Wireless sensors for structural health monitoring and damage detection techniques

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Structural health monitoring (SHM) is an emerging field in civil engineering, offering the potential for continuous and periodic assessment of the safety and integrity of civil infrastructure. Based on the knowledge of the condition of the structure, certain preventive measures can be taken to prolong the service life of the structure and prevent catastrophic failure. Damage detection strategies can ultimately reduce life-cycle cost. Using traditionally wired sensors to implement such a SHM system with a dense array of sensors is quite challenging because of the difficulties in deploying and maintaining the associated wiring. Recent development of smart sensors has created the possibility of dense array of sensors in SHM. Damage detection algorithms which can take advantage of the distributed computing environment offered by smart sensor technology are highly desired but currently limited. Dense arrays of low-cost smart wireless sensor networks (WSNs) have the potential to improve the quality of the SHM dramatically using their on-board computational and wireless communication capabilities. These WSNs provide rich information which SHM algorithms can utilize to detect, locate and assess structural damage caused by severe loading events and by progressive environmental deterioration as well as economical realization of the SHM system. Information from densely instrumented structures is expected to result in deeper insight into the physical state of the structural system. In this article, recent research and development activities in the field of smart wireless sensors and application of smart sensing, monitoring and damage detection techniques for civil infrastructures are presented.

Keywords: Damage detection techniques, smart sensors, structural health monitoring, wireless sensors, wireless sensor networks.

OUR daily lives are becoming more and more dependent on civil infrastructure, including bridges, buildings, pipelines, offshore structures, etc. Much of the existing infrastructure in India has been in service for many years. These structures are still being used despite ageing and the associated accumulation of damage. Hence monitoring the condition of these structures to provide the necessary maintenance has become critically important to our society. Moreover, evaluation of the condition of critical facilities and civil infrastructure is extremely important after natural hazards such as earthquakes or man-made disasters such as terrorist attacks. These emergency facilities have to be evaluated and repaired immediately to minimize the impact of the disaster and to facilitate the recovery of our society. Tragic disasters on the civil structures, like the collapse of bridges or buildings, often result in a large number of casualties as well as social and economic problems.

Structural health monitoring (SHM) is an emerging field in civil engineering, offering the potential for continuous and periodic assessment of the safety and integrity of civil infrastructure. Based on knowledge of the condition of the structure, certain preventive measures can be taken to prolong the service life of the structure and prevent catastrophic failure. Damage detection strategies can ultimately reduce life-cycle cost. Thus most of the industrialized countries are on the verge of increasing their budget for SHM of their major civil infrastructure. The SHM system often offers an opportunity to reduce the cost for the maintenance, repair and retrofit throughout the life of the structure. In the most general terms, damage can be defined as changes introduced into a system that adversely affects its performance. As far civil engineering structures are considered, changes in materials, connections, boundary conditions, etc. which cause deteriorated performance of the structure, can be defined as damage. Normal activities can introduce damage to the structure. Buildings can be damaged due to corrosion, ageing and daily activities. Traffic and wind loads cause damage to bridges, whereas offshore structures suffer from wave loading and corrosion due to sea water. On the other hand, excessive loads produced by cyclones, hurricanes and earthquakes also can potentially cause damage to structures. The effect of damage on structures can be classified as linear and nonlinear. Linear damage can be defined as the case when structures still behave linear-elastically after occurrence of the damage, whereas nonlinear damage causes structures to show nonlinear behaviour after damage has occurred. In civil engineering structures, metal corrosion and concrete spalling/scour are typical damage events that may be defined as linear damage. Examples of nonlinear damage in civil engineer-

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ing include cracks formed in concrete or metal members, loose connections of steel members, etc.

Numerous SHM methods have been proposed in the past few decades; however, challenges have to be overcome before they can be applied to civil engineering structures. Most existing SHM methodologies require direct measurement of the input excitation for implementation. However, in many cases, there is no easy way to measure these inputs – or alternatively, to externally excite the structure. This difficulty has limited the application of existing SHM methods which require the measurements of input excitations. Methods based on ambient vibration have become more important in the field of SHM and damage detection. More research efforts should be directed towards the development of SHM methodologies which minimize the need to measure the input excitation and can handle the ambient vibration cases. Another challenge results from the fact that damage in structures is an intrinsically local phenomenon. Sensors close to the damaged site are expected to be more heavily influenced than those remote to the damage site. Therefore, to effectively detect damage at an arbitrary location in a structure, sensors must be densely distributed throughout the structure. Most existing SHM methods assume the measured data are to be centrally acquired. Using traditionally wired sensors to implement such a SHM system with a dense array of sensors is quite challenging because of the difficulties in deploying and maintaining the associated wiring plant. The wiring system for a large civil infrastructure is obviously much more complicated and therefore difficult to manage. In addition, tremendous amount of data are expected to be generated that would need to be sent to the central station. Managing such a large amount of data is also challenging and is not cost-effective. Therefore, damage detection of large civil infrastructure employing traditionally wired sensors is intractable. Recent development of smart sensors has made SHM using a dense array of sensors feasible. The essential feature of a smart sensor is the on-board microprocessor, which grants sensors the 'smart' characteristics. Programming can be embedded in the microprocessor of the sensor, which allows smart sensors to save data locally, perform the desired computation, make 'if–then' decisions, scan valuable information, send results quickly, etc. Therefore, a portion of the computation can be done at the local sensor level for damage detection. Extraneous information can be discarded, reducing the information that needs to be transferred back to the central station. Note that all smart sensors to date are wireless as well, with data transmission based on radio frequency (RF) communications. Damage detection algorithms which can take advantage of the distributed computing environment offered by smart sensor technology are highly desired, but currently limited. Dense arrays of low-cost smart wireless sensors have the potential to improve the quality of SHM dramatically using their on-board computational and wireless communication capabilities. These wireless sensors provide rich information which SHM algorithms can utilize to detect, locate and assess structural damage caused by severe loading events and by progressive environmental deterioration as well as economical realization of the SHM system. Information from densely instrumented structures is expected to result in deeper insight into the physical state of the structural system.

Wireless sensors-based structural health monitoring

Cho *et al.*[1] present the results of international cooperative research on smart wireless sensors and SHM of civil structures among Korea Institute of Science and Technology, the University of Michigan, and the University of Illinois at Urbana-Champaign. They discuss the state-of-the-art in the smart wireless sensor technology and the subsystems of a smart wireless sensor and available wireless sensor platforms developed in the academia and industry are reviewed. Three smart wireless SHM systems developed by the authors and applied to SHM of various types of civil structures have been presented. The first system is a distributed modal identification system using a smart wireless sensor platform, which is applied to the modal identification of a balcony structure in a historic theatre. The second one is a low-cost and autonomous wireless tension estimation system for cable-stayed bridges, which is employed for modal identification and tension estimation of a stay cable. The last one is an autonomous decentralized SHM system, which is applied to damage detection on a 3D steel truss structure. Various available smart wireless sensor platforms are shown in Figure 1.

Heo and Jeon[2] developed a smart monitoring system based on ubiquitous computing technique for infrastructural system. This system is designed to enable the use of TCP/IP network protocol, communicating the data measured by a wireless sensing unit based on bluetooth technology. In order to verify this system, a randomly excited self-anchored suspension bridge was tested for real-time monitoring by remote network user. Dynamic characteristics were identified using the acquired data from the monitoring test. Real-time structural monitoring tests were performed under ambient vibration, instead of using the input excitation devices (Figure 2). To validate this system, monitoring tests were carried out on randomly excited prototype self-anchored suspension bridge. Monitoring test results were sufficient to satisfy the sensing ability of identification of structural integrity of the monitored structure.

Wang *et al.*[3] carried out validation of an integrated network system for real-time wireless monitoring of civil structures. They present an integrated real-time wireless SHM system that addresses some of the technical issues. The proposed system supports real-time data acquisition

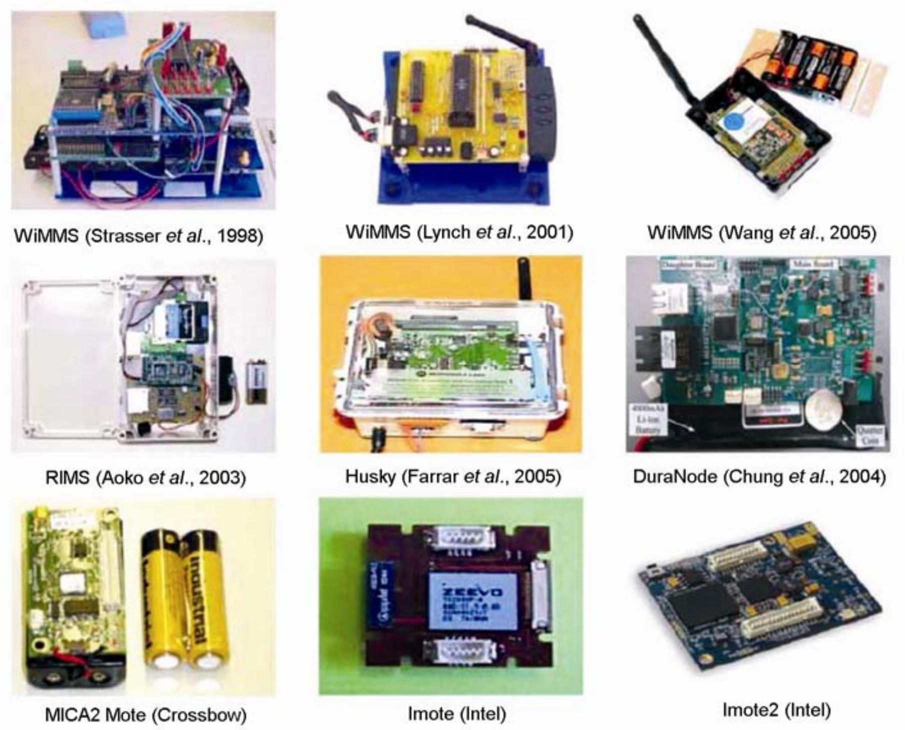

Figure 1. Various available wireless sensor platforms.

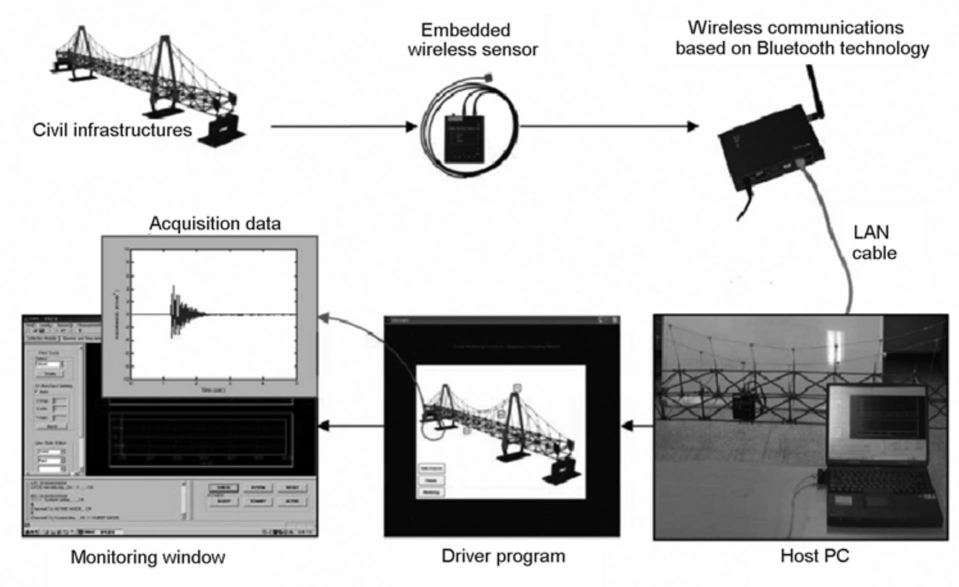

Figure 2. Ubiquitous smart monitoring test set-up.

from multiple wireless sensing units, which can simultaneously collect and analyse data from a heterogeneous set of analog sensors. Low-cost signal conditioning circuits are incorporated to improve the quality of sensor signals. The feasibility and reliability of this integrated wireless SHM network system are corroborated by extensive laboratory and field tests. An overview of the prototype system is illustrated in Figure 3. Kim *et al.*[4] present health monitoring of civil infrastructure using wireless sensor networks (WSNs). A WSN for SHM is designed, implemented, deployed and tested on a 4200 ft long main span and the south tower of the Golden Gate Bridge (GGB)[4]. Ambient structural vibrations are reliably measured at low cost and without interfering with the operation of the bridge. Requirements that SHM imposes on WSN are identified and solutions to meet these requirements are proposed and implemented. This work has three major contributions to WSNs. First, requirements are identified to obtain data of sufficient quality to have real scientific value to civil engineering research for SHM. Second, the system is designed to scale to a large number of nodes to allow dense sensor coverage of real-world structures. Third, this network is deployed in a real-world structure solving a myriad problems encountered in a real deployment in difficult conditions.

Chung *et al.*[5] carried out studies on real-time visualization of structural response with wireless Micro Electro Mechanical Systems (MEMS) sensors. This study developed and investigated reliability and accuracy of wireless MEMS-type sensors for real-time seismic monitoring of bridges. The wireless capability added to the developed MEMS sensors makes it possible to avoid the use of lengthy multiple cables for bridge monitoring. By further developing the embedded micro-computer units and functions such as detecting frequency responses, possible damage of bridge structures can be detected to give early warning to citizens and prevent the loss of life or damage to property. The sensors can have numerous other uses and offer great potential for carrying out structural monitoring missions in harsh environments. Performance monitoring of the Geumdang Bridge, Korea using a dense network of high-resolution wireless sensors has been carried out by Lynch *et al.*[6]. In this study, a network of low-cost wireless sensors (Figure 4) was installed in the Geumdang Bridge to monitor its response to truck loading. A total of 14 wireless sensors were installed in the concrete box girder span of the Geumdang Bridge to record acceleration responses to forced vibrations introduced by a calibrated truck. The performance of the complete wireless monitoring system was compared to a commercial tethered monitoring system that was installed in parallel. The performance of the wireless monitoring system is shown to be comparable to that of the tethered

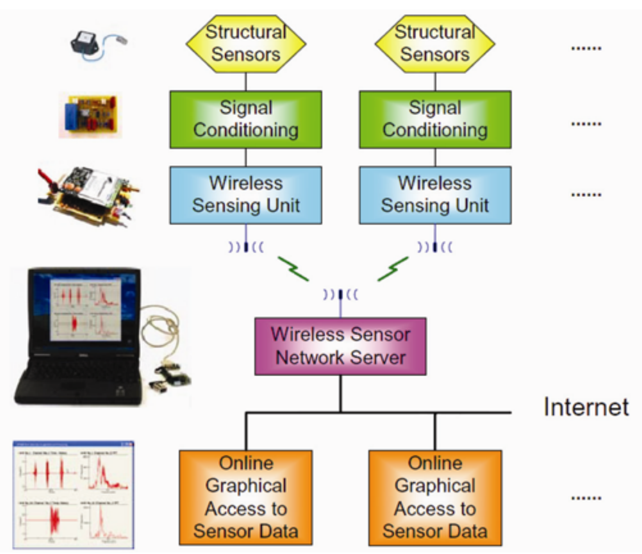

Figure 3. Overview of the developed prototype system.

counterpart. This form of distributed processing of measurement data by a network of wireless sensors represents a new data management paradigm associated with wireless structural monitoring.

Lynch *et al.*[7] have carried out the design of a wireless sensing unit for SHM. Employing an enhanced RISC microcontroller, the sensing unit has powerful computational capabilities for data aggregation and processing. Two MEMS-based accelerometers were also employed in this study. With a completed working prototype unit, the functionality of the unit was first validated through various controlled experiments in the laboratory. In the first validation experiment, the sensor unit was placed upon a flat static laboratory surface and queried for acceleration data from the on-board ADXL210 accelerometer. In the second experiment, the sensor unit was tested for performance characteristics during sinusoidal excitations. The measured data coincide well with the input signal with some noise incorporated within the signal. However, appropriate filtering techniques can be included within the microprocessor in the sensor unit or remotely in a data-logging unit to obtain the clean true signal from the noisy measured data. Work has also been carried out on instrumentation of bridges for SHM[8]. As the state-of-the-art in bridge design is advancing towards a performance-based design, it becomes increasingly important to monitor and evaluate the long-term structural performance of bridges. In this study[8], sensor systems for long-term structural performance monitoring have been installed on two highway bridges. On one bridge, ambient vibration data have been collected based on which natural frequencies and mode shapes have been extracted using various methods and compared with those obtained by the preliminary finite element (FE) analysis. On the other bridge, braking and bumping vibration tests have been carried out using a water truck in addition to ambient vibration tests. Natural frequencies and mode shapes have been derived and the results by the breaking and bumping vibration tests have been compared. The peak picking method, the random decrement method and the frequency domain decomposition method were used to extract modal parameters, including natural frequencies and mode shapes from the ambient vibration data. The results showed that the high and the horizontal modes were more contaminated by noises than the low and the vertical modes and the frequency domain decomposition method was considered as the best among the three methods. With the sensor systems permanently installed on these two highway bridges, their structural performance will be continuously monitored in the future.

Coupling sensing hardware with data interrogation software for SHM has been carried out by Farrar *et al.*[9]. They have addressed the SHM problem in the context of a statistical pattern recognition paradigm. In this paradigm, the process can be broken down into four parts: (1) operational evaluation, (2) data acquisition and cleansing,

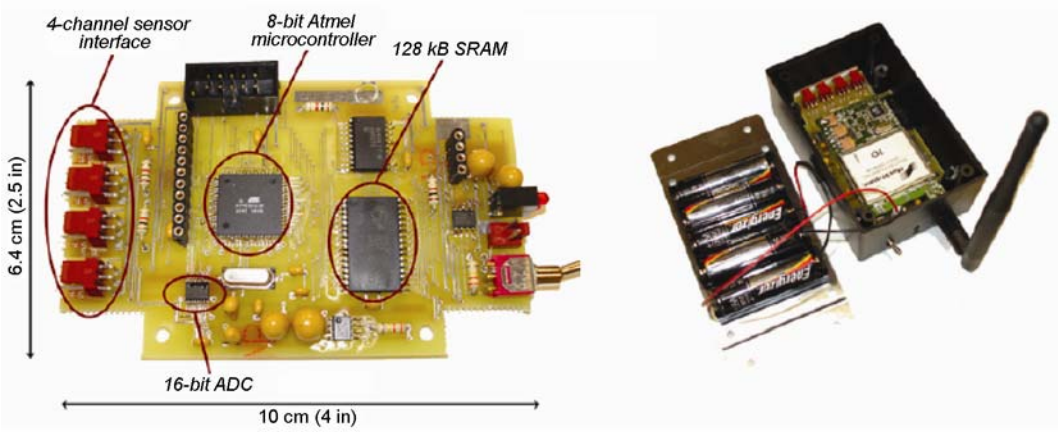

Figure 4. Wireless sensor prototype for structural health monitoring.

(3) feature extraction and data compression and (4) statistical model development for feature discrimination. These processes must be implemented through hardware or software and, in general, some combination of these two approaches will be used. More specifically, this work addresses the need to take an integrated hardware/ software approach to developing SHM solutions. To develop a true integrated SHM system, the data interrogation processes must be transferred to embedded software and hardware that incorporates sensing, processing and the ability to return a result either locally or remotely. Many integrated systems are inflexible because of tight integration between the embedded software, the hardware and sensing. The LANL/Motorola research team is beginning the process of planning the next-generation system that will address these issues.

Knecht and Manetti[10] present SHM using Global Positioning System (GPS). This technology can provide position information with accuracy up to a few millimetres in near real time. It is shown that using carrier phase differential GPS, a network of receiver modules can be installed in order to perform monitoring and surveillance operations for small movements. Typical applications for this type of sensor network include monitoring of structures such as buildings, dams, bridges, as well as measuring the movement of landslides and rock formations. The system consists of a number of small receivers installed on the object to be monitored. A radio-linked base station provides data collection, post-processing and monitoring for correct operation of the network. The results presented by the authors indicate that a base precision of less than 1 cm is achievable in many practical monitoring situations.

Lee *et al.*[11] present the health-monitoring method for bridges under ordinary traffic loadings. A method for damage estimation of a bridge structure is presented using ambient vibration data caused by the traffic loadings. The procedure consists of identification of the operational modal properties and assessment of damage locations and severities. A method is presented for the element-level damage assessment of a bridge using the modal properties obtained from the vibration data caused by ordinary traffic loadings and verified by a series of vehicle tests on a bridge model. It has been found that most of the inflicted damages can be detected successfully for various vehicle load conditions; however, the degree of damage severity generally tends to be slightly overestimated. For practical applications, accuracy of the estimated damage severities may be less important, as long as the damage locations can be detected precisely.

Rice and Spencer[12] carried out the SHM sensor development for the Imote2 platform. They have explored the development of a versatile Imote2 sensor board with on-board signal processing specifically designed for the demands of SHM applications. The components of the accelerometer board have been carefully selected to allow for the low-noise and high-resolution data acquisition that is necessary to successfully implement SHM algorithms. The design and testing of a newly developed Structural Health Monitoring Accelerometer (SHM-A) board that interfaces with the Imote2 wireless sensor platform is presented and experimentally verified.

Lynch *et al.*[13] carried out the validation of a wireless modular monitoring system for structures. A wireless sensing unit for use in a Wireless Modular Monitoring System (WiMMS) has been designed and constructed. Drawing upon advanced technological developments in the areas of wireless communications, low-power microprocessors and MEMS sensing transducers, the wireless sensing unit represents a high-performance yet low-cost solution to monitoring the short-term and long-term performance of structures. The novel concept of employing the computational core of the wireless sensing unit for local data interrogation schemes has been investigated. A Fast Fourier Transform (FFT) has been successfully implemented and the primary modes of response of a structure identified locally by a wireless sensing unit mounted on a test structure.

A review of guided-wave SHM was carried out by Raghavan and Cesnik[14]. The authors have presented the state-of-the-art in the field of guided-wave SHM. They begin with an overview of damage prognosis and a description of the basic methodology of guided-wave SHM. Next they review developments from the open literature in various aspects of this truly multidisciplinary field. They also highlight the broad spectrum of applications in which this technology has been tested, with some studies that have attempted to combine guided-wave approaches with other complementary SHM technologies for better system performance. Park *et al.*[15] carried out studies on an active sensing-based real-time non-destructive evaluation for steel bridge members. They present an experimental study on the applicability of piezoelectric lead–zirconate–titanate (PZT)-based active sensing techniques for non-destructive evaluation (NDE) of steel bridge members. In this study, the impedance-based damage detection method and the lamb wave-based damage detection method were applied to steel bridge members. Results from the experiments showed the validity of the proposed methods.

Kanga *et al.*[16] carried out studies on the structural system identification (SI) in time domain using measured acceleration, to estimate stiffness and damping parameters of a structure. An error function is defined as the time integral of the least-squared errors between measured acceleration and calculated acceleration by a numerical model of a structure. The validity of the proposed method is demonstrated by a numerical simulation study on a two-span truss bridge and by an experimental laboratory study on a three-storey shear building model. Anastasi *et al.*[17] carried out studies on WSNs for SHM of historical buildings. The authors describe the use of WSNs on a cultural heritage building with a great historical and artistic interest, namely the church of St. Teresa in the Kalsa district, Palermo, Italy, a baroque building dating back to early 1700. One sensor board equipped with an accelerometer was positioned on the base of the iron cross on top of the building. A second accelerometer was positioned on a stable area inside the attic of the building, in line with the first one, in order to provide a comparison measurement. In the same area, a few strain gauges were also deployed in correspondence with two cracks in the walls. Each crack was monitored by two gauges, positioned along the horizontal and vertical axes. MicaZ nodes belongs to the mote family and are well suited for low-cost, resource constrained applications. The Intel's Stargate platform, on the other hand, is typically used for higher-performance tasks or for mote coordination. The Stargate node acting as base station will take care of sending the proper commands, and will also supervise time synchronization between nodes. Collected data are again processed and compressed at the base station, and forwarded to the local storage and then to the remote processing unit via a radio link.

Paek *et al.*[18] studied the performance of a WSN for SHM. The authors evaluated the performance of WISDEN – a wireless multi-hop sensor network-based data acquisition system for SHM applications. They deployed WISDEN in two real environments: a seismic test structure and a four-storey office building. The performance of WISDEN was not up to the mark during this experiment, primarily due to the software bug. Lu *et al.*[19] carried out studies on the application of wireless sensors for SHM and control. To validate the performance of the proposed WiMMS on the vibration measurement of large-scale civil structures, a three-storey half-scale steel structure was instrumented with a wireless monitoring system assembled from a network of six wireless sensors and tested on a shaking table to ensure reliability of data communication. The results show that WiMMS can provide broad applications to monitoring and control of civil infrastructure. With the designed converter different sensor signals can be used as input to the wireless sensing unit for monitoring purpose. For structural control purpose, one can embed the control gain as well as the control algorithm in the sensing unit.

Impedance-based structural health monitoring systems

Overly *et al.*[20] developed an extremely compact impedance-based wireless sensing device for SHM and piezoelectric active-sensor self-diagnostics. The sensor node uses a recently developed, low-cost integrated circuit that can measure and record the electrical impedance of a piezoelectric transducer. The sensor node also integrates several components, including a microcontroller for local computing, telemetry for wireless transmission of data, multiplexers for managing up to seven piezoelectric transducers per node, energy harvesting and storage media, and a wireless triggering circuit into one package to truly realize a comprehensive, self-contained wireless active-sensor node for various SHM applications. It is estimated that the developed sensor node requires less than 60 mW of total power for measurement, computation and transmission. In addition, the sensor node is equipped with active-sensor self-diagnostic capabilities that can monitor the condition of piezoelectric transducers used in SHM applications. The performance of this miniaturized device was compared with previous results and its broader capabilities were demonstrated. The WID2 was developed to meet a need in the SHM field for a small, power-efficient and flexible wireless impedance node. There are several factors that contribute to the flexibility of WID2. First, the ability to quickly and efficiently change the code on the microcontroller, through the on-board ISP header, allows one to perform a wide variety of data manipulation with minimal effort. Second, the ability to accept power from diverse sources through the built-in power port and its low power consumption increase its versatility. Finally, the WID2 is capable of controlling multiple sensors per node (up to seven sensors) and is equipped with several triggering options, i.e. wireless triggering or timer triggering. All of the above factors contribute to make the WID2 an attractive device for SHM applications.

Mascarenas *et al.*[21] developed an impedance-based wireless sensor node for SHM. The principle behind this technique is to apply high-frequency ultrasonic excitations to the structure through surface-bonded piezoelectric transducers. In this study, the authors have developed a wireless impedance sensor node equipped with a low-cost integrated circuit chip that can measure and record the electrical impedance of a piezoelectric transducer, a microcontroller that performs local computing and a wireless telemetry module that transmits the structural information to a base station. The performance of this miniaturized and portable device has been compared to results obtained with a conventional impedance analyser and its effectiveness has been demonstrated in an experiment to detect loss of preload in a bolted joint. Furthermore, the authors also considered the problem of wireless powering of such SHM sensor nodes, where they used RF wireless energy transmission to deliver electrical energy to power the sensor node. In this way, the sensor node does not have to rely on the on-board power source and the required energy can be wirelessly delivered.

Grisso and Inman[22] developed an autonomous on-orbit impedance-based SHM system for thermal protection. The development of a digital signal processor (DSP)-based prototype is the focus for initial efforts in realizing a fully self-contained active sensor system utilizing impedance-based SHM. All of the structural excitation, data acquisition, and health monitoring analysis are performed in a matter of seconds, whereas with traditional impedance techniques, after the data are acquired, all of the analysis must still be done using processing software to determine whether there is damage.

A system-on-board approach for impedance-based SHM was carried out by Kim *et al.*[23]. By introducing a new excitation method and implementing a new damage detection scheme, reliance on both analog-to-digital and digital-to-analog conversion is circumvented. To verify the functionality and evaluate the performance of the prototype, a test structure was developed. Measurement results obtained using the test structure proved that the developed SHM prototype provides reliable performance. This prototype utilizing digital low-power SHM algorithm successfully demonstrated the feasibility of system-on-board implementation of the SHM system. Multiple crack detection of concrete structures using impedance-based SHM techniques was carried out by Park *et al.*[24]. The authors present a feasibility study for practical applications of an impedance-based real-time health monitoring technique applying PZT patches to concrete structures. First, comparison between experimental and analytical studies for damage detection on a plain concrete beam was made. In the experimental study, progressive surface damage inflicted artificially on the plain concrete beam was assessed using both lateral and a thickness mode of the PZT patches. Then, an analytical study based on FE models was carried out to verify the validity of the experimental results. This study showed successful damage prediction results with a consistent trend in the variation of the impedance signature of the PZT patches, according to the progressive surface damage on the concrete beam.

Displacement-based structural health monitoring

Lee and Shinozuka[25] carried out the real-time displacement measurement of a flexible bridge using digital image processing techniques. This is innovative, highly cost-effective and easy to implement, yet maintains the advantages of dynamic measurement and high resolution. First, the measurement point is marked with a target panel of known geometry. A commercial digital video camera with a telescopic lens is installed on a fixed point away from the bridge (e.g. on the coast) or on a pier (abutment), which can be regarded as a fixed point. Then, the video camera takes a motion picture of the target. Meanwhile, the motion of the target is calculated using image-processing techniques, which require a texture recognition algorithm, projection of the captured image and calculation of the actual displacement using target geometry and the number of pixels moved. The applicability and effectiveness of the present method was verified through two field applications on a bridge with steel plate girders and a bridge with steel box girders. Lee *et al.*[26] present the development and application of a vision-based displacement measurement system for SHM of civil structures. The effectiveness of the proposed system was verified by comparing the load carrying capacity of a steel-plate girder bridge obtained from the conventional sensor and the present system. For the purpose of verification, the measured displacement by a synchronized vision-based system was compared with the data measured by conventional contact-type sensors, linear variable differential transformers (LVDT) from a laboratory test.

Damage detection techniques

Kessler *et al.*[27] carried out studies on damage detection in composite materials using Lamb waves. This paper presents part of an experimental and analytical survey of methods for *in situ* damage detection of composite materials. Experimental results are presented for the application of Lamb wave techniques to quasi-isotropic graphite/epoxy test specimens containing representative damage modes, including delaminations, transverse ply cracks and through-holes. Park *et al.*[28] present the modal flexibility-based damage detection technique of steel beam by dynamic strain measurements using FBG sensors. It has been found that the strain-flexibility approach using dynamic strain measurements from FBG sensors can successfully detect and localize multiple small damages near the sensors. Kim *et al.*[29] carried out studies on the temperature effects on frequency-based damage detection in plate-girder bridges. The variability of modal properties caused by temperature effects was assessed in order to adjust modal data used for nondestructive damage detection in structures. The relationship between temperature and natural frequency was analysed and a set of empirical frequency-correction formulas were obtained for the test structure. Results of the analysis indicated that the temperature correction scheme works for the accurate damage localization and severity estimation in the test structure. Experimental study of SI-based damage assessment on structures was carried out by the Jang *et al.*[30]. Damage assessment algorithms based on the SI method are examined through laboratory experiments. The SI method considered herein identifies structural parameters in a FE model by minimizing the error between measured and analytically computed responses. Static displacements from static loading and modal data from impact vibration were measured through laboratory experiments on a grid-type model bridge. The baseline structural model and baseline properties were determined with experimental data obtained from the tests on the undamaged model structure. Damage was simulated by saw-cutting the cross-section with various depths and identified as the reduction in the structural stiffness of the elements around the crack. Through the experimental works, the applicability of the SI-based damage assessment algorithms has been rigorously investigated. Lee and Yun[31] presented the damage localization for bridges using probabilistic neural networks (PNNs). The damage location of a bridge is identified using PNNs. At first, modal parameters are identified from the ambient vibration data and are utilized as the feature vectors for PNNs. The results obtained from field tests can be summarized as follows: (1) PNN showed good estimation results in detecting single damage location. (2) PNN using sequential estimation scheme was successfully utilized to detect multiple damages. (3) The conventional back-propagation neural networks (BPNNs) can be an alternative to detect multiple damages. (4) It is easy to implement PNN and it is more effective for complex structures than conventional neural networks.

Data aggregation techniques

Nagayama *et al.*[32] presented the model-based data aggregation for structural monitoring employing smart sensors. Smart sensors densely distributed over structures can provide rich information for structural monitoring using their computational and wireless communication capabilities. One key issue in such monitoring is data aggregation. Model-based data aggregation is proposed using both structural and network analyses. A structural analysis algorithm, the Natural Excitation Technique, motivates adaptation of correlation function estimation to smart sensor networks. The data size is reduced by a factor of 20–40, depending on the degree of averaging in the aggregation. This averaging also addresses the wireless communication data-loss problem. The algorithm is implemented on Mica2 and experimentally validated using a scale-model building. The proposed data aggregation scheme is directly applicable to SHM strategies such as the recently developed Distributed Computing Strategy (DCS) approach. Sim *et al.*[33] carried out the decentralized random decrement technique for efficient data aggregation and system identification in wireless smart sensor networks (WSSNs). They present a decentralized data aggregation approach for SI based on the Random Decrement Technique (RDT). Following a brief overview of the RDT, which is an output-only SI approach, a decentralized hierarchical approach is described and shown to be suitable for implementation in the intrinsically distributed computing environment found in WSSNs. The performance of decentralized RDT was assessed in terms of (1) accuracy of the estimated modal properties and (2) efficiency in the wireless data communication. From experimental implementation, the efficacy of the RDT-based decentralized data aggregation strategy has been demonstrated.

Energy harvesting for wireless sensors

Mateu and Moll[34] present a review of energy harvesting techniques and applications for microelectronics. They present several methods to design an energy harvesting device depending on the type of energy available. Kim *et al.*[35] present an all-digital low-power SHM system. The digital techniques are implemented onto a prototype which achieves substantial reduction in size and power consumption. Compared to the impulse-like sine-wave excitation employed in the first prototype, the proposed digital low-power approach reduces power dissipation by 80%. The measurement results obtained from the prototype are compared with those collected from a traditional impedance analyser. Results of this comparison showed that the proposed digital low-power approach provides a reliable means of detecting damage compared to the impedance analyser measurement data. A review of power harvesting from vibration using piezoelectric materials is presented by Sodano *et al.*[36]. The process of acquiring the energy surrounding a system and converting it into usable electrical energy is termed power harvesting. In the last few years, there has been a surge of research in this area. This is due to the modern advances in wireless technology and low-power electronics such as MEMS. The advances have allowed numerous options for power harvesting systems in practical real-world applications. The use of piezoelectric materials to capitalize on the ambient vibrations surrounding a system is one method that has seen a dramatic rise in use for power harvesting. Piezoelectric materials have a crystalline structure that provides them with the ability to transform mechanical strain energy into electrical charge and vice versa – to convert an applied electrical potential into mechanical strain. This property provides these materials with the ability to absorb mechanical energy from their surroundings, usually ambient vibration and transform it into electrical energy that can be used to power other devices. While piezoelectric materials are the major method of harvesting energy, other methods do exist; for example, one of the conventional methods is the use of electromagnetic devices. Srivastava[37] presents the challenges of next-generation WSNs and their impact on society. The author discusses about classification of WSNs and challenges of the next-generation WSNs. One of the major challenges of next-generation WSNs is reduction of power consumption. Two approaches are discussed: ultra-low-power networks and energy harvesting. The paper also discusses some major applications such as designing low-cost secured intelligent buildings, in-home health care and agriculture.

Obstructions in wireless communication

Janek and Evans[38] carried out studies on predicting the ground effects of omnidirectional antennas in WSNs. Omnidirectional antennas are often used for RF communication in WSNs. Outside noise, electromagnetic interference (EMI), overloaded network traffic, large obstacles (vegetation and buildings), terrain and atmospheric composition, along with climate patterns can degrade signal quality in the form of data packet loss or reduced RF communication range. This study explores the RF range reduction properties of a particular WSN designed to operate in agricultural crop fields to collect aggregate data composed of subsurface soil moisture and soil temperature. The study, using simulation, anechoic and field measurements shows that the effect of antenna placement close to the ground (within 10 cm) significantly changes the omnidirectional transmission pattern. The authors then develop and propose a prediction method that is more precise than current practices of using the Friis and Fresnel equations. This prediction method takes into account environmental properties for RF communication range based on the height of nodes and gateways. Thongsopa *et al.*[39] studied the measurement of UHF signal strength propagating from the road surface with vehicle obstruction. Radio wave propagation on the road surface is a major problem in WSNs for traffic monitoring. The authors compare receiving signal strength on two scenarios: (1) an empty road and (2) a road with a vehicle. They investigate the effect of antenna polarization and antenna height to the receiving signal strength. The transmitting antenna was installed on the road surface. The receiving signal was measured 360° around the transmitting antenna with the radius of 2.5 m. Measurement results show the receiving signal fluctuation around the transmitting antenna in both scenarios. Receiving signal with vertical polarization antenna results in higher signal strength than horizontal polarization antenna. The optimum antenna elevation is 1 m for both horizontal and vertical polarizations with the vehicle on the road.

Ilyas and Mahgoub[40] have edited a handbook of sensor networks for compact wireless and wired sensing systems. It provides technical information about various aspects of sensor networks, networks comprising multiple compact and intercommunicating electronic sensors.

Summary

In this article, recent R&D and application of smart sensing, monitoring and damage detection for civil infrastructure have been presented. Smart sensors such as optical fibre sensors, piezoelectric sensors, wireless sensors and their applications were discussed. Recent developments in the structural monitoring techniques were presented, particularly on ambient vibration-based bridge monitoring/assessment, global damage assessment using soft computing algorithms, WSNs without data collision and excessive energy consumption, local damage detection using wireless impedance sensor nodes, guided wave-based crack damage detection using piezoelectric sensors, wireless power transmission methodology using laser/optoelectronic devices and energy harvesting systems adapted for civil infrastructure.

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