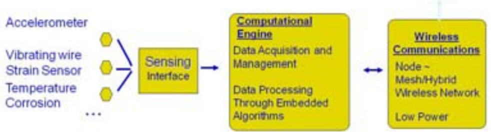


Fig. 2. Components of the sensing unit..

2.2. *Wireless Communications Network*

The wireless network is the system by which individual sensing units communicate among themselves and with the central control and command center. The fundamental building blocks of the wireless network are the sensing unit with its wireless radio, routers and coordinator. The radio in the sensing unit has both, receive and transmit functions, and as such can serve as the router. Simple radio units, however, were developed, however to serve as routers to increase transmission distances and further reduce the possibility of dropped signals. In the past fifteen years we have seen considerable developments in wireless networking protocols and supporting software that enable wireless radios to transmit information through that network. While some radios come with Zig Bee compliant software, oftenj such software is rather limited and additional or totally independent networking software needs to be developed. The most frequently used topologies for these systems are the star and mesh formations. In reality, a hybrid network which combines the star and mesh topologies need to implemented. The hybrid network allows for greater flexibility in network design. For example, a star formation can be used at a substructure level and then the mesh network can be applied when the various substructures are combined forming a hybrid wireless network. As will be described in subsequent sections, such a hybrid wireless network was developed and deployed during the test on a quarter-scale four-span and three-pier reinforced concrete bridge.

2.3. *Decision Support System*

In our design, the data and information are transmitted into the decision support system. However, the decision support system serves more purposes than just as a repository of data and information. The decision support system is the command and control center for the overall system. It performs the following functions:

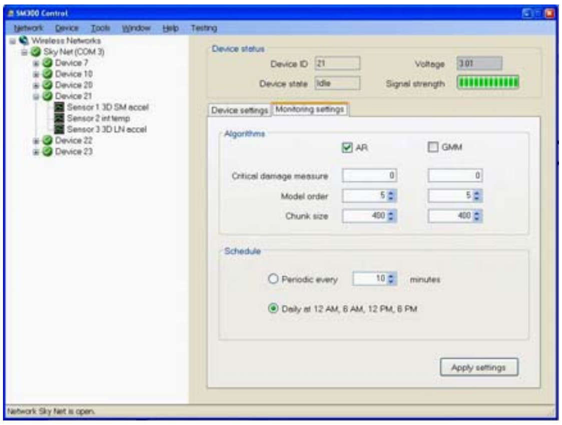
- Serves as the communications centre between the user and the sensor network where information can be transmitted to a sensing node or retrieved from a sensing node. Alternatively, as new sensors are added or the network is modified communication is established through the decision support channels and the system is accordingly modified.
- Stores information on each sensing unit such as location of the sensing unit, number and type of sensors, amount of local storage, wireless transmission distance, and type and capacity of battery, for example.
- Stores information on the structure – geometry, material properties, member sizes, connection types, year of construction, etc.,
- Archives the information in a database that can be easily accessed either remotely or at the command centre.
- Has a graphical interface for delivering all information in an easy visual format.
- Serves as the alert centre where assessments of data are reported and alerts are issued.
- Provides recommendations for follow on actions are made to corrective action.
- Enables web services for wide distribution of alerts and other information and remote access by operators and other users.

Figure 3 shows an example of the wireless network control window. This window serves to define:

(a) the device status,

(b) the device settings
(c) the monitoring settings.

Under the device status, information is provided on the device ID number, the device functionality status (i.e., idle, collecting data, non-functional), the strength of the wireless signal, and the remaining battery life. Under the device settings, two types of functions are included – algorithm selection and device scheduling. The user has the ability to select from several embedded damage algorithms and the parameters for these algorithms. It is important to recognize that this part of the decision support system will need to be set by a user who is intimately familiar with the algorithms to be used in order to set the proper parameters. Default values, of course, can always pre-set or, alternatively, a drop down menu can be provided giving additional information on logical or desired values for the algorithm parameters. In the figure, two algorithms are listed that have been embedded on the sensing node – the autoregressive (AR) and the Gaussian Mixture Model (GMM) algorithms. These algorithms are discussed in greater detail in [2-5] and are not included in this paper.



Device status
Device ID 21
Voltage 3.01
Device state Idle
Signal strength

Algorithms

	☑ AR	☐ GMM
Critical damage measure	0	0
Model order	5	5
Chunk size	400	400

Schedule
○ Periodic every 10 minutes
● Daily at 12 AM, 6 AM, 12 PM, 6 PM

Network Sky Net is open.

Fig. 3. Wireless network control window

The monitoring schedule can be defined on this window in addition to the algorithm selection. The choices currently include often should measurements be taken – once every day, three times a day, etc., or the specific times within a 24 hr time frame, and the duration of measurement – 60 seconds, 2 minutes, etc. The monitoring schedule will depend on the type of structure, the importance of the structure, its geographic location and the desires of the owner/operator. A monitoring schedule can be changed at any time by the operator providing flexibility to modify the operations of the system as information on its operation becomes increasingly more available. An example of a monitoring schedule is: “collect ambient acceleration data four times a day every Sunday”. For this schedule the user will set the day of the week, the times when the data collection is performed and the algorithm to be used after that collection. The decision support system sends a signal to the sensing units in the network at the set time and day, instructs them to start collecting data. The sensing unit, collects the data, stores it on the miniSD card and runs the damage algorithms that have been assigned to be used with that data collection. If damage has been identified, then the sensing unit sends an alert back to the decision support system with the parameters of the damage detection algorithm, an estimated alert level as described earlier and a confidence level for that alert level. The result is a color display on the graphical user interface of the decision support system. Seasonal changes can be accommodated by setting different schedules at different times of the year. Similarly, collection times during a 24 hour period can reflect variations in temperatures and humidity.

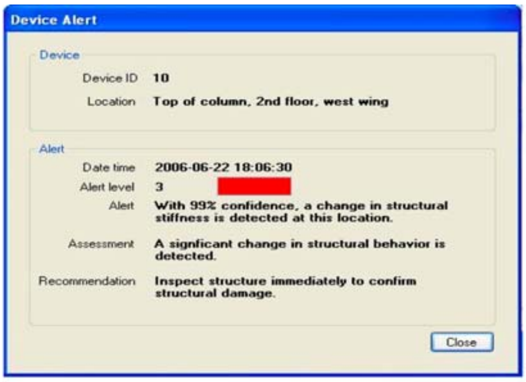
Figure 4 shows an example of the visual interface for the decision support system. The system, in general can be used for many different structures and as an alert is issued by a specific monitoring system on a structure in the portfolio, the user can click on the side bar with that structure and bring the structure in full view. A typical window shows the structure with information on the sensing node locations and the various alert issued by a particular sensor.

Network: Bay Bridge
View: UndersideView

Fig. 4. Example of a window from the decision support system showing the structure with the location of the sensing units showing red and yellow alerts issued by particular nodes.

Figure 5 shows the window with the specific structure and the sensing node locations. The different colouring indicates various levels of alerts. As an example, the green, yellow and red colouring at the sensing nodes on the bridge correspond to none, moderate and high alert levels, respectively. When a sensing node is selected then a secondary window drops down showing the sensing node location, the type of sensors present at that sensing node, the sensor(s) that are indicating the alert level, date and time of alert issue, and possible recommendations are made for follow up actions. Various enhancements have also been implemented such as alert confidence level.

Figure 5 shows an example of the drop down window capturing the information. This information in these windows was developed for a system with 20 sensing nodes expandable to 100 nodes. The system could easily be scaled to several thousand nodes without any difficulty. For each node, the information shown on this window can be retrieved through the decision support system.


Device Alert

Device

Device ID: 10

Location: Top of column, 2nd floor, west wing

Alert

Date time: 2006-06-22 18:06:30

Alert level: 3 🟥

Alert: With 99% confidence, a change in structural stiffness is detected at this location.

Assessment: A signficant change in structural behavior is detected.

Recommendation: Inspect structure immediately to confirm structural damage.

Fig. 5. Example of a drop down window from the decision support system showing the information produced at a sensing node with the location of the sensing units showing red alert and other relevant information.

In addition to the scheduled data collection and structural assessments, the user/operator can request these operations on demand. Table 1 shows the list of the commands that the operator will follow when performing this function.

Table 1
Initiation actions for network system

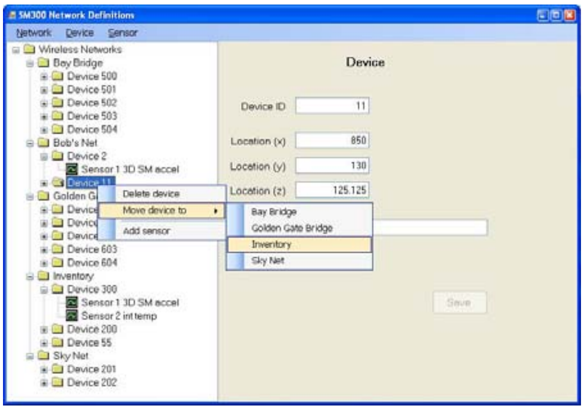
Network-level actions
- Open network

Device-level actions
- Ping device
- Get settings
- Begin/abort manual data collection
- Single analysis

Other actions
- "Assisted" data collection
- Monitoring
- Network definitions

Another critical operation that is performed within the command and control mode of the decision support system is the monitoring the functionality of the sensor system. In this mode, the operator broadcasts a signal to the sensing units in the system and requests information back on the status of the sensing units. If a problem is detected at a particular sensing unit, the return code identifies the sensing unit ID, its location, and the specific sensors that are not functioning. In addition to the sensor operational status, the display shows the status of the power supply. If the power supply of the sensing unit reaches a critical point, then an alert is issued advising appropriate action such as replacement of battery or providing alternate power source.

Prior to these operations, however, the user needs to set up the network. This function is performed within the network definitions window shown in Figure 6. It is within this window that the device ID is specified, its location is identified, and the sensor types that are present on the unit are listed. These operations are not necessarily accessible to the everyday operator/user for security purposes.


SM300 Network Definitions

Device

Device ID: 11

Location (x): 850

Location (y): 130

Location (z): 125.125

Fig. 6 Network definitions

The final function of the decision support system is to serve as the web portal. Through the web portal, information on the system status, damage alerts or power alerts can be broadcast via the internet to appropriate authorities. Similarly, authorized users can access the decision support system remotely and check on the monitoring system status or on the structure status.

Other features can easily be added to the system as those become apparent. In addition, the system can be augmented or modified depending on the particular application or use.

The various features of the sensing network and the decision support system were tested under laboratory conditions as described in the next section. In addition to the laboratory test, the system was also tested in a field experiment conducted by the US Army Corps of Engineers that evaluated a section of the levee in New Orleans, Louisiana. A tilt algorithm was developed specifically for that test and was embedded in the units to measure the slope of the levee as the water in a cofferdam built adjacent to the levee was increased to various levels simulating potential flooding as a result of a hurricane or excessive rainfall. Both tests demonstrated the feasibility of the wireless network system under laboratory and field conditions and well as showed the utility of the decision support system.

3. Conclusions and Discussion

In this paper, the design and implementation of a wireless structural monitoring system is briefly presented. The focus of the paper is on the development of the decision support system. The main function of the decision support system is to serve as the command and control centre for one or more structural monitoring systems. It provides the visual interface through which the system functions can be defined or modified and through which information from the system is delivered to the user/operator. Moreover, the decision support system can be designed to make recommendations for follow-on corrective actions once an alert is issued informing the user/operator that potential damage has been identified. It is important to recognize that with the increased ease and efficiency of wireless systems, one of the main impediments to the implementation of such systems in practice is the ease with which the system can be operated and the delivery of information rather than row data. A repeated complain of facility operators and managers is that monitoring systems do not provide information, only row data that then requires expertise for interpretation.

Thus, in addition to a robust decision support system, it is imperative that appropriate damage detection algorithms be used to enable the extraction and delivery of reliable damage diagnosis. In general, such a diagnosis should (a) identify that damage has occurred, (b) should provide the location of where damage has occurred, and (c) should either describe the type of damage or provide the degree of damage based on some relative measure. This component of the overall structural monitoring system, whether wired or wireless is still most lacking and challenging.

Although there research on damage detection algorithms has been conducted for more than three decades, robust damage detection algorithms are still lacking. Global methods that rely on system identification techniques are computationally tasking and are particularly challenging for implementation with wireless systems. The first issue is that, in order to perform system identification, it is necessary to download the data from all the sensors. These data then have to synchronized and analyzed on a powerful computer. Repeatedly downloading data from wireless sensing nodes will deplete the battery greatly reducing its life. Even if all data are downloaded, the computational effort to identify damage using these methods is often prohibitive particularly when more than two damage locations are present in the structure. This is even greater if damage id to be quantified.

Over the past decades, significant effort has been devoted to the development of damage detection algorithms that utilize statistical pattern recognition methods. Such methods have increasingly been used for DNA identification and for various other damage analyses. However, no one method can address the variety of damage patterns that can be found in a structure. Most of the current methods utilize vibration, temperature and humidity measurements and thus, the damage is typically related to member damage or larger joint damage, such as large brakes or softening of a member. Such methods, however, cannot detect cracks at the welded joints of a steel frame, as an example.

What has become apparent is that, it is first necessary to develop an array of sensors, each with a specific damage detection purpose. For example, we need sensors to detect cracks in steel joint, different sensors to detect corrosion initiation in steel rebars in RC members, direct displacement sensors, and so on. Then, these sensors can be placed at appropriate locations on a structure and statistical pattern recognition-based algorithms can then be developed for each sensor. This type of approach will not only enable direct identification and characterization of damage, but will also provide information on location as the sensor ID will directly point to the damaged area. It is thus recommended that significant effort be devoted to the development of appropriate damage specific sensors, and then development of appropriate algorithms.

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References

[1] Lynch, J.P., Wang, Y. Lu, K-C., Hou, T-C. and Loh, C-H. (2006). "Post-Seismic Damage Assessment of Steel Structures Instrumented with Self-Interrogating Wireless Sensors," *Proceedings of the 8th National Conference on Earthquake Engineering* (8NCEE), San Francisco, CA.

[2] Nair, K.K. (2007). *"Signal Processing Based Damage Detection Algorithms for Structural Health Monitoring"*, Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305

[3] Nair, K.K., Kiremidjian, A.S. and Law, K.H. (2006). "Time Series-Based Damage Detection and Localization Algorithm with application to the ASCE Benchmark Structure," *Journal of Sound and Vibration*, 291(2), 349-368.

[4] Nair, K.K. and Kiremidjian, A.S. (2007). "Time Series-Based Structural Damage Detection Algorithm Using Gaussian Mixtures Modeling," *Journal of Dynamic Systems, Measurement*, and Control, 129, 285-293.

[5] Noh, H., Nair, K.K., Kiremidjian, A.S and Loh, C-H. (2007). "Application of a Time Series-Based Damage Detection Algorithm to the Taiwanese Benchmark Experiment," *International Conference on Applications of Statistics and Probability in Civil Engineering*, CD Rom, Chiba, Japan. ISBN 978-0-415-45211-3

[6] Straser, E. G. and Kiremidjian, A. S. (1998) Modular Wireless Damage Monitoring System for Structures, *Technical Report No. 128,* John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.

[7] Wang, Y., Lynch, J.P. and Law, K.H. (2006). "Wireless sensing, actuation and control with applications to civil structures," *Intelligent Computing in Engineering and Architecture* (Ed. Smith, I.F.C.), Springer, Berlin, Germany