Wireless Sensor Network and its Application in Civil Infrastructure

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Abstract - Civil engineering infrastructures are designed using standardized building codes and design methodologies for public use. But structures are often subjected to long term structural deterioration due to harsh loading and environmental conditions. Several attempts, ranging from the traditional wired mechanisms to autonomous wireless systems, have been made to examine the health monitoring of these infrastructures. This paper reviews the trends in autonomous health monitoring with wireless system networks. A brief introduction to the problem was presented and thereafter, architectural design of a typical wireless sensing unit was described. Wireless network topology and with optimal sensor arrangement were also described, to achieve the most efficient configuration for health monitoring. Applications of these systems in famous buildings, bridges, dams, turbines and pavements were also reviewed. This gives an overall insight to the application of wireless systems in structural health monitoring.

Key Words: structural health monitoring; wireless sensor; civil infrastructures; bridges; building; dams; pavements; turbines.

1. INTRODUCTION

Civil engineering structures such as bridges, buildings, roads, dams etc, are designed using standardized building codes and design methodologies for public use. But structures are often subjected to long-term structural deterioration due to harsh loading, environmental conditions (strong winds, heavy rains, high humidity, huge temperature variations) and to catastrophic events (earthquakes, hurricanes, floods) such as Northridge (1994), Kobe (1995), Izmit, Turkey (1990), Kashmir, Pakistan (2005), Nepal earthquake (2015) and so on [1]. The I-35W Mississippi River bridge collusion during the evening rush hour on August 1, 2007, is another typical example with at least 7 people being killed, more than 60 injured, and 20 people missing [2].

According to ASCE Infrastructure Report Card 2017, 56,007 number (9.1% of total number of bridge 614,387 bridges) of the nation's bridges were structurally deficient in 2016. Average 188 million trips are made across a structurally deficient bridge each day, and $123 billion needs to be spent on bridge rehabilitation [3]. Figures 1 and 2 below summarizes the comparison of deficient bridges between years 2010 and 2016 according to the US National Bridge Inspection Survey. These suggest that bridge health monitoring and repair are imperative and advanced quantitative methods to locate damages are of pressing importance. Manual inspection of civil engineering structures is time-consuming, dangerous to the personnel who takes the inspection, sometimes, it is hard to reach to inspection location, and very expensive. For example, biannual visual inspection cost of Brooklyn Bridge in New York is about $1 Million [4]. Hence, an autonomous monitoring system such as wireless sensor networks (WSN) is required to as an alternative to the manual inspection approach.

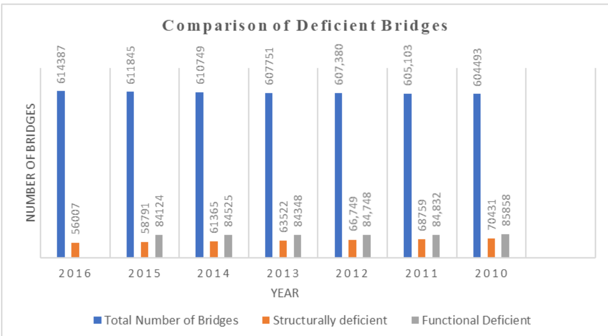

Figure 1: Number of deficient bridges from 2016 to 2010 years [5].

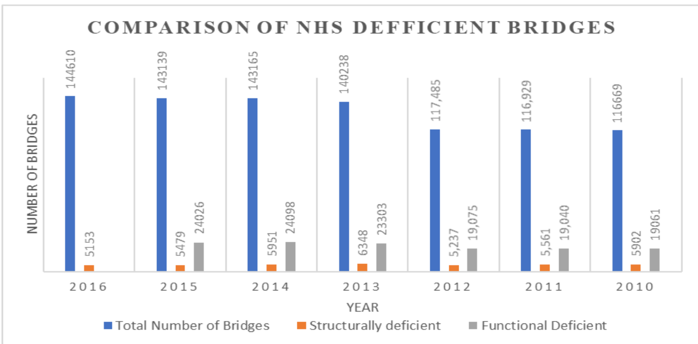

Figure 2: Comparison of NHS deficient bridges from 2016 to 2010 years [5].

Identification of potential problems of civil engineering structures at early stage and improvement of those problems can prevent tragic incidents [6]. The SHM systems through wireless sensor networks (WSN) provide an opportunity to repair, reduce the maintenance cost and retrofit of the structure through its lifetime. Traditional SHM approaches suffer from problems like expensive sensor installation/wiring, signal degradation along lengthy cables, and data flooding. With the rapid wireless technology systems, WSN offers low-cost instrumentation with fast and dense deployment and easy maintenance of sensors. It increases the accuracy of the collected SHM data using their onboard computational and wireless communication capabilities [7]. Kiremidjian and Straser (1998) were the first who used the wireless sensor for structural health monitoring to reduce the health monitoring cost [8].

Advantages of wireless sensor instrumented structures are: evaluation of the behavior of structure in service condition, dynamic characteristics determination, structural performance monitoring at induced excitations, structural design security revision with previous regulation, detection of potential danger due to the damage in the structure, collected information can be used for hypothesis verification and results of diverse mathematic models (for example allows calibrating of finite element method), extrapolation of the actual response of the structure for expected a strong earthquake, and facilitate the decision makers to make repair, maintenance or rehabilitation as a safeguard of the occupants [9].

The two approaches of SHM are direct damage detection (including visual inspection, x-ray, etc.) and indirect damage detection (detecting changes in structural properties or system behavior) [7]. This paper describes the indirect damage detection of SHM through the measurement and interpretation of ambient vibrations and strong motion by WSN.

2. Overview of Structural Health Monitoring paradigm

The goal of structural health monitoring includes; detection of existence of damage on the structure, locating the damage, identifying its type, and quantifying the magnitude of severity. These can be achieved using different methods. However, regardless of the method adopted, health monitoring of structures is executed in three broad phases namely; data acquisition phase, feature selection phase and statistical model development phase. In the data acquisition phase, the health monitoring data is identified. This data is refined and process for the subsequent phases. In the second phase, a decision is made about the features of the data that are best for damage detection. In the last phase, a statistical model for classifying damages is developed. The processes involved within these broad phases are summarized in figure 3 below.

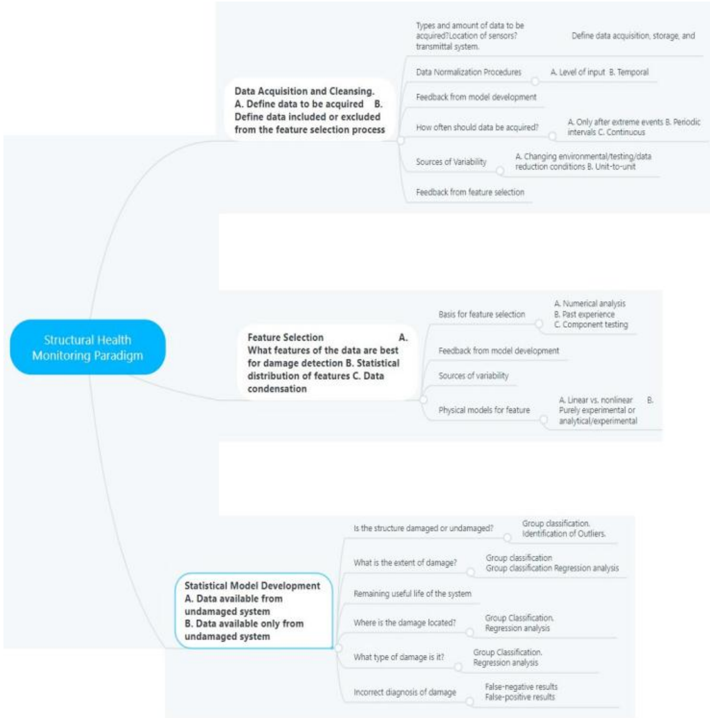

Figure 3: Structural health monitoring paradigm [10]

3. Architectural design of wireless sensor unit

There are three functional modules of a hardware system of wireless sensor unit. These are data acquisition system (sensing interface), computational core, and wireless communication channel.

(a) Data acquisition subsystem

Data acquisition subsystem collects sensor data with equivalent accuracy. For capturing high-order global response mode of structure the sampling rate should be 500Hz to 1-2KHz and for low-order global response mode, the sampling rate should be below 100Hz. The design generalization of data acquisition system should not be specified for any one type of sensor; rather it should design for any types of sensor data acquisition. The resolution of an analog-to-digital converter (ADC) with at least 16 bits resolution to convert analog sensor output to digital data. The microelectromechanical system (MEMS) sensor provides outputs modulated by digital square wave [11].

(b) Computational core

The computational core controls the overall operation of the sensing unit, such as the collection of data from the sensors, executes the embedded algorithm, and manages the wireless data flow within the wireless communication medium. The computational core is an assemblage of microcontrollers with on-chip computing devices. These on-chip devices support the computational algorithm that interrogates the measurement data. Random access memory

(RAM) provides the opportunity to accommodate the collected data. For example, a 256 KB of RAM provides 128000 data points (as 16-bit digit number) storage at a time. Also, 256 KB of read only memory (ROM) provides ample space for the processing response data software [11].

(c) Wireless communication channel

The wireless communication channel is a medium through which data is transmitted from the wireless sensor to the node (e.g computer). Reliability and range are the two criterions when selecting an appropriate wireless technology. During wireless communication, data losses happen due to channel interface, multi-path reflections, and path losses. Spread spectral wireless radios can distribute data across full radio spectrum so that integrity of the data can be maintained. For additional reliability a network protocol (e.g. transmit control protocol, internet protocol) can also be employed to the spread spectrum wireless channel. For large civil structures, at least 100 m range requirement is recommended [11]. According to Seidel and Rappaport (1992), radio signal attenuates when it propagats through floor, partitions, concrete wall [12]. Due to attenuation of radio signals, a wireless radio with 200 m range in an unobstructed open range is preferred. Shorter range wireless communication needs closer space together and repeated transmission of data to arrive the desired location [11].

(d) Prototype wireless sensor unit

Straser et al. (1998) were the first to propose the design of wireless sensor unit. Their sensor prototype consisted of an eight channel 16 bit ADC, a Motorola 68HC11 microcontroller core and 900 MHz Proxim ProxLink radio with 1950 cm3 in volume and 300 m range [13]. Lynch et al. (2002) designed their wireless sensor prototype using three channels 16 bits resolution Texas Instruments ADS7821 ADC with 100 kHz maximum sampling rate. The computational core was designed by 8-bit Atmel AT90S8515 AVR microcontroller. 8KB of ROM memory permits the storage of embedded software and 32 KB of external static RAM (SRAM) permits data storage. The Proxim RangeLAN 2 radio modem which was 2.4GHz radio, radio data rate 1.6 Mbps, 300 m range in open-space and 150 m in enclosed structural interiors. Fig. 4 gives the architecture provided by Lynch et al. (2003a). The fast Fourier transform (FFT) was embedded in the computational core [14]. Later Lynch et al. (2003a) add a second higher computational core 32-bit Motorola PowerPC MPC555 microcontroller. The microcontroller provides additional 448 KB of ROM and 26 KB of RAM memory. But the microcontroller needs 110 mA while AVR needs 8 mA. For storage of the data created by the execution of embedded software an additional 515 KB external SRAM is added [15]. The academic prototype costs less than $500 and 300 cm3 in volume. Wang et al. (2007) proposed 240 cm3 in volume and less than $ 200 cost a wireless sensing unit [16].

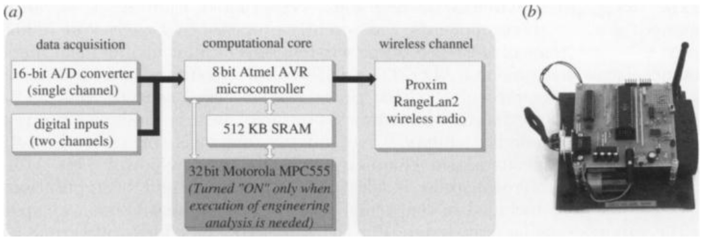

Figure 4: (a) architecture prototype and (b) low-cost academic prototype [15].

4. Engineering analysis algorithm

There are several algorithms that can be used for the structural health monitoring of a structure. These algorithms can generally be divided into three major classes namely; supervised learning, unsupervised learning and semi-supervised. Supervised learning algorithms (such as group classification and regression analysis) are employed when data are available from both the undamaged and damaged structure, while unsupervised learning (such as outlier analysis) refers to the class of algorithms that are applied to data not containing examples from the damaged structure [17]. Some of the algorithms commonly used in recent times, with their corresponding analyses types and validation study, are listed in the table 1 below.

Table 1: Algorithms for Structural Health Monitoring

Algorithm	Analysis type	Validation study
Fast Fourier Transform (FFT)	System ID	Alamosa Canyon Bridge [18]
	Damage detection	five degree of freedom mounted on a shaking table [19]
AR-ARX damage detection pattern recognition method	Damage detection	a lumped-mass laboratory structure [20]
Huffman Coding	Power efficiency	Lossless data compression of a five degree of freedom shear structure to reduce the data packet size that is wirelessly transmitted [21]
Wavelet transform (WT)	Damage and power efficient	Five degree of freedom shear structure time-history data compression [21]

5. Power efficient data management

One advantage of wireless sensing approach to health monitoring is its ability to generate intelligent (real-time and accurate) results. However, this often requires the generation of big data such as modal frequencies, location, and severity, of potential structural damage, and sensor status information [20], thus increasing the energy requirement of the wireless system. They highlighted that the transfer of long records of measured time-history data, as well as the associated energy requirement, is not an efficient use of the wireless medium and should be avoided for real-time communications when possible. They emphasized that the computational strengths of the system's unit core be leveraged instead since this is where major analyses take place. This, according to them, will first interrogate raw time history data, store locally, and then transmit or communicate the results to adjacent wireless sensor nodes later.

Furthermore, J.P Lynch et. al. (2004) pointed out that the computational core, which is the main driver of the wireless system, be strategically designed to optimize power without compromising its functional capabilities. To design of a power efficient computational core, there are numerous architectures that have been developed. Lynch et al (2004), for example, utilized a form of a master-slave assemblage of microcontrollers embedded in the computational core. An eight-bit microcontroller was incorporated with a 32-bit microcontroller. The eight-bit can easily accommodate the operation of the sensing unit with minimal power consumption but may not handle high-end analyses. The 32-bit, on the other hand, would perform well with high-end analyses, but with high energy requirement. The combination of both microcontrollers makes it possible for either of them to leverage on each other's advantages, to perform the computations efficiently. In fact, the 32-bit microcontroller does the major analyses while the eight-bit microcontroller does normal operations of wireless sensing, switches on the 32-bit when data is ready for processing, records the results and turns off the 32-bit microcontroller thereafter [20].

6. Wireless network topology

A wireless sensor network can be structured into three topologies for civil infrastructure: star; peer to peer; multi-tier network topologies as shown in fig. 5 [1]. In a star topology, each node can communicate only with a designated central server through coaxial or fiber optical cable and the central server must have the capability of data storage and high rate transmission. Each node can communicate in a peer to peer topology without the central server. This leaves the sensors to communicate each other and provides resiliency in the system if a sensor is added or fail. Multi-tier network topology, on the other hand, has more than one central server and those central servers can communicate with each other as well as designated wireless sensors [1, 14, 22-24].

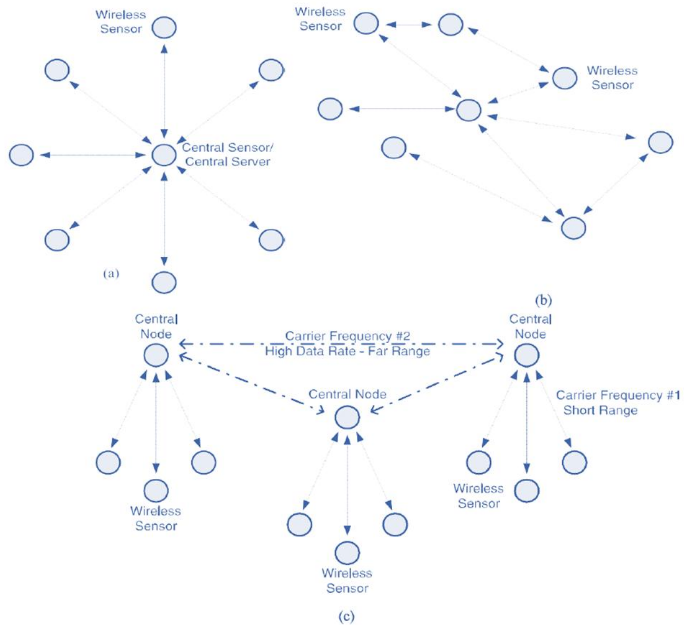

Figure 5: Wireless network topologies: (a) star, (b) peer-to-peer; (c) multi-tier network topologies [1, 22].

7. Optimal sensor placement

A methodology for sensor connectivity location was investigated by Ruiz-Sandoval et al as shown in Fig 6. In Fig. 7 five sensor location arrangement was proposed and in Fig. 8, A, B, C, D, and E show the location of central nodes in which information will be collected. Two different networks Depth First Search (DFS) and Breadth First Search (BFS) were included together in the network that permits transmitting data collected over the structure without buffer overflow. Depth First Search (DFS) algorithm and Breadth First Search (BFS) algorithm are shown in Fig 9 and Fig. 10 respectively. Firstly, DFS is implemented and later BFS is implemented. DFS constructs connectivity tree with only one threat without collisions in the network. BFS provides a route for data retrieval and assures the robustness of the network. A computer program combines DFS and BFS to simulate the data transmission in the network. Fig. 11 shows the simulation result of III and IV frames. The result demonstrates that the time required to reach maximum data collection depends more on interconnection route compared to central node connection position [9].

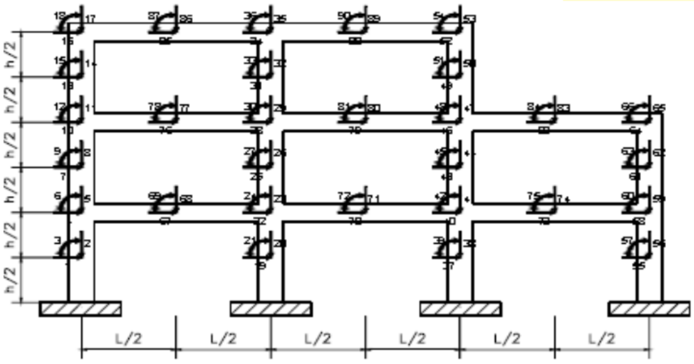

Figure 6: Planar frame with 90 sensor placement locations [9]

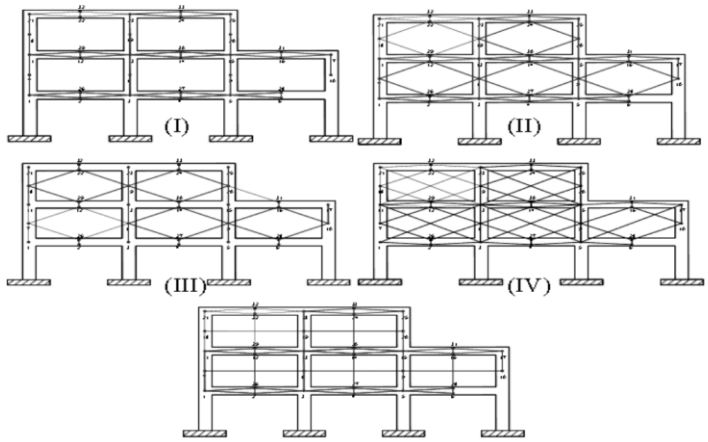

Figure 7: Sensor connectivity tress [9]

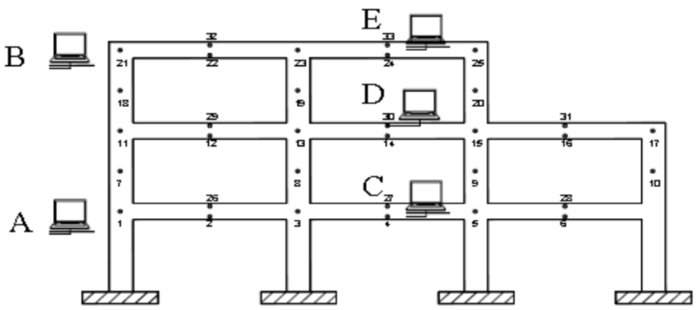

Figure 8: Central node location A,B,C,D, and E [9]

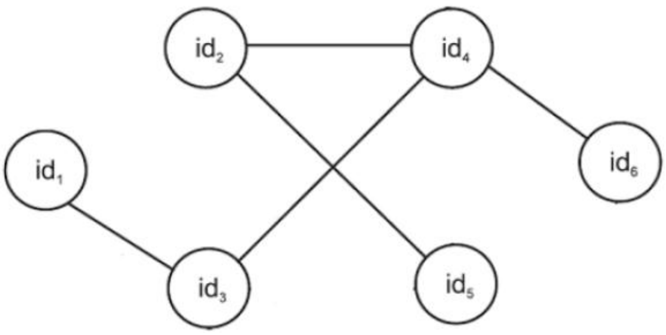

Figure 9: Tree constructed by DFS algorithm [9]

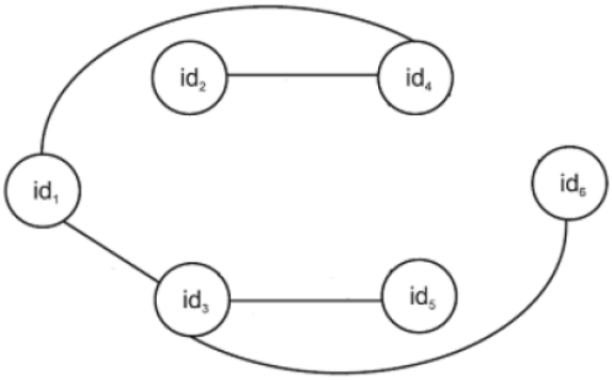

Figure 10: Tree constructed by BFS algorithm [9]

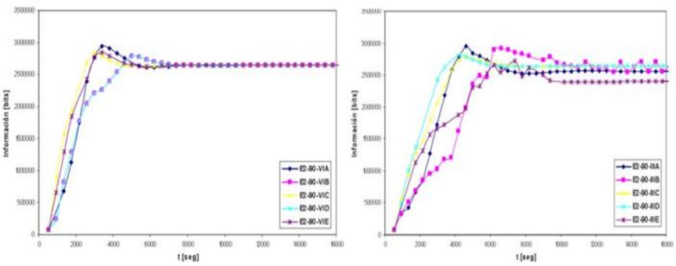

Figure 11: Comparison of Information (bits) vs. time for frame III and IV [9]

Shah and Udwadia (1978) investigated the optimal sensor location for estimation of dynamic properties. Their methodology is based on the covariance matrix. They found the optimal sensor location at the floor level immediately above the basement observing a variety of structures with different heights, different stiffness distributions and for different inputs [25]. Later Udwadia (1994) developed a methodology for parameter identification using noisy measurement data and it is applicable for both linear and nonlinear system. Fisher information matrix used in this methodology. The experiment conclusions are that the optimal sensor location depends on nature of the structure, the number of sensors, different parameters specific values in the system model, identification time duration, the specific parameters to be identified, and input forces nature and location [26].

Heredia (1996) developed a criterion to evaluate the optimal sensor location for the identification of uncertain structural parameters based on the Bayesian loss function. This function expected value is expressed into the expected trace of the Fisher information matrix inverse. Results showed that the optimal sensor location depends on the noise level of structure [27].

Optimal sensor location and number is required to get most useful data that represent the real behavior of the structure and to avoid the insufficient excitation and response bandwidth. Ka-Veng et al. (2001) developed a methodology based on an information entropy measure of the uncertainty in the model parameter that estimates the number of required sensors and their location based on the desired modal shapes [28].

Cherng et al. (2003) developed a new model for optimal sensor placement called signal

subspace correlation techniques (SSC). By means of SSC, Bayard-Hadaegh-Meldrum (BHM) and Lim Gawronski (LG) methods were analyzed to identify model parameter. Finally, it is concluded that 'modified LG' (MLG) and Backward Deletion Algorithm (BDA) is faster than BHM. Both MLG and BDA performs similar to BHM but BHM method is time consuming to identify the data [29]. Cobb and Liebst (1996) [30]; Hemez and Farhat (1994) [31]; Zavoni and Esteva (1998) [32]; Papadimitriou et al (2000) [33]; Jaynes (1978) [34]; Katafygiotis et al (1999) [35]; Gawronski and Lim (1996) [36]; Tongco and Meldrum (1996) [37]; Lim (1992) [38]; Liu and Tasker (1996) [39]; Panossian et al (1998) [40]; and Shi et al (2000) [41] also investigated the optimal sensor number and location.

8. Commercially available sensor types

Academic and commercial wireless sensors platforms are proposed for SHM. Table 2 and

Table 3 gives a comprehensive summary of the performance features of the academic and commercial prototypes. Table 3 shows a comparison between wireless and wired sensors feature.

Table 2: Development of academic wireless sensor platform 1998 to 2009 [1, 22, 24, 42]

Developer and Year	Processor	Radio	Frequency	Data Rate
Straser et al. [13]	Motorola 68HC11	Proxim/ProxLink	900 MHz	19.2 kbps
Bennett et al. [43]	Hitachi H8/329	Radiometrix	418 MHz	40 kbps
Lynch [14]	Atmel AVR8515	Proxim RangeLan2	2.4 GHz	1.6 Mbps
Mitchell et al.[44]	Cygnal 8051	Ericsson Bluetooth	2.4 GHz	--
Kottapalli et al.[45]	Microchip PIC16F73	BlueChip RBF915	900 MHz	10 kbps
JP Lynch et al.[46]	AV90S8515	Proxim RangeLan2	2.4 GHz	1.6 Mbps
Aoki et al.[47]	Renesas H8/4069F	RealtekRTL-8019AS	–	--
Basheer et al.[48]	ARM7TDMI	Philips Blueberry	2.4 GHz	--
Casciati et al.[49]	–	Aurel XTR-915	914.5 MHz	100 kbps
Xueshen Wang et al.[50]	Analog ADuC832	Linx Technologies	916 MHZ	33.6 kbps
Mastroleon et al.[51]	Microchip PIC-micro	BlueChip RFB915B	900 MHz	19.2 kbps
Sazonov et al.[52]	MSP 430F1611	Chipcon CC2420	2.4 GHz	250 kbps
Farrar et al.[53]	Intel Pentium	MotorolaneuRFon	2.4 GHz	230 kbps
Pei et al.[54]	Motorola 68HC11	Max-stream Xstream	2.4 GHz	Research
Musiani et al.[55]	ATMega128L	ChipconCC1100	1 MHz	0.6-250 kbps
Yang Wang et al.[16]	ATMega128	9XCite	900 MHz	26 kbps
Bocca et al.[56]	MSP430	ChipconCC2420	2.4 GHz	20 kbps
Zhou et al.[57]	MSP430	ChipconCC2500	2.4 GHz	250 kbps
Zhu et al.[58]	Atmega128	XStream	2.4 GHz	20 kbps

Table 3: Commercial sensing unit protocol [1, 43-49]

Developer and Year	Processor	Radio	Frequency Brand	Data Rate
UC Berkeley Crossbow WeC (1999)	Atmel AT90LS8535	TR1000	868 / 916 MHz	10 kbps
UC Berkeley Crossbow Rene (2000)	Atmega163L	TR1000	868 / 916 MHz	10 kbps
UC Berkeley Crossbow MICA (2002)	ATmega103L	TR1000	868 / 916 MHz	40 kbps
UC Berkeley Crossbow MICA2 (2003)	ATmega128L	Chipcon CC1000	315, 433, or 868 / 916MHz	38.4 kbps
Intel iMote, Kling Intel iMote, Kling (2003)	Zeevo ARM7TDMI	Wireless BT Zeevo	2.4 GHz	600 kbps
Microstrain, Galbreath et al. (2003)	MicroChip PIC16F877	RF Monolithics DR-3000-1	916.5 MHz	75 kbps
Rockwell, Agre et al. (1999)	Intel StrongARM 1100	Conexant RDSSS9M	916 MHz	100 kbps

Table 4: Comparison between wireless and wired sensors [24]

Type	Cost	Flexibility	Design Level	Sensibility to environmental effect
Wireless sensor system for SHM	Economic (approx. $100)	Yes	Difficult	Yes
Wired sensor system for SHM	Expensive (approx. $1,000)	No	Easy	No

9. Traditional Sensing Technology and sensors

Sensors are employed in bridges for monitoring three types of parameter: (a) structural responses (displacement, inclination, strain, and acceleration); (b) loading sources (seismic, wind, and traffic loading); (c) environmental effects (temperature, rain, humidity, and corrosion). Diverse types of sensors and sensing technology are listed below [50]:

1. Displacement measurement sensors: linear variable differential transformers (LVDT), level sensing station, GPS, and so forth.

2. Strain gauges: foil strain gauges, vibrating wire strain gauges, and fiber optic strain gauges.

3. Accelerometer: piezoelectric, piezoresistive, capacitive, and servo force balance type. For long-term use piezoelectric type accelerometer is commonly used and for civil flexible structure piezoresistive and capacitive are adequate.

4. Wind measurement sensors: Doppler radar, GPS drop-sonde, Doppler sonar, propeller, and ultrasonic anemometers. Propeller and ultrasonic anemometers are commonly used for measuring wind velocity.

5. Seismic sensors: seismometer.

6. Traffic loading: Weigh-in-motion (WIM) can measure the axle load of passing the vehicle and convert these data into traffic loading. Types of WIM: bending plate WIM system, piezoelectric WIM system, load cell WIM system, capacitive-based WIM system, and dynamic WIM system.

7. Temperature: Temperature is one of the influencing factors for bridge overall deflection and deformation. Most used temperature sensors are thermocouples, thermistors, and resistance temperature detectors.

8. Weather stations: A typical weather station usually consists of temperature, humidity, rainfall, air pressure, and solar irradiation sensors.

9. Fiber optic sensors: intensity modulated sensors, interferometric sensors, polarimetric sensors, and spectrometric sensors [51].

10. Surface vibration measurement: laser Doppler vibrometer (LDV).

10. Structural Health Monitoring of Civil Infrastructures

Civil infrastructures include buildings, bridges, pavements, dams, turbines etc., which are critical to the development of every nation. Their structural health monitoring, being critical as, are explained briefly in the subsequent sections.

10.1. Structural Health Monitoring of Bridge

Maser et al. (1996) developed Wireless Global Bridge Evaluation and Monitoring System (WGBEMS). This system consists of two levels of wireless communication. The first level wireless connectivity is intended to short range measured data transfer from the transducer (e.g. strain gage or accelerometer) to an on-site data repository and the second level wireless communication transfer the aggregated bridge response data to transportation officials situated far from the instrumented bridge site [52].

Bennett et al. (1999) used two strain gages to measure the tensile strain of the asphalt lower surface of an actual asphalt highway and two thermometers to measure the asphalt temperature. 100% data from embedded wireless sensors are received by a laptop acting as the data repository unit over a 20-minute period. The experimental results showed that the system records the strains with resolutions of 5–10 με and the asphalt temperature with an accuracy of 0.2°C [53].

Department of Electrical Engineering and Computer Sciences with Civil and Environmental Engineering department of University of California at Berkeley designed, implemented, deployed and tested the Wireless Sensor Network (WSN) for Structural Health Monitoring (SHM) on the 4200ft long main span and the south tower of the Golden Gate Bridge (GGB) with 64 nodes distributed over the main span and the tower shown in Fig. 12. These nodes collected ambient vibrations synchronously at the 1kHz rate, with less than 10μs jitter, and with an accuracy of 30μG. The experimental data agreed excellently with previous data and theoretical data and the deployment is the largest WSN on SHM [54].

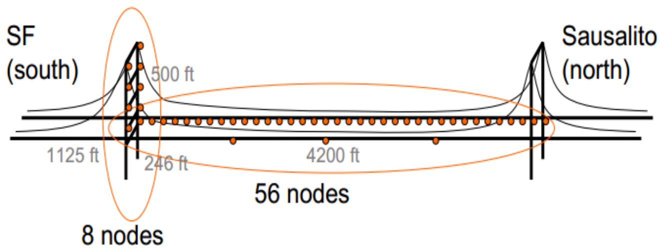

Figure 12: Layout of long linear topology of 64 nodes in 46 hop network in The Golden Gate Bridge [54]

Wang et al. (2005) designed hardware and software of a wireless structural monitoring system as shown in Fig 13. The hardware design meets the requirement for low power consumption and the requirement for long-distance communication and enough computational power. While the software design satisfies the data synchronization requirement for dynamic data analysis from multiple wireless sensing units associated with multiple heterogeneous sensors [55]. Researchers used this sensor in the Geumdang Bridge (concrete box girder bridge recently constructed in Icheon, South Korea) to monitor the behavior of the bridge during truck traffic loading. A tethered structural monitoring system installed parallel with 14 wireless sensing units in the interior spaces of the concrete box as shown in Fig. 14. Geumdang bridge acceleration response was recorded by two systems during forced vibration testing. Fig 15 shows the acceleration response for three trucks (15, 30 and 40 tons) transverse sequentially at 80 km/hr at sensor location #8. The experimental result reveals that the wireless sensor system has sufficiently precise determination of the primary modal frequencies and operating deflection shapes of the bridge [56].

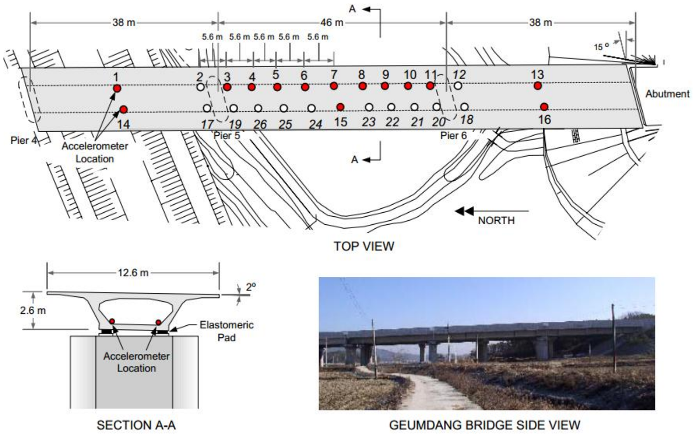

Figure 14: Schematic view of the Geumdang Bridge including the location of the instrumented accelerometers [56]

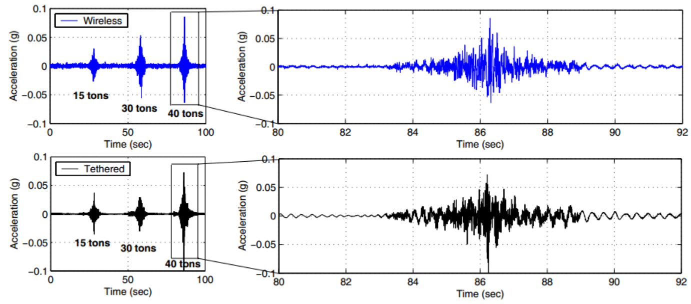

Figure 15: Acceleration response by the wireless (top) and tethered (bottom) monitoring systems both collect data at 200 Hz [56]

To evaluate the accuracy of the data collected by the wireless sensor nodes, a test was performed on a wooden bridge built to scale, 420 cm long, 65 cm wide, and 33.5 cm high, which has iron joints as shown in Fig. 16. Six wireless sensor nodes were attached to the joints of the structure and the bridge is connected to an electronic programmed motor to generate sinusoidal vibrations having pre-defined amplitudes and frequencies. Wired high sensitivity digital 1-axis accelerometers (Kistler 8712A5M1) are attached near the joints as a reference sensor to evaluate the accuracy of the data collected by wireless sensors. The monitoring system works in two parts: the wireless network in which sensor nodes are incorporated with 3- axis accelerometer and a MATLAB program. The MATLAB program connects to the sink node process and visualizes the real data collected from the sensor nodes. The collected data spectrum by the wired accelerometer (solid line) and wireless sensors (dashed line) showed a little inconsistency due to some instrumentation error but the error is small as shown Fig. 17. The analysis of the frequency spectrum shows that the sensor provides almost accurate data of the vibration of the structure [57].

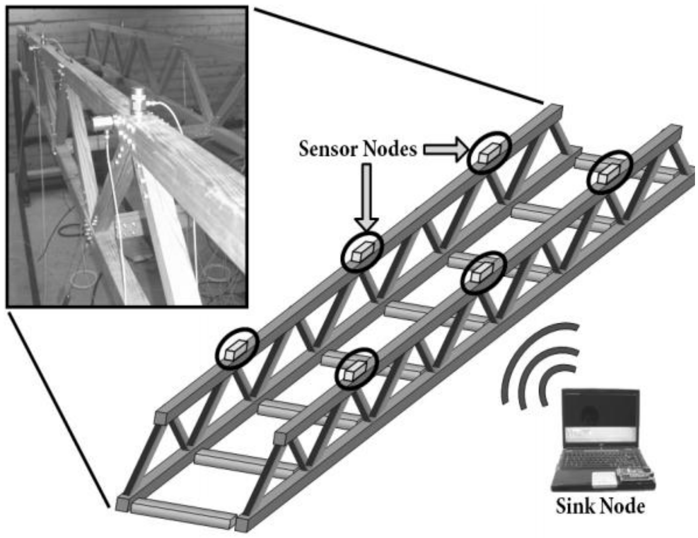

Figure 16: A prototype bridge to evaluate the wireless sensor performance [57]

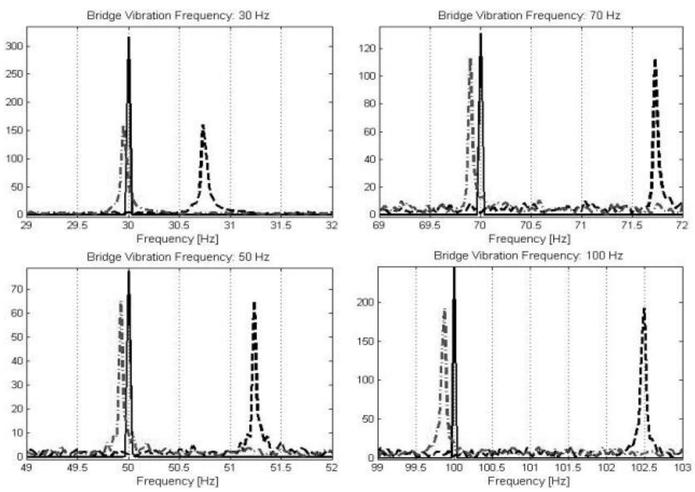

Figure 17: Comparison of spectrum data collected by wireless sensors and wired accelerometers.

The wired sensors (solid line), the wireless sensors (dashed line) [57]

A feasibility study of wireless strain sensor network (WSSN) for measuring large structural dynamic strain Liu et al. developed a strain sensor board with integrated IRIS mote hardware/software platform. The prototype structure is a steel truss with 14 bays, 52 longitudinal chords, 50 crosswise chords, and 54 diagonal chords as shown in Fig. 18. The wireless sensor nodes are attached at left even across (node 1,2, and 3) and right odd across (node 4,5, and 6) of the upper chords of the model truss.

Figure 7: Truss prototype [7]

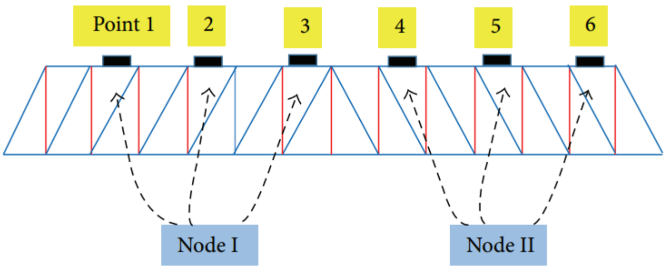

Figure 18: Arrangement of the measured nodes [7]

To evaluate strain modal parameters (vibration modes and natural frequencies), frequency domain decomposition (FDD) method is used to analyze the data. Table 4 shows a good agreement of the natural frequency data obtained by WSSN and FE simulation. In Fig. 19 the first vertical and first lateral modal shapes of the test structure are shown and the model shapes are almost identical with FE simulation. For low-order vibration modes, WSSN can accurately identify the strain data but for higher order vibration modes are irregular, due to the large stiffness of the test structure and time synchronization error. As the real civil engineering infrastructure face, low frequency compared to test structure (8.518 Hz), WSSN satisfy the SHM requirements [7].

Table 5: natural frequency data obtained by WSSN and FE simulation [7]

Method	1st vertical	1st lateral	Lateral and torsional	Vertical and torsional	2nd vertical
WSSN	8.518	14.080	19.643	26.770	30.420
FE	8.785	11.239	19.833	28.934	32.365

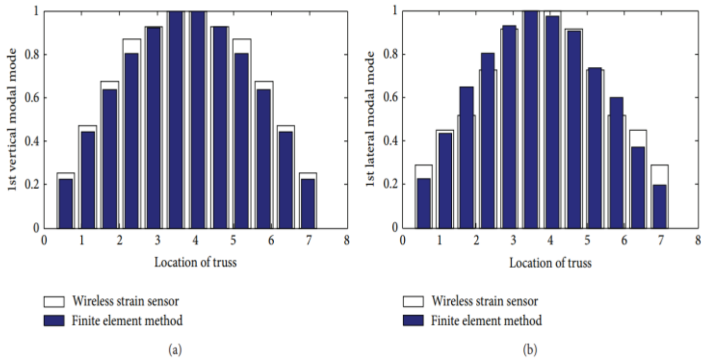

Figure 19: Modes identified by the WSSN: (a) 1st vertical mode and (b) 1st lateral mode [7]

Jerome P Lynch et al. performed a field validation test of the wireless sensor on the Alamosa Canyon Bridge, located in Truth or Consequences, New Mexico, constructed in 1937. The 50ft long and 24ft wide bridge has 7in. concrete deck supported by six W30x116 steel girder. Two excitation inputs were considered to produce a sizable vibration response: the first one is impact blow on the span from a model hammer and the second excitation source was a large truck driven at 40 miles per hour over a wood plank placed at the center of the span instrumented as shown in fig. 20. Wireless sensors were installed upon the bridge girder and a commercial tethered monitoring system is installed parallel to the wireless sensor to permit a baseline for performance. Dactron SpectraBook dynamic signal analyzer was the data acquisition system with 8 simultaneous input channels and 21kHz sampling rate. Piezotronics PCB336C accelerometer used in the cable-based monitoring system to measure dynamic response of the bridge and Crossbow CXL01LF1 MEMS accelerometer used in wireless sensing unit to measure bridge vibration. One of the channels of SpectraBook was directly connected to the accelerometer mounted on the structure. From the SpectraBook, a Window-based laptop with RT PRO Signal Analysis software control the system and collect data. A Linux-based laptop with a custom designed data acquisition system control and collect data from the wireless communication channel of the wireless sensing unit. To measure the input force from the model hammer a load cell instrumented on the tip of the hammer. Impact point of the hammer was the center of the deck (with respect to both length and width). Fig. 21 shows the accelerometer installation locations. All accelerometers were mounted at the midpoint of the girder's web except for Location S4. PCB336 accelerometer installed at the girder midpoint and CXL01LF1 with wireless sensing unit place upon the girder flange. 7 tests were performed to measure acceleration at all sensor locations resulting 14 time-history recording (7 generated by Dactron System and 7 from wireless sensor unit). The Dactron systems employ RT Pro Signal Analysis to compute the frequency response function from time-history data. The embedded FFT algorithm (this implementation employs the Cooley-Turkey FFT algorithm) in wireless sensor unit calculated the frequency response function and transmitted to a laptop. From the frequency response function, 6.7,8.2 and 11.4 Hz response was evident. They concluded that the wireless sensor gives a good agreement with wired sensor data and the installation time for the wireless sensor is half of the time taken by wired sensors. There is a disagreement in the frequency response function at low frequency [58].

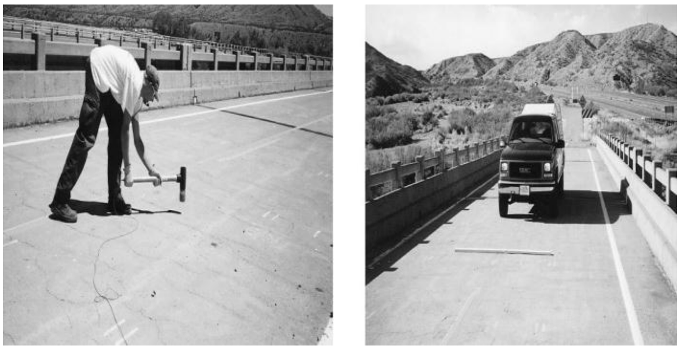

Figure 20: Model hammer excitation (left) and flatbed truck driving over a wood stud place on the center of the span (right) [58].

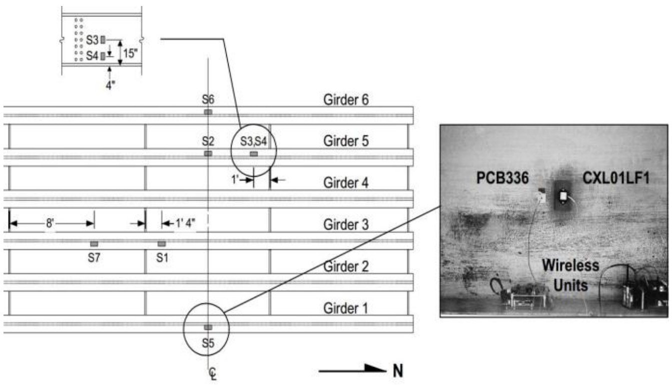

Figure 21: Accelerometer installation locations [58].

10.2. Structural Health Monitoring of Building

A shaking table test on a 3-story half-scale laboratory structure (floor area: 3m2m and story height: 3m, weight: 19 tons) was performed to validate the performance of wireless sensors as shown in Fig. 22. The input motion sources were Both El Centro and Chi-Chi earthquake and the accelerometers the Crossbow CXL02 MEMS (± 1.0g) were installed on each floor. The Maxstream 9XCite wireless modem is used for wireless communication subsystem. Wired and wireless sensors were used to collect the response data and a good agreement is found as shown in Fig. 23. The experimental outcome provides that the WiMMS (wireless modular monitoring system) capable to provide control and monitoring of civil infrastructure [59].

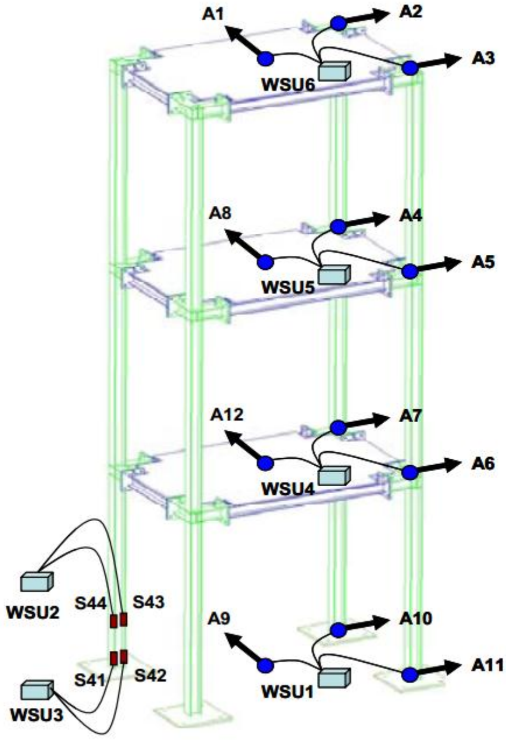

Figure 22: A 3-story steel frame structure with wireless sensor [59]

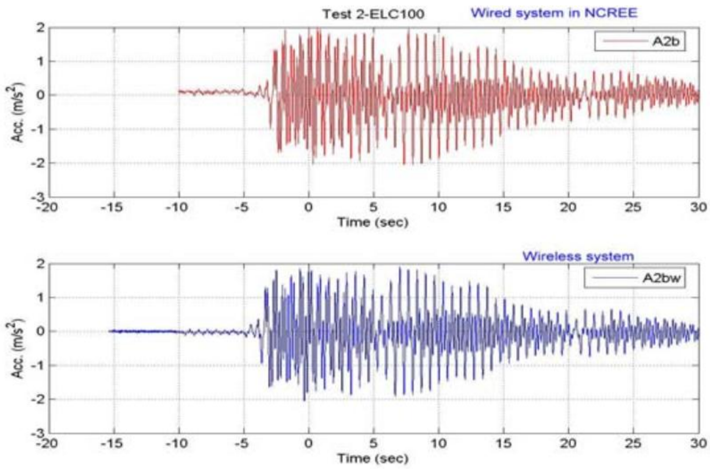

Figure 23: Comparison between wired and wireless sensor on 3rd floor of the test structure [59]

The United States Geological Survey's National Strong Motion Project developed a system for damage detection and alerting collaboration with the U.S. Department of Veterans Affairs to monitor 21 hospital buildings which are in high and very high seismic hazard regions in the U.S. In the Memphis, Tennessee VA Medical Center a seismic array of 24 sensors in the 5-story Bed Tower with uniaxial and triaxial force balanced accelerometers (FBAs) were deployed as shown in Fig 24. The system consists of sensing and analysis components. Sensing unit consists of firmware and sensors intended to measure the response of the building and the analysis unit includes several data processing modules integrated into an open source software package. The software compresses a large amount of data into useful information to assess the building's condition before and after an event. The system sends alarm messages after the algorithm agrees with different damage detection such as variation in the inter-story drift, mode shapes and damping values, shear-wave travel time between consecutive floors, modal frequencies, and exceedance of base shear capacity. This information is useful for rapid building safety assessment, and a guideline for decision making for repair, maintenance, and rehabilitation [60].

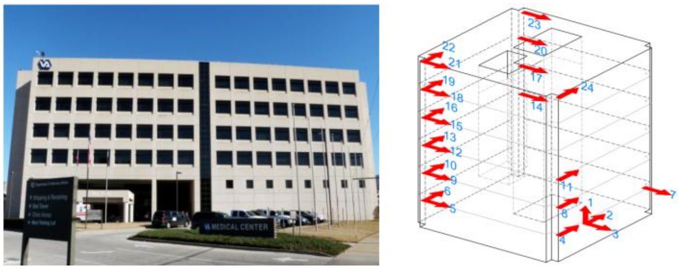

Figure 24: 5-story Memphis, Tennessee VA Medical Center (left). In the right schematic, motion sensors have been deployed permanently on each floor. Arrows indicate the locations of sensors from ground level to roof and their orientation [60, 61]

Clayton et al. used wireless sensor mote to detect experimental damage on a cantilever beam. Using Damage Location Assurance Criterion (DLAC) method, damage localization and identification achieved successfully [62].

Lei et al. proposed two-time synchronization algorithms to treat asynchronous data recorded by a wireless sensor. The first algorithm is ARX models for the input-output pairs when the input data is measurable. The second algorithm is ARMAV model for a pair of output data which can synchronize recorded outputs from structures under ambient excitation. The experimental data on a benchmark building proposed by ASCE Task Group showed that the second model can accurately synchronize output measurements [63].

10.3. Structural Health Monitoring of wind turbines

The United States produces 11,575 megawatts energy from wind and the rate of energy generation increases 30% annually. This wind energy accounts only 0.8% of the total energy in the United States while in Germany 7% of total energy comes from wind energy [64]. According to Department of Energy (DOE), if the United States generates 20% of its total energy by wind, 2 billion tons of carbon emissions will drastically reduce by 2050 [65]. As a result, the health monitoring of turbines becoming a critical issue. In 2005 Dunbar, Scotland, sudden blade failure resulting in £1.25 million in repair costs and significant downtime [66].

Swartz et al. conducted a study on the structural health monitoring of turbines using wireless sensors. Wireless sensors were installed in three operational turbines: two 78m tall, 2MW Vestas V-80 turbines and one NEG-Micon 250KW turbine with 40m height as shown in fig. 13. The objectives of turbine installation are wireless sensors range and reliability testing, comparison with wired sensor performance, develop operational deflection shape, impulse load analysis, and model shape analysis. Four and three wireless sensor nodes were installed in Vestas#1, Micon turbines and Vestas #2 respectively in various levels. Each wireless sensor node was connected to two accelerometers measuring lateral acceleration in orthogonal directions (in fig 25, denoted as X and Y). Stanford WiMMS sensor unit, MEMS accelerometer, YFLA-5-5L metal foil strain gauge and a model analysis software package called DIAMOND (Damage Identification And Modal Analysis for Dummies [67]) were used in this study. In parallel to wireless sensor PCB 3701 accelerometer was installed that connected with coaxial wire to a commercial DAQ (Data Acquisition) as shown in Fig. 26. Eigenfunction realization algorithm (ERA) was used to identify model frequencies and model shapes. 50, 100 and 500 Hz were the sample frequency to collect data. The study result demonstrated that the wireless sensors can measure the ambient excitation and capable of communicating data from all levels of tower to a basement server. In comparison with wired sensors, wireless sensor gave almost same result. At frequency 0.76 and 3.70 Hz there were yielding in the tower [64].

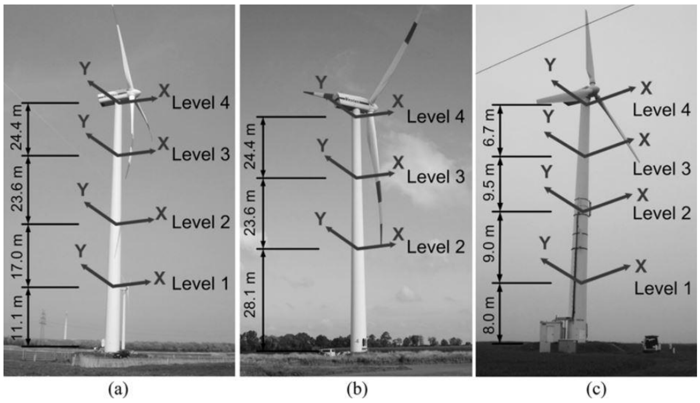

Figure 25: (a) Vestas #1, 78m tall, (b) Vestas #2, 78m tall, (c) Micon turbines, 40m tall [64]

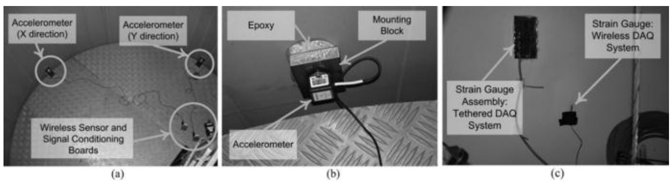

Figure 26: (a) one sensing note with two accelerometers, (b) details of accelerometer installation, and (c) details of strain gauge installation [64]

Rolfes et al. used Gasch's proportionality-method to detect early damage of tower and rotor blades of offshores wind turbines [68]. Another study conducted by Raimund Rolfes et al. concluded that the data transfer of wireless sensor network did not experience any radio interference as a result of an unfavorable (electromagnetic) EM environment [69]. Schulz and Sundaresan concluded that continues sensor is practical for health monitoring of large structures. They developed a smart blade that uses continuous sensors and microelectronics to mimic the biological nervous system [70]. Tanner et al. analyze wireless sensor to monitor the health of bolts joints and the wireless sensor provide a good agreement with the real-time data [71]. Hau and von Renouard analyze turbine manufacturing cost, sales price of commercial turbines, specific cost and reference parameters etc. [72].

10.4. Structural Health Monitoring of Dams

A number of approaches, such as the use advanced satellite technologies and three-dimensional laser scanner, have been used in recent years for structural health monitoring of dam. [73], for example, in their work titled "structural health monitoring of dams by advanced satellite SAR interferometry" explores three cases where satellite techniques, such as InSAR and A-DInSAR, have been successfully applied to structural health monitoring of dams. Two of them, i.e. The Gorges Dam in China and the Plover Cove Dam in Honk Kong, have been mentioned here. The Three Gorges Dam along the Yangtze River in China is the largest hydroelectric project in the world; about 2.3 km long and185m high, and it creates a water reservoir 660 km long and as such it's stability is of great concern for the Hubei region and the whole of China at large [73]. The Plover Cove Dam, on the other, was built in 1973 in the Plover Cover, Honk Kong, to provide a capacity of the reservoir for 230 million m3 of water.

P. Mazzanti et al (2015), used the A-DInSAR to analyze an area of about 50 km2 (including the dam itself, surrounding buildings, towns of Zigui and Snadoupingzhen and a few topographic relief) centered around the Three Gorges Dam. The dataset was formed by two COSMO-SkyMed images stacks, one ascending and the other one descending, 29 images each [73]. The data was acquired in the period from February to August 2011. All acquisitions were then stripped map in interferometric mode. To retrieve the terrain deformation, PSI A-DInSAR analyses, were performed in both datasets. Fig. 27 shows the main outcome of the analysis, namely the displacement rate observed in the analyzed time span. The color-scale of the two pictures ranges values from -60 (red) to 20 (dark blue) mm/year. Negative values indicate movements away from the satellite, while positive values are for movements toward the satellite [73].

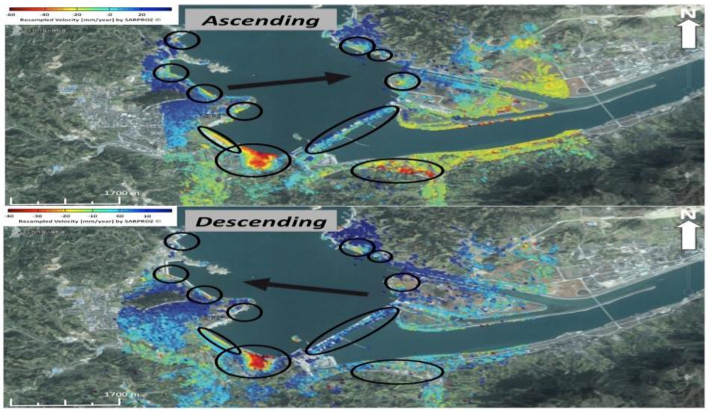

Figure 27: Results of the Three Gorges Dam A-DInSAR analyses: displacement rate (mm/year) during the period covered by the images. Black arrows show the orientation of the LOS. Black circles identif the areas affected by significant displacements [73]

The results show important movements of the river banks and a relative stretch between up and down river sides. Mazzanti et al, however, identified that the main challenge of the study has been the difficulty in separating seasonal movements of the river banks from linear displacement because of limited time (i.e less than 1 year) of observation.

In the case of the Plover Cove Dam in Honk Kong, in order to evaluate the dam deformations, used 62 TerraSAR-X and 11 TanDEM-X (German Space Agency - DLR) strip map images acquired in ascending orbital geometry with an angle of the line of sight from nadir equal to 37.3° was used. 73 high-resolution SAR images in approximately three and a half years' time range suppose an optimal configuration, with a high probability of proper estimation and removal of atmospheric disturbance as shown I fig. 28 [73].

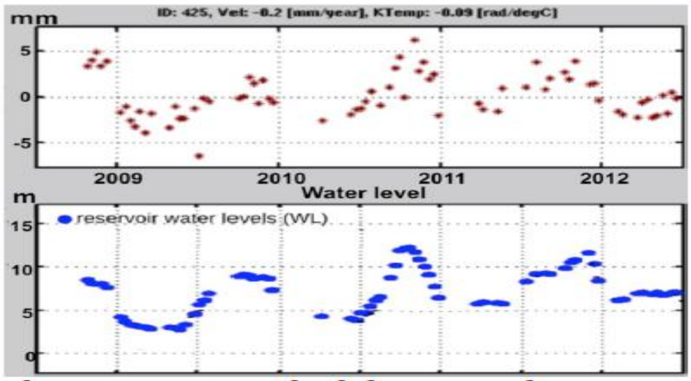

Figure 28: Main result of the Plover Cove Dam: cyclic deformation of a measurement point over the daam in relation with the water level variation of the reservoir [73].

Mazzanti et al (2015) related another contribution derived from interferometric phase signal to deformation modelled with the temperature data acquired in the study area simultaneously with the satellite images acquisition. According to them, even if the correlation seemed clear, the influence appeared very small when compared with other factors discussed earlier [73].

10.5. Structural Health Monitoring of Pavement

The structural health monitoring of pavements has taken multiple dimensions just as is the case with other infrastructures. Several efforts, over the years, have been expended to make this possible, with more recent attempts incorporating wireless sensor networks for pavement. This mitigates the challenges of installation, cost and reliability with the conventional wired methods, while recording significant feat of success in pavement health monitoring.

Bennett et al. (1999) first performed a study to examine the performance of wireless sensors for monitoring temperature changes and deformations (strains) in asphalt pavements. They developed an instrumented cylindrical core containing two carefully placed strain gauges and thermometers each, and then place this device within the pavement as an embedment.

The data collected from these sensors was channeled to a roadside node (computer) via a wireless communication channel (in this case, a radio frequency wireless link) situated about 4m from the core. According to them, a success rate test conducted revealed that the wireless system network had good reliability.

Recently, the Iowa department of transportation (IOWA DOT) constructed a new jointed plain concrete pavement (JPCP) near the southeast area of Ames, Iowa to evaluate the performance of MEMS wireless sensors, identify the limitations, and the data sensing capability to monitor concrete pavement. During their study, devices used include an i-Q32T radio frequency identification (RFID) temperature tag, portable handheld transceiver pro, sensirion SHT71 sensor with evaluation kit, thermochron iButtons with USB cable, geokon model 4200 strain gauges and datalogger.

Four RFID embedded probes, 4 iButtons and 2 strain gauges were instrumented at mid-span of the pavement. The installation distance from the pavement surface of RFID were 3, 5, 6, and 7.5 inch and iButtons were at distances of 4, 5, 8.5, and 10 inch, while the distance of the strain gauges were at 2 and 8.5 inch. Field evaluation after one month traffic opening showed that, approximately 78 percent of the embedded sensors remained functional and after 10 months traffic opening, there were only 20 percent functional sensors. According to them, the reasons for the failure of the sensor functioning include alkali-cement hydration reaction in concrete, harsh climate, slab movement, low range of wireless communication, steel reinforcement in the concrete, corrosion of sensor wires, and battery issues. From the monitored data of temperature, moisture, and strain profiles, the sensor provides accurate report of weather seasonal changes. Similarly, the sensor sensor strain curve reveals that the top and bottom concrete layers had opposite curvature, conforming with the mechanism of rigid pavement behavior [22].

11. Other Damage detection categories and methods

Damage detection methodology evaluate the location, type and quantify the state of the structure at a given time. Vibrations characteristics of a structure is the focus of many researchers for structural health monitoring [74-78]. A damage detection algorithm is required to identify, locate and evaluate damage in the structure [79]. Final stage of structural health monitoring is to identify amount of damage before the structure reaches a critical stage. For identification and evaluation of the structures a damage detection algorithm is run the whole process [10]. Fig. 29 provides vibration-based damage detection process and fig. 30 gives an overview of damage detection categories and methods.

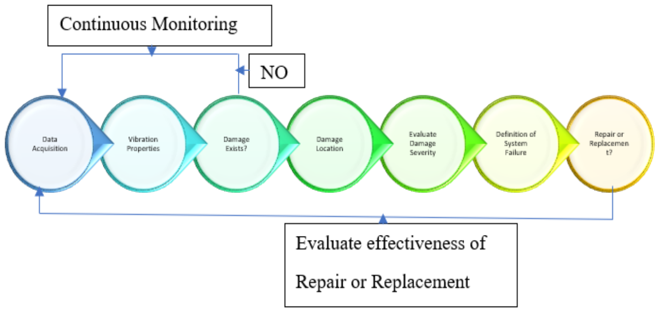

Figure 29: Vibration based damaged detection [79]

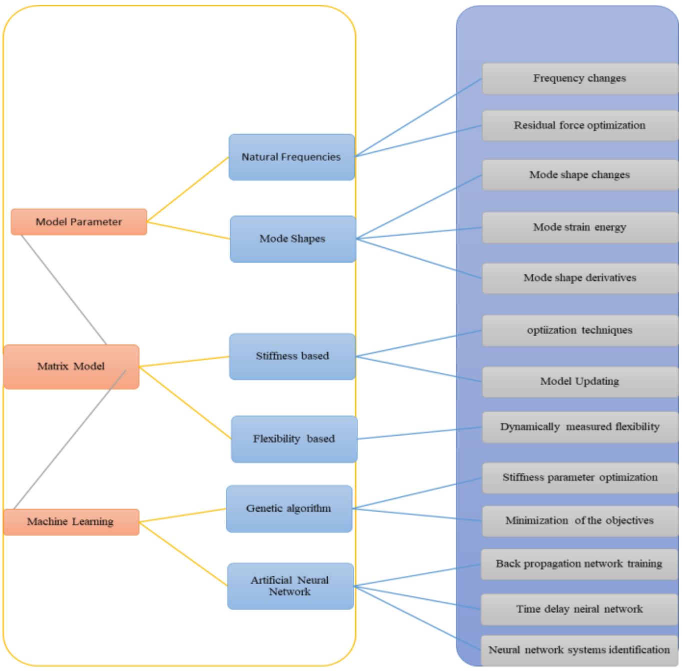

Figure 30: Damage detection category and Method [79]

12. CONCLUSION

The advantage of wireless network systems for structural health monitoring cannot be over-emphasized. Unlike the manual approach to health monitoring which is costly, time-consuming, and sometimes inaccurate, the wireless system is an autonomous method that utilizes an optimized arrangement of sensors to get health information of the building and synchronizes this to a central processing unit, thus making it possible to effectively and efficiently perform health monitoring of infrastructures on a real-time basis. For this reason, and in fact, due to the advancement in wireless technologies, it is not a gainsaying to conclude that wireless health monitoring has helped raise structural health monitoring to a significant feat.

13. Recommendations

The wireless sensor node can be developed by adding a piezoelectric and solar energy harvester so that it can convert the vibrations of the structure into energy for the batteries, hence extending the life time of the nodes.

14. For further study

Researchers (Ref)	Study
Jang et al. (2007) [80]	Developed Damage locating vector (DLV) to detect damage on a laboratory truss prototype.
Shenton and Chajes (1999) [81]	deployed a SHM system to measure the strain, deflections, temperature, and humidity of the structure on the first polymer composite bridge in Delaware.
Cruz and Salgado (2009) [82]	Developed six vibration-based damage detection methods using different conditions of cracking and noise levels.
He et al. (2008) [83]	Design a model based on a calibrated finite element (FE) model and a wind excitation model to realize the damage scenarios of Vincent Thomas Bridge located in San Pedro, California.
Parks et al. (2007) [84]	Used terrestrial laser scanning (TLS) to evaluate deformation of the structure.
Jiang and Adeli (2005) [85-89]	Developed dynamic fuzzy wavelet neural network (WNN) model and discussed a damage detection model of high-rise building structures subjected to seismic excitations.
Naeim et al. (1997) [90]	Provide information about how to utilize the hundreds of strong grounds motion and building response accelerograms to investigate the building response and necessary observation to build building coding in near future.
Vaghefi et al. [91]	Discussed about 12 potential sensor technologies for assessing superstructure as well as bridge deck health condition.
Bagavathiappan et al. [92]	A review on infrared thermography (IRT) and its opportunities in condition monitoring of civil engineering structure health.
Pla-Rucki and Eberhard [93]	Summarizes radiography, ground penetrating radar, infrared thermology to locate steel reinforcement, delamination, crack, honeycombs and other concrete flaws.
Kurita et al. [94]	Developed a methodology to detect hidden defects on elevated concrete structure using a 6-kW air-cooled xenon arc lamp and a scanner system.
Doebling et al. [95]	Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics
Humar et al. [96]	Performance of vibration-based techniques for the identification of structural damage
Hsieh et al. [97]	Overview of vibrational structural health monitoring with representative case studies
Moaveni et al. [98]	Uncertainty and sensitivity analysis of damage identification results obtained using finite element model updating
Umesha et al. [99]	Crack detection and quantification in beams using wavelets
Huang et al. [100]	Identification of Time-Variant Modal

	Parameters Using Time-Varying Autoregressive with Exogenous Input and Low-Order Polynomial Function
Chen and Liu [101]	Mobile agent computing paradigm for building a flexible structural health monitoring sensor network
Huang et al. [102]	Exploring the deterioration factors of RC bridge decks: A rough set approach
Yang et al.[103]	Wireless Sensing, Actuation and Control – With Applications to Civil Structures

15. References

[1] J. P. Lynch and K. J. Loh, "A summary review of wireless sensors and sensor networks for structural health monitoring," Shock and Vibration Digest, vol. 38, no. 2, pp. 91-130, 2006.

[2] L. S. Saulny and Susan. (2007). Bridge Collapse in Minneapolis Kills at Least 7. Available: https://www.nytimes.com/2007/08/02/us/02bridge.html

[3] ASCE. (2017). Bridges. Available: https://www.infrastructurereportcard.org/cat-item/bridges/

[4] S. K. U. Rehman, Z. Ibrahim, S. A. Memon, and M. Jameel, "Nondestructive test methods for concrete bridges: A review," Construction and Building Materials, vol. 107, pp. 58-86, 2016.

[5] (2018). 2016 - Deficient Bridges by County - National Bridge Inventory - Bridge Inspection - Safety - Bridges & Structures - Federal Highway Administration. Available: https://www.fhwa.dot.gov/bridge/nbi/no10/county16d.cfm#tn

[6] V. Giurgiutiu, J. M. Redmond, D. P. Roach, and K. A. RACKOW, "Active sensors for health monitoring of aging aerospace structures," Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US)2000.

[7] C. Liu, J. Teng, and N. Wu, "A wireless strain sensor network for structural health monitoring," Shock and Vibration, vol. 2015, 2015.

[8] A. Kiremidjian and E. Straser, "A modular wireless damage monitoring system for structures," ed: Report TR128, Blume Centre, Stanford CA, 1998.

[9] M. Ruiz-Sandoval, X. Argueta, and R. Marcelin, "DYNAMIC CHARACTERIZATION OF BUILDINGS USING WIRELESS SENSOR NETWORKS."

[10] C. R. Farrar and H. Y. Sohn, "Condition/damage monitoring methodologies," Los Alamos National Laboratory2001.

[11] J. P. Lynch, "An overview of wireless structural health monitoring for civil structures," Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, vol. 365, no. 1851, pp. 345-372, 2007.

[12] S. Y. Seidel and T. S. Rappaport, "914 MHz path loss prediction models for indoor wireless communications in multifloored buildings," IEEE transactions on Antennas and Propagation, vol. 40, no. 2, pp. 207-217, 1992.

[13] E. G. Straser, A. S. Kiremidjian, and T. H. Meng, "Modular, wireless damage monitoring system for structures," ed: Google Patents, 2001.

[14] J. P. Lynch, "Decentralization of wireless monitoring and control technologies for smart civil structures," Stanford University Stanford, CA, 2002.

[15] J. P. Lynch, A. Partridge, K. H. Law, T. W. Kenny, A. S. Kiremidjian, and E. Carryer, "Design of piezoresistive MEMS-based accelerometer for integration with wireless sensing unit for structural monitoring," Journal of Aerospace Engineering, vol. 16, no. 3, pp. 108-114, 2003.

[16] Y. Wang, J. P. Lynch, and K. H. Law, "A wireless structural health monitoring system with multithreaded sensing devices: design and validation," Structure and Infrastructure Engineering, vol. 3, no. 2, pp. 103-120, 2007.

[17] H. Sohn, C. R. Farrar, F. M. Hemez, and J. J. Czarnecki, "A review of structural health review of structural health monitoring literature 1996-2001," Los Alamos National Laboratory2002.

[18] J. P. Lynch et al., "Design and performance validation of a wireless sensing unit for structural monitoring applications," Structural Engineering and Mechanics, vol. 17, no. 3-4, pp. 393-408, 2004.

[19] J. P. Lynch et al., "Validation of a wireless modular monitoring system for structures," in SPIE's 9th Annual International Symposium on Smart

Structures and Materials, 2002, pp. 124-135: International Society for Optics and Photonics.

[20] J. P. Lynch, A. Sundararajan, K. H. Law, A. S. Kiremidjian, and E. Carryer, "Embedding damage detection algorithms in a wireless sensing unit for operational power efficiency," Smart Materials and Structures, vol. 13, no. 4, p. 800, 2004.

[21] J. P. Lynch, A. Sundararajan, K. Law, A. Kiremidjian, and E. Carryer, "Power-efficient data management for a wireless structural monitoring system," in Proceedings of the 4th International Workshop on Structural Health Monitoring, 2003, vol. 1, pp. 15-17: USA: Stanford University.

[22] S. Yang, "Health monitoring of pavement systems using smart sensing technologies," Iowa State University, 2014.

[23] F. Lewis, "Smart environments: technologies, protocols, and applications," Wireless Sensor Networks. John Wiley, 2004.

[24] B. Aygü and V. Cagri Gungor, "Wireless sensor networks for structure health monitoring: recent advances and future research directions," Sensor Review, vol. 31, no. 3, pp. 261-276, 2011.

[25] P. Shah and F. Udwadia, "A methodology for optimal sensor locations for identification of dynamic systems," ASME, Transactions, Journal of Applied Mechanics, vol. 45, pp. 188-196, 1978.

[26] F. E. Udwadia, "Methodology for optimum sensor locations for parameter identification in dynamic systems," Journal of Engineering Mechanics, vol. 120, no. 2, pp. 368-390, 1994.

[27] E. Heredia-Zavoni, "Optimal instrumentation of structural systems," in Proc. 11th World Conf. on Earthquake Engineering, Acapulco, Mexico, 1996.

[28] K.-V. Yuen, L. S. Katafygiotis, C. Papadimitriou, and N. C. Mickleborough, "Optimal sensor placement methodology for identification with unmeasured excitation," Journal of dynamic systems, measurement, and control, vol. 123, no. 4, pp. 677-686, 2001.

[29] A.-P. Cherng, "Optimal sensor placement for modal parameter identification using signal subspace correlation techniques," Mechanical Systems and Signal Processing, vol. 17, no. 2, pp. 361-378, 2003.

[30] R. G. Cobb and B. Liebst, "Sensor location prioritization and structural damage localization using minimal sensor information," AIAA J, vol. 35, no. 2, pp. 369-374, 1996.

[31] F. M. Hemez and C. Farhat, "An energy based optimum sensor placement criterion and its application to structural damage detection," in PROCEEDINGS-SPIE THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING, 1994, pp. 1568-1568: SPIE INTERNATIONAL SOCIETY FOR OPTICAL.

[32] E. Heredia-Zavoni and L. Esteva, "Optimal instrumentation of uncertain structural systems subject to earthquake ground motions," Earthquake engineering & structural dynamics, vol. 27, no. 4, pp. 343-362, 1998.

[33] C. Papadimitriou, J. L. Beck, and S.-K. Au, "Entropy-based optimal sensor location for structural model updating," Journal of Vibration and Control, vol. 6, no. 5, pp. 781-800, 2000.

[34] E. Jaynes, "Where do we stand on Maximum Entropy? RD Levin and M. Ritbus (eds) The Maximum Entropy Principle," ed: Cambridge, MA: MIT Press, 1978.

[35] L. Katafygiotis, K. Yuen, and C. Papadimitriou, "An optimal sensor location methodology for designing modal experiments," STRUCTURAL DYNAMICS, VOLS 1 AND 2, 1999.

[36] W. Gawronski and K. Lim, "Balanced actuator and sensor placement for flexible structures," International Journal of Control, vol. 65, no. 1, pp. 131-145, 1996.

[37] E. Tongco and D. Meldrum, "Optimal sensor placement of large flexible space structures," Journal of Guidance Control and Dynamics, vol. 19, pp. 961-962, 1996.

[38] K. Lim, "Method for optimal actuator and sensor placement for large flexible structures," Journal of Guidance, Control, and Dynamics, vol. 15, no. 1, pp. 49-57, 1992.

[39] C. Liu and F. A. Tasker, "Sensor placement for time-domain modal parameter estimation," Journal of guidance, control, and dynamics, vol. 19, no. 6, pp. 1349-1356, 1996.

[40] H. Panossian, W. Gawronski, and H. Osman, "Balanced shaker and sensor placement for modal testing of large flexible structures," in SPIE proceedings series, 1998, pp. 829-839: Society of Photo-Optical Instrumentation Engineers.

[41] Z. Shi, S. Law, and L. Zhang, "Optimum sensor placement for structuraldamage detection," Journal of Engineering Mechanics, vol. 126, no. 11, pp. 1173-1179, 2000.

[42] S. Cho, C.-B. Yun, J. P. Lynch, A. T. Zimmerman, B. F. Spencer Jr, and T. Nagayama, "Smart wireless sensor technology for structural health monitoring of civil structures," Steel Structures, vol. 8, no. 4, pp. 267-275, 2008.

[43] A. Hasnat, M. Qurishee, I. Iqbal, M. Zaman, and M. Wahid, "Effectiveness of Using Slag as Coarse Aggregate and Study of its Impact on Mechanical Properties of Concrete."

[44] B. Atolagbe, "Automatic mesh representation of urban environments," 2019.

[45] M. Qurishee, I. Iqbal, M. Islam, and M. Islam, "Use of slag as coarse aggregate and its effect on mechanical properties of concrete," in International Conference on Advances in Civil Engineering, CUET, 2016, vol. 3, pp. 475-479.

[46] M. A. Qurishee, "Low-cost deep learning UAV and Raspberry Pi solution to real time pavement condition assessment," 2019.

[47] W. Wu, M. A. Qurishee, J. Owino, I. Fomunung, M. Onyango, and B. Atolagbe, "Coupling Deep Learning and UAV for Infrastructure Condition Assessment Automation," in 2018 IEEE International Smart Cities Conference (ISC2), 2018, pp. 1-7: IEEE.

[48] M. Al Qurishee, "Application of Geosynthetics in Pavement Design," 2017.

[49] M. Al Qurishee and I. Fomunung, "Smart Materials in Smart Structural Systems."

[50] Y. L. Xu and Y. Xia, Structural health monitoring of long-span suspension bridges. CRC Press, 2011.

[51] J. R. Casas and P. J. Cruz, "Fiber optic sensors for bridge monitoring," Journal of bridge engineering, vol. 8, no. 6, pp. 362-373, 2003.

[52] K. Maser, R. Egri, A. Lichtenstein, and S. Chase, "Field evaluation of a wireless global bridge evaluation and monitoring system (WGBEMS)," in Engineering Mechanics, 1996, pp. 955-958: ASCE.

[53] R. Bennett, B. Hayes-Gill, J. A. Crowe, R. Armitage, D. Rodgers, and A. Hendroff, "Wireless monitoring of highways," in 1999 Symposium on Smart Structures and Materials, 1999, pp. 173-182: International Society for Optics and Photonics.

[54] S. Kim et al., "Health monitoring of civil infrastructures using wireless sensor networks," in Proceedings of the 6th international conference on Information processing in sensor networks, 2007, pp. 254-263: ACM.

[55] Y. Wang, J. P. Lynch, and K. H. Law, "Wireless structural sensors using reliable communication protocols for data acquisition and interrogation," Ann Arbor, vol. 1001, p. 48109, 2005.

[56] J. P. Lynch, Y. Wang, K. H. Law, J. H. Yi, C. G. Lee, and C. B. Yun, "Validation of a large-scale wireless structural monitoring system on the Geumdang Bridge," in Proceedings of 9th International Conference on Structural Safety and Reliability, 2005, pp. 19-23.

[57] M. Bocca, E. Cosar, J. Salminen, and L. Eriksson, "A reconfigurable wireless sensor network for structural health monitoring," in Proceedings of the 4th international conference on structural health monitoring of intelligent infrastructure, 2009, pp. 22-24.

[58] J. P. Lynch et al., "Field validation of a wireless structural monitoring system on the Alamosa Canyon Bridge," in Smart structures and materials, 2003, pp. 267-278: International Society for Optics and Photonics.

[59] K. C. Lu, Y. Wang, J. P. Lynch, P. Y. Lin, C.-H. Loh, and K. H. Law, "Application of Wireless Sensors for Structural Health Monitoring And Control," (in en), The Eighteenth KKCNN Symposium on Civil Engineering, research-article December 19-21, 2005 2005.

[60] H. Ulusoy, E. Kalkan, J. Fletcher, P. Friberg, W. Leith, and K. Banga, "Design and Implementation of A Structural Health Monitoribg Monitoring Monitoring and Alerting System for Hospital Buildings in the United States."

[61] E. Kalkan, J. P. B. Fletcher, W. S. Leith, W. S. McCarthy, and K. Banga, "Real-time seismic monitoring of instrumented hospital buildings," US Geological Survey2327-6932, 2012.

[62] E. H. Clayton, B.-H. Koh, G. Xing, C.-L. Fok, S. J. Dyke, and C. Lu, "Damage detection and correlation-based localization using wireless mote sensors," in Intelligent Control, 2005. Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation, 2005, pp. 304-309: IEEE.

[63] Y. Lei, A. S. Kiremidjian, K. Nair, J. P. Lynch, and K. H. Law, "Time synchronization algorithms for wireless monitoring system," in Proceedings of SPIE 10th Annual International Symposium on Smart Structures and Materials 2003, 2003, pp. 308-317.

[64] R. A. Swartz, J. P. Lynch, S. Zerbst, B. Sweetman, and R. Rolfes, "Structural monitoring of wind turbines

using wireless sensor networks," Smart structures and systems, vol. 6, no. 3, pp. 183-196, 2010.

[65] M. E. Himmel et al., "Biomass recalcitrance: engineering plants and enzymes for biofuels production," science, vol. 315, no. 5813, pp. 804-807, 2007.

[66] K. Tweedie, "Wind farm fears as blade snaps," The Times, vol. 16, 2005.

[67] S. W. Doebling, C. R. Farrar, and P. J. Cornwell, "DIAMOND: A graphical interface toolbox for comparative modal analysis and damage identification," in Proceedings of the 6th International Conference on Recent Advances in Structural Dynamics, Southampton, UK, 1997, pp. 399-412.

[68] R. Rolfes, W. Gerasch, G. Haake, J. Reetz, and S. Zerbst, "Early damage detection system for towers and rotor blades of offshore wind turbines," in Proceedings of the Third European Workshop on Structural Health Monitoring, 2006, pp. 455-462.

[69] R. Rolfes, S. Zerbst, G. Haake, J. Reetz, and J. P. Lynch, "Integral SHM-system for offshore wind turbines using smart wireless sensors," in Proceedings of the 6th International Workshop on Structural Health Monitoring, 2007, pp. 11-13.

[70] M. Schulz and M. Sundaresan, "Smart Sensor System for Structural Condition Monitoring of Wind Turbines: 30 May 2002--30 April 2006," National Renewable Energy Laboratory (NREL), Golden, CO.2006.

[71] N. A. Tanner, C. R. Farrar, and H. Sohn, "Structural health monitoring using wireless sensing systems with embedded processing," in Proceedings of SPIE, 2002, vol. 4704, pp. 215-224.

[72] E. Hau and H. von Renouard, "Wind Turbine Costs," Wind Turbines: Fundamentals, Technologies, Application, Economics, pp. 703-750, 2006.

[73] P. Mazzanti, D. Perissin, and A. Rocca, "Structural health monitoring of dams by advanced satellite SAR interferometry: investigation of past processes and future monitoring perspectives," in 7th Internation Conference on Structural Health Monitoring of Intelligent Infrastructure, Torino, Italy, 2015.

[74] A. Aktan, F. Catbas, K. Grimmelsman, and C. Tsikos, "Issues in infrastructure health monitoring for management," Journal of Engineering Mechanics, vol. 126, no. 7, pp. 711-724, 2000.

[75] K. Park, G. W. Reich, and K. Alvin, "Structural damage detection using localized flexibilities," Journal of intelligent material systems and structures, vol. 9, no. 11, pp. 911-919, 1998.

[76] O. Salawu, "Assessment of bridges: use of dynamic testing," Canadian Journal of Civil Engineering, vol. 24, no. 2, pp. 218-228, 1997.

[77] C. Sikorsky, "Development of a health monitoring system for civil structures using a level IV non-destructive damage evaluation method," in Proc., the 2nd International Workshop on Structural Health Monitoring, 1999, pp. 68-81.

[78] N. Stubbs, S. Park, C. Sikorsky, and S. Choi, "A global non-destructive damage assessment methodology for civil engineering structures," International Journal of Systems Science, vol. 31, no. 11, pp. 1361-1373, 2000.

[79] L. S. Lee, V. M. Karbhari, and C. Sikorsky, "Investigation of integrity and effectiveness of RC bridge deck rehabilitation with CFRP composites," SSRP, vol. 8, 2004.

[80] S. Jang, S. Sim, and B. Spencer Jr, "Structural damage detection using static strain data," in Proceedings of the World Forum on Smart Materials and Smart Structures Technology, China, 2007.

[81] H. W. Shenton III and M. J. Chajes, "Long-term health monitoring of an advanced polymer composite bridge," in 1999 Symposium on Smart Structures and Materials, 1999, pp. 143-151: International Society for Optics and Photonics.

[82] P. J. Cruz and R. Salgado, "Performance of vibration-based damage detection methods in bridges," *Computer-Aided Civil and Infrastructure* Engineering, vol. 24, no. 1, pp. 62-79, 2009.

[83] X. He, B. Moaveni, J. P. Conte, A. Elgamal, and S. F. Masri, "Modal Identification Study of Vincent Thomas Bridge Using Simulated Wind-Induced Ambient Vibration Data," *Computer-Aided Civil and* Infrastructure Engineering, vol. 23, no. 5, pp. 373-388, 2008.

[84] H. Park, H. Lee, H. Adeli, and I. Lee, "A new approach for health monitoring of structures: terrestrial laser scanning," *Computer-Aided Civil and Infrastructure* Engineering, vol. 22, no. 1, pp. 19-30, 2007.

[85] (2017). Magnetorheological damper - Wikipedia. Available: https://en.wikipedia.org/wiki/Magnetorheological_damper

[86] X. Jiang and H. Adeli, "Dynamic wavelet neural network for nonlinear identification of highrise buildings," *Computer-Aided Civil and Infrastructure* Engineering, vol. 20, no. 5, pp. 316-330, 2005.

[87] X. Jiang and H. Adeli, "Dynamic fuzzy wavelet neuroemulator for non-linear control of irregular building structures," International Journal for Numerical Methods in Engineering, vol. 74, no. 7, pp. 1045-1066, 2008.

[88] X. Jiang and H. Adeli, "Neuro-genetic algorithm for non-linear active control of structures," International Journal for Numerical Methods in Engineering, vol. 75, no. 7, pp. 770-786, 2008.

[89] X. Jiang, S. Mahadevan, and H. Adeli, "Bayesian wavelet packet denoising for structural system identification," Structural Control and Health Monitoring, vol. 14, no. 2, pp. 333-356, 2007.

[90] F. Naeim, "Performance of extensively instrumented buildings during the January 17, 1994 Northridge earthquake," An Interactive Information System, Report No. 97, vol. 7530, 1997.

[91] K. Vaghefi et al., "Evaluation of commercially available remote sensors for highway bridge condition assessment," Journal of Bridge Engineering, vol. 17, no. 6, pp. 886-895, 2011.

[92] S. Bagavathiappan, B. Lahiri, T. Saravanan, J. Philip, and T. Jayakumar, "Infrared thermography for condition monitoring–a review," Infrared Physics & Technology, vol. 60, pp. 35-55, 2013.

[93] G. F. Pla-Rucki and M. O. Eberhard, "Imaging of reinforced concrete: State-of-the-art review," Journal of infrastructure systems, vol. 1, no. 2, pp. 134-141, 1995.

[94] K. Kurita, M. Oyado, H. Tanaka, and S. Tottori, "Active infrared thermographic inspection technique for elevated concrete structures using remote heating system," Infrared Physics & Technology, vol. 52, no. 5, pp. 208-213, 2009.

[95] S. W. Doebling, C. R. Farrar, M. B. Prime, and D. W. Shevitz, "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review," 1996.

[96] J. Humar, A. Bagchi, and H. Xu, "Performance of vibration-based techniques for the identification of structural damage," Structural Health Monitoring, vol. 5, no. 3, pp. 215-241, 2006.

[97] K. H. Hsieh, M. W. Halling, and P. J. Barr, "Overview of vibrational structural health monitoring with representative case studies," Journal of Bridge Engineering, vol. 11, no. 6, pp. 707-715, 2006.

[98] B. Moaveni, J. P. Conte, and F. M. Hemez, "Uncertainty and sensitivity analysis of damage identification results obtained using finite element model updating," *Computer-Aided Civil and* Infrastructure Engineering, vol. 24, no. 5, pp. 320-334, 2009.

[99] P. Umesha, R. Ravichandran, and K. Sivasubramanian, "Crack detection and quantification in beams using wavelets," *Computer-Aided Civil and Infrastructure Engineering,* vol. 24, no. 8, pp. 593-607, 2009.

[100] C. Huang, S. Hung, W. Su, and C. Wu, "Identification of Time-Variant Modal Parameters Using Time-Varying Autoregressive with Exogenous Input and Low-Order Polynomial Function," *Computer-Aided Civil and Infrastructure Engineering,* vol. 24, no. 7, pp. 470-491, 2009.

[101] B. Chen and W. Liu, "Mobile agent computing paradigm for building a flexible structural health monitoring sensor network," *Computer-Aided Civil* and Infrastructure Engineering, vol. 25, no. 7, pp. 504-516, 2010.

[102] R. Y. Huang, I. Mao, and H. K. Lee, "Exploring the deterioration factors of RC bridge decks: A rough set approach," *Computer-Aided Civil and Infrastr*ucture Engineering, vol. 25, no. 7, pp. 517-529, 2010.

[103] Y. Wang, J. P. Lynch, and K. H. Law, "Wireless Sensing, Actuation and Control – With Applications to Civil Structures," in Intelligent Computing in Engineering and Architecture: 13th EG-ICE Workshop 2006, Ascona, Switzerland, June 25-30, 2006, Revised Selected Papers, I. F. C. Smith, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 670-689.

BIOGRAPHIES

I have a diverse knowledge of fiber optics, drone, network engineering, construction management, and ITS. Passionate to learn new technology and new areas of knowledge.

Five+ years hands-on extensive experience on linear and nonlinear finite element analysis (FEA,FEM).

Babatunde Atolagbe is a transportation engineer in the bridge inspection and remedial engineering unit at the Maryland Department of Transportation. His interests are in concrete materials, infrastructure performance modeling & life-cycle analysis, and computational simulation to mention a few.

Experienced Engineering Manager with a demonstrated history of working in the government administration industry. Finished PhD courses in Vanderbilt University.

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