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A review on sensors and systems in structural health monitoring: current issues and challenges

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Abstract. Sensors and systems in Civionics technology play an important role for continuously facilitating real-time structure monitoring systems by detecting and locating damage to or degradation of structures. An advanced materials, design processes, long-term sensing ability of sensors, electromagnetic interference, sensor placement techniques, data acquisition and computation, temperature, harsh environments, and energy consumption are important issues related to sensors for structural health monitoring (SHM). This paper provides a comprehensive survey of various sensor technologies, sensor classes and sensor networks in Civionics research for existing SHM systems. The detailed classification of sensor categories, applications, networking features, ranges, sizes and energy consumptions are investigated, summarized, and tabulated along with corresponding key references. The current challenges facing typical sensors in Civionics research are illustrated with a brief discussion on the progress of SHM in future applications. The purpose of this review is to discuss all the types of sensors and systems used in SHM research to provide a sufficient background on the challenges and problems in optimizing design techniques and understanding infrastructure performance, behavior and current condition. It is observed that the most important factors determining the quality of sensors and systems and their reliability are the long-term sensing ability, data rate, types of processors, size, power consumption, operation frequency, etc. This review will hopefully lead to increased efforts toward the development of low-powered, highly efficient, high data rate, reliable sensors and systems for SHM.

Keywords: sensors; Civionic; structural health monitoring; sensor classes; wireless sensor network

1. Introduction

Structural health monitoring (SHM) is an important issue related to the structural safety, integrity, durability, validity and the life-span or the health of a structure (Han *et al.* 2008). Sensors and SHM are correlated terms in advanced civil engineering fields such as building, bridge, tower, and dam monitoring. SHM is the evaluation of a structure's condition using sensor technology based on measuring and transferring monitoring data. Today, SHMs use sensor networks to increase awareness of deterioration, lack of performance of the infrastructural systems and effective maintenance of the deficient structures (Hassan *et al.* 2011). The use of sensor networks reduces maintenance complexity and costs associated with SHM systems (Barbezat *et al.* 2004, Annamdas *et al.* 2017) by integrating sensors into structures, machinery, and the environment which coupled with the efficient delivery of sensed information, provides tremendous benefits to society. These potential benefits include fewer catastrophic failures, conservation of natural resources, improved manufacturing productivity, improved emergency response, and enhanced homeland security applications related to SHM (Barbezat *et al.* 2004, Jang *et al*. 2008).

In general, SHM research includes three major components: the sensor systems, data processing system and health evaluation system as shown in Fig. 1. The sensor systems include the sensor technologies and sensor networks. Fig. 1 mainly highlighted the involvement of the component and the sensor systems for SHM applications. The main components of Civionics technology for the real-time monitoring of a structure are the sensors, transmitters, a receiver that includes diagnostic algorithms and the information management system. As an example, an advanced wireless bridge girder health monitoring system is shown in Fig. 2. In fact, Civionics is the synergistic combination of civil engineering, electrical and electronics engineering, computer engineering, photonics and other disciplines for structural health monitoring. The term "Civionics" was first coined in Canada by the Centre for Innovative Sensing for Innovative Structures (ISIS) and is derived from the concept of implementing electronics in the civil engineering fields (Casciati *et al*. 2014, Mufti 2007). The sensor can be used to collect structural behaviour measurement parameters such as the acceleration, deflection, humidity and strain of each structural component. These data are transceived, processed to obtain the original data at the receiver, stored and subsequently visualized using a computer. The monitoring data are subsequently compared with threshold values to identify the structural change of a structure using diagnostic algorithms (Hassan *et al.* 2011, Jang *et al*. 2008, Hassan *et al*. 2010).

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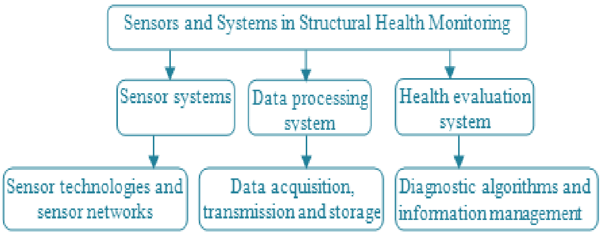

Fig. 1 Major components in structural health monitoring

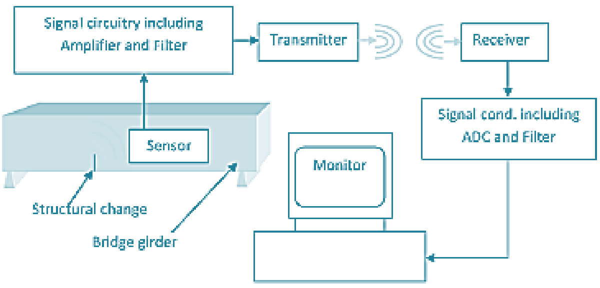

Fig. 2 An advanced Civionics technology for bridge girder monitoring.

In recent years, SHM technology has played an important role in continuously facilitating real-time structural health monitoring systems and provides the necessary feedback to engineers in optimizing design techniques, understanding infrastructure's performance, behavior and current condition (Mufti *et al.* 2007, Cazzulani *et al.* 2013, Nasrollahi *et al*. 2017).

SHM is the engineering branch where the serviceability of constructions is assessed by non-destructive indirect measurements and monitors of physical properties like vibration, temperature, deflection, noise, moisture content, etc. Increase level of these properties will create uncertainties in detecting real changes in the dynamic characteristics of the structure in real-life field applications (Moore *et al.* 2001). These uncertainties or effects can be avoided during the planning stage adopting technologies that make bridge smarter by acquiring continuous data, expert visual inspection and comparative analysis with the threshold, respectively (Chen *et al*. 2017). Moreover, the variations in the data due to uncertainties, an advanced algorithm could be implemented to check the violence and to determine the severity of the structural health. If the violence and severity exceed the threshold level after a consecutive time, an alarm could be sent and successive alarm will provide information of damage and whether immediate attention is required. The successful integration of intelligent sensing system in structures allows structural engineers to expand the design envelope by taking risks in introducing new design concepts, materials and innovations in civil engineering. Real-time monitoring systems also help engineers to determine the actual behavioral change of a structure during the service life of the structure. During the service life of the structure, a number of significant factors such as dynamic loading, fatigue loading, sustained loading, concrete strength and aging, freezing and thawing frequency and many other environmental and construction related issues influence the structure's lifetime and increase the structure's failure rate (Hassan *et al*. 2011). To prevent structural failures, sensor technology is becoming an emerging issue in Civionics research. The aim of this article is to provide a sufficient background on the challenges and problems that are being faced and will lead to increasing development of new, improved and appropriate solutions for reliable SHM.

2. Related surveys and Taxonomy in Civionics Research

Civionics is a new discipline concerned with the use of electronic devices for the monitoring of civil engineering infrastructure, such as bridges, buildings, dams, and tunnels. Civionics produces engineers capable of constructing so-called "smart" structures that contain the necessary SHM equipment to provide needed structural information to avoid major structural failures (Mufti 2003, Rivera *et al*. 2007). This discipline, therefore, assists engineers and others in realizing the full benefits of monitoring civil engineering structures and allows structural engineers to evaluate new concepts and materials and understand aging buildings. Detail of the Civionics related researches are explained below.

2.1 Related Civionics research in SHM

In recent years, Civionics research has been conducted on the continuous monitoring of infrastructure such as bridges, buildings, dams, tunnels, and tower monitoring systems. The first studies on Civionics were performed by ISIS Canada to introduce significant innovations in the design and construction of civil engineering structures (Bogdabovic *et al*. 2005). Therefore, it is imperative that innovative structures be monitored for their health so that modifications in design and construction can be accepted. Over the past few years, researchers from the ISIS network have installed numerous fiber optic sensors (FOS) in demonstration projects across Canada (Mufti *et al.* 2007). ISIS Canada provides smarter ways to build, repair, and monitor structures using high-strength, non-corroding, fiber-reinforced polymers and fiber optic sensing systems. For example, in 1992, the Beddington Trail Bridge in Calgary, Canada was outfitted with FRP tendons and a system of structurally integrated optical sensors to facilitate remote monitoring (Mufti and Neale 2008). Fiber Bragg grating (FBG) strain and temperature sensors were used to monitor the structural behavior during construction and maintenance (Chen *et al.* 2017). A 4-channel Bragg grating fiber laser sensing system was developed as a data acquisition system and placed at various locations along the bridge girders to monitor a bridge at the Institute for Aerospace Studies, University of Toronto. In addition, ISIS Canada has monitored the structural health of the Salmon River Bridge, Chatham Bridge, Confederation Bridge, Crowchild Trail Bridge, Taylor Bridge, Joffre Bridge, Waterloo Creek Bridge, and Hall's Harbourt Wharf (Mufti and Neale 2008).

The Civionics Research Centre at the University of Western Sydney, Australia attempts to substantially increase the performance of Civionics research by producing high-quality, high-impact studies (Mufti 2007). Their initial areas of focus were intelligent infrastructure design, SHM, and the intelligent repair and maintenance of infrastructure. Civionics, a US company established in 2009, provides customized wireless sensing and embedded control solutions to the SHM (Civionics 2009). Since 2010, Civionics has been working with the US Department of Homeland Security to develop a low-cost wireless monitoring system for urban search and rescue personnel tasked with finding survivors in partially and totally collapsed buildings. The Civionics team has successfully installed wireless monitoring systems in civil engineering laboratories at the University of Michigan, Stanford University, the University of Minnesota, the University of California – San Diego, and at National Taiwan University, among others. The team has also successfully implemented wireless monitoring systems on long-span bridges in New Mexico, Michigan, California, Korea, and Taiwan (Lynch *et al.* 2006).

Civionics research is concerned with civil and structural engineering, sensor technology and sensor networks for structural health monitoring. In civionics research, applications, sensor technologies and sensor networks are integrated both from new and traditional disciplines as shown in Fig. 3. Structural engineering is concerned with the analysis and design support to ensure that the design criteria and predicted safety parameters are met by using physical laws and empirical knowledge of a structure's performance and serviceability (Mufti and Neale 2008). SHM involves the observation of a system using periodically sampled dynamic responses from an array of sensors, the extraction of damage-sensitive features, and the statistical analysis of these features to evaluate structural health indicators such as age and degradation (Yu and Tian 2013, Ubertini *et al.* 2014). Deformation monitoring is the systematic measurement and tracking of alterations in shape or dimension of an object that may be used for further computation, deformation analysis, predictive maintenance and alarming (Tastani and Pantazopoulou 2008). Automatic deformation monitoring systems provide a critical function that has saved lives and prevented the loss of millions of dollars in infrastructure and income (Liu *et al.* 2014).

Sensor technology includes strain gauge sensors, FBG sensors, accelerometers, transducers, tensometers, ultra-sonic sensors etc. Details of these sensor technologies in SHM are given in section 3. A strain gauge sensor consists of an insulating flexible backing that supports a metallic foil pattern and is used to measure the strain of an object (Binici 2005). The most common sensors that are used for bridge testing and monitoring applications are the electrical resistance strain gauge sensors and vibrating-wire strain gauge sensors. A FBG is constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits by creating a periodic variation in the refractive index of a specially designed dielectric mirror that is used as an inline optical filter to block certain wavelengths or as a wavelength-specific reflector (Ye *et al*. 2014, Maheshwari *et al*. 2016).

Accelerometer sensors, such as piezoelectric accelerometers that provide a charge output, piezoelectric accelerometers with internal electronics that provide a voltage output, piezoresistive accelerometers, capacitive accelerometers, servo force balance accelerometers and micro-electro-mechanical system (MEMS) accelerometers, are used in infrastructure health monitoring (Bao *et al.* 2011). A transducer converts one type of energy to another in the form of electrical, mechanical, electromagnetic, light, chemical, acoustic or thermal energy and is mainly used in measuring instruments. A tensometer is used to evaluate the Young's modulus and other tensile properties of materials such as tensile strength by applying a force to a specimen on a universal testing machine loaded with the specimen held between two grips (Tensometer 2012). Ultrasonic sensors are based on a principle similar to radar or sonar where the evaluation of attributes of a target is performed by interpreting the echoes from radio or sound waves, respectively (Shih *et al*. 2010). Ultrasonic sensors generate high-frequency sound waves that are used to measure material properties to detect cracks, voids, and delamination of the structural components of buildings, bridges etc. (Bai *et al.* 2017).

Due to technological advancements in wireless sensing, SHM systems have become popular because of their low cost, low profile and other flexibility issue (Choi *et al.* 2017, Liu *et al.* 2017). A number of challenging issues such as signal conditioning using low power, large scale measurements, data synchronization and accuracy and reliability of the transmission system exist. There are many modern telemetric devices used in SHM systems due to low cost and easy integration with the sensor networks (Shih *et al.* 2010). Remote sensing is the acquisition of information without physically contacting the object by using aerial sensor technologies to detect and classify objects by means of propagated signals. A wireless sensor network (WSN) consists of spatially distributed, autonomous sensors that monitor physical or environmental conditions such as temperatures, sounds, vibrations, pressures, motion or pollutants and cooperatively pass their data through the network to a main location (Fang *et al.* 2017).

Bi-directional WSNs are motivated by military, industrial and consumer applications such as battlefield surveillance process monitoring and control, machine health monitoring etc. The data acquisition of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware (Kareem *et al.* 2005). However, data normalization, cleansing and separation are become very important to the damage identification process. Thus, above selection process and data normalization can improve the data acquisition process. Recently, a number of researchers have developed different types of methods for SHM. These methods include using new signal processing methods, new sensor applications, control systems, global positioning systems, laser-based systems, vision-based systems, thermal-base systems, infrared systems, and electromagnetic sensors implementations have been performed that are based on electromagnetic-wave-guided media such as electromagnetic acoustic transducers (EMATs), wedge transducers, air-/fluid-coupled transducers, and laser-based, non-contact methods (Hyeonseok *et al.* 2010).

3. Sensor technologies in structural health monitoring

The sensor technologies are not a new technology in the construction of buildings, dams, tunnels, bridges etc. For a number of years, several types of sensors have been used in civil engineering structures to determine the service life condition of the structure and to detect any damage. The structural health (SH) conditions, currently available sensor technologies, sensor categories and application are listed in Table 1. In most cases, strain gauge sensors including electrical resistance strain gauge sensors, vibrating-wire strain gauge sensors, and fiber optic strain gauge sensors are used to measure structural strain properties for the evaluation of the infrastructure's current condition and identification of cracks (Hassan *et al.* 2011, Hassan 2010, Kerrouche e*t al*. 2010). However, there are number of drawback of FOS such as installation cost, need several special test equipment, higher communication cost, lack of communication in rural area FOS implementation. Fiber optic strain gauze sensors are extremely susceptible to temperature, thus temperature compensation is crucial. Moreover, due to bending and breaking of optical fiber cables intrinsic and extrinsic losses are occurred in fiber optics based on FOS material size, shape and placement (Kinet *et al*. 2014).

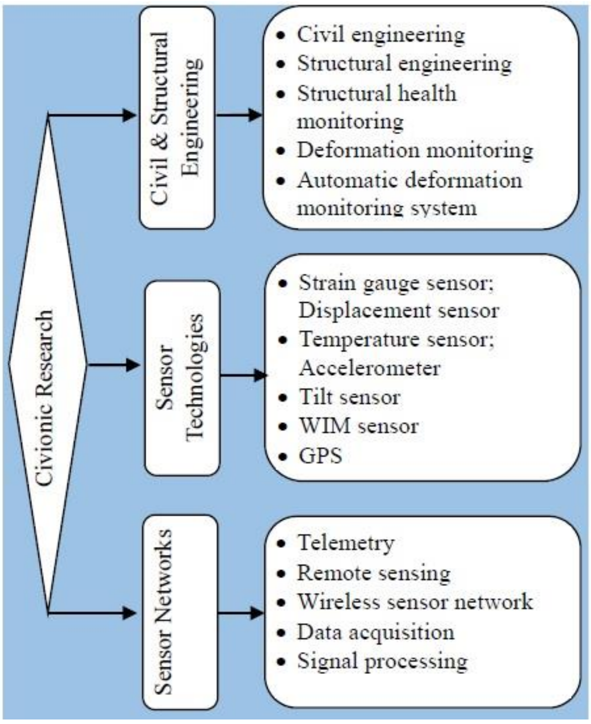

Fig. 3 Applications, sensor technologies and networks for structural health monitoring

While fiber optic strain gauge sensor is immune to voltage surge, radio frequency interference and electromagnetic interference, its implementation is accompanied by a few major drawbacks. Firstly, fiber optic strain gauge sensor faces issue on the cross-sensitivity between temperature and strain (Guemes *et al*. 2002). This is because this type of sensor will react to both temperature and strain. In addition, for fresh or wet concrete surface, fiber optic strain gauge sensor is proven to be unreliable due to the uncertainties of the epoxy bonding technique. Linear displacement and position measurement sensors such as cable extension transducers, linear variable differential transforms (LVDT), direct current differential transformers (DCDTs), and vibrating-wire crack meters have been used to measure the displacement of a bridge's structural components and crack width of a bridge crack (Lee *et al.* 2014). Thermocouples, thermistors and resistance temperature detectors (RTDs) are widely used temperature sensors that are used to measure temperature changes to detect cracks formed from thermal contraction, especially in steel bridge structures (Wang *et al.* 2007). The most widely available accelerometers are piezoelectric accelerometers, piezoelectric accelerometers with internal electronics, piezoresistive accelerometers, capacitive accelerometers, servo force balance accelerometers and MEMS accelerometers. All of these accelerometers measure the proper acceleration of the bridge structure and by subsequently processing the acceleration data, the frequency, damping and mode shape of the bridge structure can be identified. Any damage that occurs in the structure causes a loss of stiffness, whereas the mass of the structural member remains constant resulting in the loss of the natural frequency of the structure, which can be used as an indicator of damage in the structure (Capoluongo *et al.* 2007). A tilt sensor is used to measure the rotation of bridge components. The most widely available tilt meters are vibrating-wire tilt meters and electrolytic tilt meters. The operating principle behind vibrating-wire tilt meters is similar to vibrating-wire strain gauges, where the wire frequency is related to the measurement taken, and the output is the rotation (Wang *et al.* 2007). High-precision electrolytic tilt meters are used to measure the internal sensing element of the transducer.

Weigh-in-Motion (WIM) systems are used to obtain the static and dynamic weight of heavy vehicles for the protection and management of bridges, pavement and other infrastructure (Hackmann *et al.* 2014). Currently, there are many types of WIM systems, such as dynamic vehicle weighing systems, piezoelectric-type systems, bending plate systems, load cell systems, optic fiber systems, microwave-based MEMS WIM systems, capacitive mats etc. (Cheng *et al*. 2007). Piezo-strip and inductive-loop-based piezoelectric types are the least expensive, but bending plate systems are more rugged and accurate than piezoelectric systems (Kim *et al.* 2013). However, bending plate systems require considerable installation times and in some cases, fail prematurely. Strain gauged load cell systems are more accurate and rugged than bending plate systems, but they are also more expensive. Fiber optic WIM sensors are a promising new technology for pavement monitoring that is not susceptible to damage caused by

Table 1 Existing sensor technologies and its applications

SH Conditions	Sensor technologies	Classification of sensor category	Applications
Concrete reinforcement	Strain gauge sensor	• Resistance strain gauges • Vibrating-wire strain gauges • Fiber optic strain gauges	Testing of reinforced concrete slabs, floors, columns, beams, bridges (Kerrouche *et al.* 2010).
Testing structural components	Linear displacement and position measurement	• Cable extension transducers • LVDT • DCDT • Vibrating-wire crack meters	Testing of bridge and building components (Lee *et al.* 2014).
Temperature structural components	Temperature measurement sensor	• Thermocouples • Thermistors • RTD	Thermal testing of steel bridge and building components (Wang *et al.* 2007).
Concrete reinforcement	Accelerometer sensors	• Piezoelectric accelerometers • Piezoresistive accelerometers • Capacitive accelerometers • Servo force balance accelerometers • MEMS accelerometers	Testing of concrete, reinforced concrete, slabs, floors, columns, beams, concrete and steel bridges and buildings, dams, tunnels, etc (Guy and Jeff 2011, Sadeghian and Vecchio 2015).
Vibration and joint rotation	Tilt measurement sensors	• Vibrating-wire tilt meters • Electrolytic tilt meters	Determination of girder and beam-column joint (Wang *et al.* 2007).
Structural weight data collection and analysis	WIM system sensors	• Dynamic weighing of vehicles • Piezoelectric WIM systems • Bending plate WIM systems • Load cell WIM systems • Optic fiber WIM systems • MEMS WIM systems • Capacitive mats	WIM data collection, traffic monitoring, characterization, analysis and weight enforcement (Hackmann *et al.* 2014, Cheng *et al.* 2007, Kim *et al.* 2013, Hong *et al.* 2013, Malekzadeh *et al.* 2014).
Structural motion and position	GPS	• GPS	Radio navigation, bridge motion, position and traffic detection (Kareem *et al.* 2005).
Humidity of the structure	Environmental sensors	• Humidity sensors	Humidity of a structure, absorption or release of water vapor (Venugopalan *et al.* 2008).
Cracks and voids	Ultrasonic sensors	• Ultrasonic range sensor modules • Ultrasonic detectors • Ultrasonic flaw detectors • Waterproof Ultrasonic Sensors	Detection of cracks, voids structural components, humid area (Peng-hui *et al.* 2015).
Testing, detection reinforcement, crack, voids, delamination	Acoustic emission (AE) sensors	• Balance head AE sensors • In-spindle AE sensors • Fluid AE sensors	Testing, concrete and reinforced flooring, slabs, columns, beams, cracks, voids, and delamination (Baifeng and Weilian 2008).
Testing and detection, crack, voids, delamination	Impact echo sensors	• Sonic Impact Echo • Ultrasonic Echo Sensors • Microseismic Echo Sensors	Testing of concrete and reinforced concrete flooring and foundation slabs, columns, beams, girder, and detection of cracks, voids, and delamination (Zhang *et al.* 2015).

lighting; however, sufficient longevity and industrial support is yet to be proven (Hong *et al.* 2013, Malekzadeh *et al.* 2014). Liu *et al*. (2014) have studied microwave-based MEMS WIM sensors to estimate the dynamic load of a moving truck using transient vibrations of a bridge and pavement.

A new design for deployable capacitance based WIM sensors that are lightweight, small, portable and highly accurate in embedded concrete have been investigated as flexible weighing devices for vehicles on a structure (Cheng *et al.* 2007). PZT sensors provide large scale monitoring of civil infrastructure. Their reliability and associated system costs are more important than for other measurement systems. They are not only reliable, but they also provide improved safety monitoring systems for SHM (Lei *et al*. 2012). Global positioning systems (GPSs) use satellites as reference points for radio navigation systems to calculate their position (Kareem *et al*. 2005). A number of methods have been developed to solve the optimal sensor placement (OSP) problem. Among these methods is a highly efficient OSP approach that tends to maximize the trace and determinant and minimize the condition number of the Fisher information matrix (FIM) corresponding to the target modal partitions (Jo *et al.* 2013, Ting-Hua *et al*. 2012). Environmental sensors, i.e., humidity sensors are used to monitor the relative humidity of a structure. The relative humidity is measured using a thin film polymer material that absorbs or releases water vapor as the relative humidity

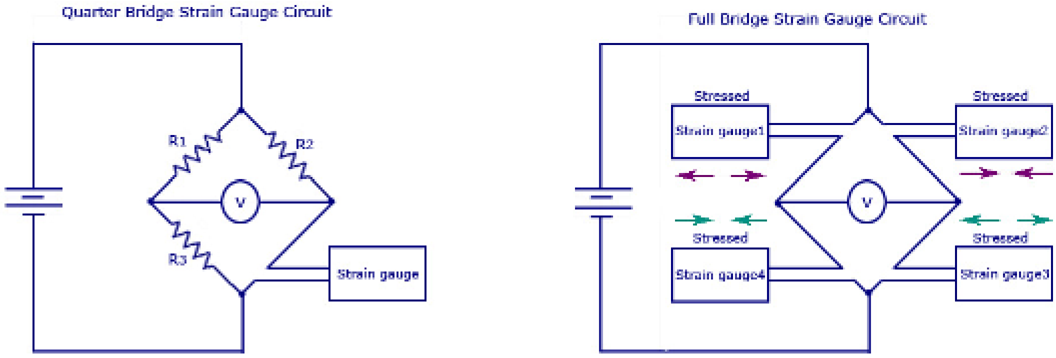

Fig. 4 Quarter and full bridge electrical resistance strain gauge sensors measurements

changes (Venugopalan *et al*. 2008). The dielectric properties of the film change with changing water content. This produces a change in the capacitance of the sensor that is directly converted to a humidity reading. Ultrasonic sensors are one of the most promising technologies for the diagnosis and prognosis of structural components and are used to detect cracks, voids, and the delamination of structural components (Peng-hui *et al.* 2015).

Acoustic emission sensors such as balance head, in-spindle, and fluid-type sensors are highly sensitive sensors that are used to detect various types of damage, such as fatigue crack growth, corrosion, impacts, and delamination (Baifeng and Weilian 2008). This high level of sensitivity coupled with the small number of sensors required potentially makes acoustic emission very attractive for SHM applications. Impact echo sensors are also used for SHM to measure the reinforcement of concrete flooring slabs, foundation slabs, columns, beams, and bridge girders to detect cracks, voids, delamination etc. (Zhang *et al.* 2015). This section explained the sensor technologies, its categories and applications. However, the explanations of the sensor classifications are very important towards the development of SHM system. Thus, section 4 would provide a brief background on the sensor classes.

4. Sensor classifications in SHM

There are many sensor classes in the SHM such as strain gauge sensors, linear variable differential transformer sensors, temperature measurement sensors and accelerometer sensors are reviewed in this paper. Detailed sensor classes and categories are listed in Table 1 and are explained in the following.

4.1 Strain gauge sensors

The concrete reinforcement of the structure is measured under different types of strain gauge sensors (SGS) such as electrical resistance, vibrating-wire are fiber optic sensors, respectively. Electrical resistance strain gauge sensors consist of a thin metallic film deposited on a non-conducting plastic film. Electrical resistance strain gauge sensors operate on the principle of the resistance change of a conductor being directly proportion to the change of its length calculated using a gauge factor as shown in Fig. 4. The resistance SGS are non-self-generating sensors that require an external power source for excitation by the data acquisition system, signal conditioner or by a dedicated power supply (Xiao *et al.* 2011). Most electrical resistance strain gauge sensors have a gauge factor of approximately 2. A higher resistance gauge sensor is preferred for most applications because it is less susceptible to self-heating effects and improves the signal-to-noise ratio of the The sensing element of a vibrating-wire strain gauge sensor consists of a length of pre-tensioned steel wire fixed at both ends that is allowed to vibrate at its natural frequency. The vibrating frequency is a function of the tension in the wire. In operation, an electromagnetic coil is attached to the gauge sensor's midpoint to pluck the wire and read the natural frequency. The relation between the strain and the natural frequency of the wire vibration can be derived from the natural frequency of a vibrating string (Teng *et al.* 2015). FBG and Fabry-Pérot (FP) sensors are two fiber optic sensor (FOS) sensors commonly used in civil applications. FBG sensors utilize a germanium-doped glass fiber core exposed to ultraviolet radiation using a phase mask to produce a periodic 'grating' of the material with a modulated index of refraction. The precise spacing of the grating reflects the incident light with a narrow band centered about the 'Bragg' wavelength. The FBG also provides a linear response based on the measurement of the wavelength shift caused by the straining of the gauge and takes into account temperature effects. An FP sensor uses an external sensing element that consists of two mirrors constructed using a semi-reflective coating deposited on optical fibers fused into a capillary (Kinet *et al.* 2014). The outputs of both sensors do not directly depend on the total light intensity levels and losses in the connecting fibers and couplers (Bhuiyan *et al.* 2015). FP technology can be very precise and has the highest resolution. FBG sensors are less precise and have comparatively less resolution using standard equipment. An FP sensor must be recalibrated every time a reading is performed, while a FBG sensor requires no such calibration (Casas 2003).

4.2 Linear displacement and position measurement sensors

The cable extension transducer, linear variable different transformer (LVDT) and vibrating-wire crack are the linear displacement sensors used in SHM. The sensing element of

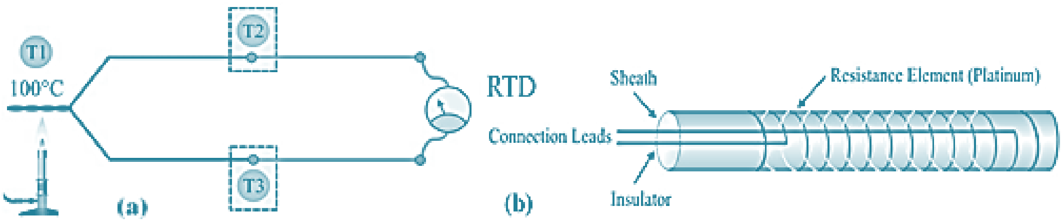

Fig. 5 Temperature sensors (a) thermocouple and (b) resistance temperature detector

a cable extension transducer is a precision potentiometer. A potentiometer uses the principle of variable resistance to measure displacement. It consists of a fixed thin-film resistor and a movable wiper electrically connected to the resistor. The change in resistance caused by the wiper's movement which is proportional to the distance traveled (Hu *et al.* 2014). The output signal of a cable extension transducer in terms of the voltage or current is measured using commercially available data acquisition systems (Yi *et al.* 2015).

LVDT sensors use an electro-mechanical device to measure displacements based on the principle of mutual inductance. The sensor consists of a hollow metallic cylinder containing a primary and two secondary electrical coils and a separate, movable magnetic core. An LVDT sensor is an electrical transformer, which requires a sinusoidal AC excitation in both frequency (2.5 kHz) and magnitude (3 V rms) to provide power. The displacement measurement ranges of an LVDT sensor generally vary from 0.005 inches to 10 inches (Zhang *et al.* 2011). However, the sensing element of a vibrating-wire crack meter sensor is an electromagnetic coil consists of a vibrating-wire sensing element anchored at one end of the sensor and connected to a spring loaded rod at the other end. The sensor utilizes a shaft connected to a spring and the vibrating wire element. The sensors are available in a number of standard ranges of 1, 2, or 4 inches. The resolution and accuracy of a vibrating-wire crack meter are typically 0.025% and 0.1% of the full range, respectively (Soil 2011). The data acquisition and signal conditioning requirements are similar to those of other vibrating-wire-type sensors.

4.3 Temperature measurement sensors

Different types of sensors such as thermocouple temperature sensors, thermistor temperature sensors and resistance temperature detector (RTD) sensors are used for temperature measurements as shown in Fig. 5. A thermocouple is a thermoelectric temperature sensor that consists of two dissimilar metals joined together at two locations at measurement and reference junctions (Huang *et al.* 2014). Thermocouples are self-generating sensors; i.e., they do not require an external power supply. In thermocouple temperature sensors, metal-constantan, chromel-alumel and two different platinum alloys are typically used. However, a thermistor is a resistive resistor used as a sensing element in thermistor temperature sensors and composed of a ceramic semiconducting material that exhibits a large change in electrical resistance when subjected to a change in temperature. Therefore, a novel multifunctional temperature sensing concept is needed to develop for SHM in terms of high frequency actuation, data acquisition and effective temperature compensation, respectively. Two types of thermistors, negative temperature coefficient (NTC) and positive temperature coefficient (PTC) are typically used. A NTC thermistor exhibits a large, negative, nonlinear change in resistance with increasing temperature while a PTC exhibits a positive, nonlinear change in resistance with increasing temperature. NTC thermistors are more sensitive to temperature changes than are PTC thermistors and are more frequently used for low-temperature measurements (Omega 2012).

RTD sensors are thin-film devices that measure temperatures and are based on the positive temperature coefficient of the electrical resistance of metals. RTD sensors are among the most precise temperature sensors available and are capable of resolution and measurement uncertainties of ± 0.1℃ or better in certain designs. They are typically encapsulated in probes for temperature sensor and measurement with an external indicator, controller or transmitter or are enclosed inside other devices where they measure temperatures as part of the device's function, such as in a temperature controller or precision thermostat. There are few drawbacks of RTD sensing systems due its self-heating system, low resistance, current source requirement and expensiveness issues. Thus, to solve the above issues, an advanced RTD sensing system including sensing elements and materials are to be design for linear, stable and accurate operation.

4.4 Accelerometer sensors

Accelerometer sensors are used to acquire structural response data that reflect practical dynamic information such as frequency, damping and shape of structures. These properties are directly related to the mass, stiffness and damping characteristics, respectively. The most common types of accelerometers used in SHM research are piezoelectric accelerometers, piezoresistive accelerometers, capacitive accelerometers, servo force balance accelerometers and MEMS (micro-electro-mechanical system) accelerometers.

Piezoelectric materials are used as a sensing element in piezoelectric accelerometer sensors. These piezoelectric sensors use a mass-spring system to generate a force proportional to the amplitude and the vibrational frequency of the structure (Guy and Jeff 2011). There are two types of piezoelectric accelerometer sensors: charge-output piezoelectric accelerometer sensor with external signal processing electronics and voltage-output piezoelectric accelerometer sensors with internal signal processing electronics. The charge-output sensor systems are expensive and difficult to operate. Voltage-output sensors are compatible with most available data acquisition systems (Grady 2000). Voltage-output sensors can be used for temperatures up to 2500 F, which is less than that of charge-output sensors. The piezoelectric accelerometer offer several advantages such as high frequency response for sensitivity, high transient response in microsecond level, high output and small in size. A few distinct advantages of utilizing piezoelectric accelerometer are wide frequency range, its suitability to be powered by low-cost current source, less susceptible to electromagnetic interference and low noise even with long cable driving. Overall, piezoelectric accelerometer sensors provide good sensitivity. However, they are extremely susceptible to ambient temperature sensitive drift, self-heating conditions, low resolution, lower frequency response and lower level of output signals which has led to a research decline recently (Aszkler 2005, Karantonis *et al*. 2006, Yang *et al*. 2009). Moreover, the single piezoelectric accelerometer approach has difficulty in distinguishing between standing and sitting postures for static activities.

Solid-state, silicon piezoresistive materials are used as a sensing element in piezoresistive accelerometer sensors. In traditional designs, discrete strain gauges are mechanically attached to cantilever beams and electrically connected in a Wheatstone bridge to produce an electrical signal proportional to the vibratory motion (Lynch *et al*. 2003). This sensor utilizes an external source of electrical energy with low output impedance that allows for its low-frequency response capability. These sensors are suitable for measuring the long-duration pulse found in transportation vibration, automotive crash studies and blast testing.

Capacitive accelerometers utilize an opposed plate capacitor to sense a capacitive shift caused by acceleration. The measuring elements form a capacitive half-bridge. Micromachined single crystal silicon is electrostatically bonded to form a parallel plate capacitive device that provides a response to DC acceleration inputs (Sadeghian and Vecchio 2015). Capacitive accelerometers are highly accurate and have excellent measurement resolutions from micro g level to 100 s of g with a frequency range from DC to very high frequencies. The capacitive accelerometer sensors can withstand very high shock level, high sensitivity, easy readout circuitry, independent of temperature variation, easy fabrication, large noise margin and compatible with CMOS technology. However, the major drawbacks are sensitive to temperature, hysteresis error, less longevity and decreased efficiency with time (Lynch *et al*. 2003, Bao *et al*. 2011). Both the piezoelectric and capacitive accelerometers do share two similarities such as requirement of signal conditioning circuit and acceleration measurement to 0 Hz. The main differences between the two are the sensitivity and shock limit. Capacitive accelerometers are generally much more sensitive, higher shock limit, lower frequency range and larger phase shift compared to piezoelectric accelerometer (Aszkler 2005).

A MEMS accelerometer is composed of a movable proof mass with plates attached to a mechanical suspension system in a reference frame (Currano *et al.* 2008). The deflection of the proof mass is measured using the capacitance difference. The free-space capacitances between the movable plate and the two stationary outer plates are functions of their corresponding displacements. If the acceleration is zero, then the capacitances are equal because the distances are equal. If the proof mass displacement is zero, then the capacitance difference can be determined. For small displacements, the capacitance change is negligible. The displacement is approximately proportional to the capacitance difference.

4.5 Tilt measurement meters

In general, there are two types tilt measurement meters are used in the SHM. Vibrating-wire tilt meter is comprises of pendulous supported strain transducer and an elastic hinge. The transducer measures changes in force caused by the rotation of the center of gravity of the mass which is suitable for monitoring of inclination and vertical rotation in structures (Wang *et al.* 2007). Tilt changes in structures may be caused due to construction activities such as excavation; tunneling and de-watering that affect the ground that supports the structure such as loading of a dam during impoundment, loading of a diaphram wall during excavation or loading of a bridge deck due to wind and traffic. This type of sensor is suitable for measuring the inclination and rotation of dams, piers and piles, monitoring tunnels for convergence and also evaluates the performance of bridges and struts under load.

The electrolytic tilt meter is a resistance potentiometer based on AC Wheatstone bridge circuit device which measures the level, angle or null with reference to gravity as shown in Fig. 6. The electrolytic tilt sensor provides an output excitation voltage that is proportional to the tilt angle expressed as either positive or negative angle depending on the direction of tilt. The tilt direction can be varies from 0°to 180° from the phase between the excitation and center electrodes. The excitation voltage and frequency are 5 volts and the frequency is 500 Hz - 5 KHz (Wang *et al.* 2007).

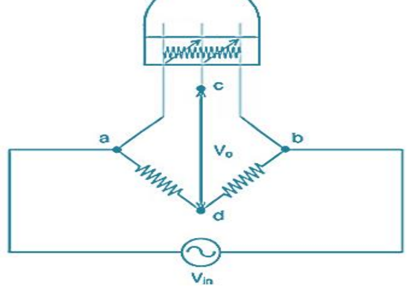

Fig. 6 Electrolytic tilt measuring circuit using Wheatstone bridge configuration

4.6 WIM system sensors

There are different types of WIM system such as piezoelectric, bending plate, load cell, fiber optic and MEM are used in SHM. Piezoelectric WIM system consists of a copper strand, surrounded by a piezoelectric material is used for data collection and tension force estimation to examine the vibration of the structure with consideration of temperature effects (Kim *et al.* 2013). When pressure is applied to the piezoelectric material, an electrical charge is produced to recalculate the tension force at a temperature of interest to measure the weight of a passing tire or axle and the vibration of the structures. However, a bending plate WIM system is consists of two weigh pads in an installation frame, two inductive loops, and an axle sensor installed in concrete. It is used to measure the strain in the plate as a tire or axle passes over and analyzed to determine the axle load of the vehicle load. The bending plate WIM system is generally more durable than a piezoelectric installation and also less dependent on the conditions of the roadway and less affected by deterioration (Kim *et al.* 2013). A load cell WIM system consists of two weigh pads in an installation frame, two inductive loops and an axle sensor to measure tire and axle loads that applied to the scale. This type of load cell is the most durable WIM technology with a long expected life which provides high performance and the integrity of the installation is not affected by the deterioration of the surrounding roadway. However, the system is costly.

A fiber-optic WIM system consists of a pneumatic tube filled with an incompressible fluid and embedded in a rubber pad, a diaphragm designed to convert pressure into displacement, and an optical displacement sensor (Hong *et al.* 2013, Wong *et al.* 2017). The fiber-optic WIM systems have the potential to reduce electromagnetic interference, less expensive, less frequency dependent, linear in response and also improve the accuracy associated with weight data collection. This system is better than that of existing WIM systems utilizing piezoelectric cable. MEMS accelerometer based WIM system consist of transducer, processing unit, sensors and actuators capable of measuring the low amplitude transient vibrations of the pavement to estimate dynamic load of the moving truck a dynamic load (Liu *et al*. 2006). The functional model of the MEMS WIM system is thoroughly calibrated to determine the acceleration parameters less than 200 µg and compared well with a reference accelerometer for its frequency response. The MEMS WIM system is actively used to measure micrometer strain, pavement roughness and temperature, micro-crack, corrosion and vibration, respectively.

4.7 GPS

GPS is a satellite-based radio navigation system which is continuously transmits digital radio signals at any location on earth unless blockages exist (Daly 1993). The GPS digital signals consist of a carrier phase code and a pseudorandom code which contain the information of satellites' locations and the exact times. Accordingly, the receiver computes the relative positions between the satellites and the receiver to identify the location and speed of the receiver by tracking the signals. For SHM based on GPS technology, two approaches such as the fixed network system and the mobile system are applied for surveying to identify position coordinates and displacement. GPS is a promising tool used in SHM for monitoring macroscopic deformation, displacement and vibration of civil structures by coordinating the exact points of defects. Accordingly, initially, the GPS techniques consist of static, fast static and real-time kinematic were developed to measure static, quasi-static and dynamic displacement responses of the structures (Gili *et al.* 2000; Kareem *et al*. 2005). However, recently, GPS has rapidly improved with their devices and algorithms to measure the low amplitudes of displacements within millimeter levels of accuracy (Roberts *et al.* 2004b, Watson *et al*. 2007). The main benefit of the GPS is the ability to detect the displacement of the structure in real time estimating reliable measurement and providing rapid performance evaluation indices (Jo *et al*. 2013). Thus, GPS showed the excellent correlation against measurements compare to the traditional technologies. Currently, GPS technology has advanced considerably which is capable of monitoring and assess the displacements in real time with static and dynamic characteristics. Although the application of GPS as a SHM method is limited due to systematic errors by multipath and constellation of satellites, however, it is still promising because of rapid development of GPS devices, algorithms, and integrated systems with other sensors which can mitigate erroneous data of GPS measurements and improve its accuracy (Seok *et al.* 2013). Thus, it is expected that GPS will be more broadly used and be an effective tool for structural health monitoring in civil structures.

4.8 Humidity sensors

Numbers of humidity sensors have been developed for concrete humidity monitoring and assessment such as resistive humidity sensor, capacitive humidity sensors, fibre optic humidity sensor, fibre Bragg gating based humidity sensor and long period gating based humidity sensors and so on. However, due to change of resistivity, moisture movement, chloride formation and carbonation, the humidity monitoring in the concrete structure are restricted (Ye et al. 2014). The main drawbacks are the packaging due to its fragile nature and costs are relatively high. The sensor is inserted into the humidity chamber through metal tubes in which salt solutions were used to create relative humidity (RH) levels (Venugopalan *et al.* 2008). However, when the coating refractive index is higher than that of the fibre cladding, the resonance conditions become more complex. Thus, for SHM, it is very important to note that the humidity sensors should be very high sensitivity on RH measurement, good repeatability and response time.

4.9 Ultrasonic sensors

There are different ultrasonic sensors such as ultrasonic range module, flaw detector and water proof sensors are used in SHM. The ultrasonic range modules consist of ultrasonic transmitters, receiver and control circuit provides 2 cm to 400 cm non-contact measurement function with maximum ranging accuracy (Peng-hui *et al*. 2015). The operation of the module need to supply a short 10 µs pulse to the trigger input to start the ranging, and then the module will send out an 8 cycle burst of ultrasound at 40 kHz and raise its echo. The Echo is a distance object that is pulse width and the range in proportion.

The ultrasonic flaw detector consist of wafer, inter-digital transducer and microfibers composites for detecting flaws in the plate and pipe like structures that propagates the wave over a long distance in SHM applications (Shih *et al.* 2010). The main objective of the ultrasonic flaw detector is to provide a comprehensive damage detection strategy such as cracks, voids and delaminated structural components for SHM using diffuse ultrasonic waves. However, the waterproof ultrasonic sensor is a high sensitive sensor that provides very short to long-range detection and ranging in a compact robust PVC or stainless steel/aluminum housing to meet water intrusion (Peng-hui *et al.* 2015). Recently, the sound cone characteristics such as wide angle sound cone and small angle sound cone are included in waterproof ultrasonic sensor module to indicate the presence of an object or disturbing object within the sensing range. The most applications of waterproof ultrasonic sensor are as remote control devices and ultrasonic distance measuring meter.

4.10 Acoustic emission sensors

Acoustic emission (AE) sensors used in SHM are balanced head, in-spindle and fluid types. Fig. 7 show traditional AE sensing system including preamplifier and signal conditioning system to minimize the noise interference and signal loss. AE sensor integrated with mechanical balancing head consists of a ba¬lancing head, an acceleration pick-up and an electronic module is used to ensure the detection, counterbalancing and compensation of imbalances in time (Baifeng and Weilian 2008, Chen *et al.* 2017). The balancing heads is mounted either in or on the end of the grinding spindle which is compact, a wide range of balancing capacities and suitable for high RPMs. However, the in-spindle AE sensors are non-contact in operation include telescopic type and spiral-cable type consists of slide tube or spiral cable, respectively. This configuration allows the acoustic sensor to spin with the spindle and to be in close proximity to the grinding event, giving a clear uninterrupted signal (Zhang *et al*. 2015).

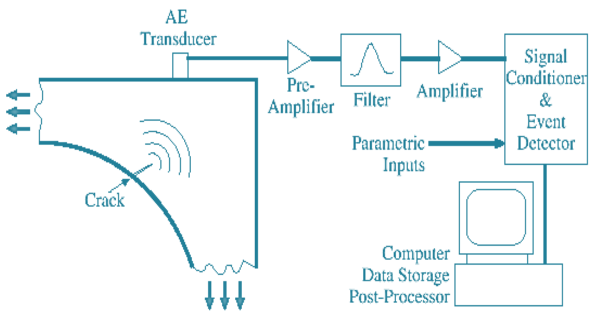

Fig. 7 Typical acoustic emission sensing system

The in-spindle sensor is used to facilitate installation appropriately within a grinding machine spindles or rotary diamond dressers. The fluid AE sensor uses the existing grinding machine coolant which can be water or oil based. A separate feed from the cutting stream is taken from near the coolant filter and is directed at the component or dresser.

The noise of the grinding wheel touching the component or dresser is then passed back up the coolant stream into the AE sensor where it is detected within 1 millisecond. The fluid AE sensor comes with a polyurethane pipe that can be easily plumbed into the grinding machine coolant supply to prevent electromagnetic noises.

4.11 Impact echo sensors

Impact echo sensors are based on stress wave theory used to assess and characterize the damage of the concrete. These assessment and characterization of the concrete damages have been performed using impact echo method. Impact echo sensors are investigating the conditions of the concrete and used to measure thickness of the concrete element, find voids, honeycombing, cracks, delamination, and other damage in concrete, giving depth, lateral location and extent of a flaw or defect. There are many types of impact echo sensors such as sonic impact echo sensors, ultrasonic echo sensors and micro-seismic echo sensors used in SHM (Rivera *et al.* 2007). Sonic impact echo sensors are used to investigate, evaluate and determine the integrity and the length of deep foundations (Zhang *et al*. 2015). Ultrasonic echo sensor is an amazing product that measures very short to long-range detection about 2 cm to 4 in a precise and stable manner with very high accuracy. It is compact in size and handy in operation for distance measurement and mapping that is easily be interfaced with microcontrollers. Micro-seismic echo sensors are used to monitor the dam condition, hydrological network of rain gauges and river level, respectively. The seismic network comprises in remote stations with echo seismic recorders and seismometers to send continuous and triggered data back to the dam for data acquisition and damage analysis.

5. Sensor networks in SHM

Sensor networking systems offer the opportunity to transmit data from sensors to servers or base stations throughout the life-cycle of the structure for structural health maintenance and monitoring. Sensor networking is performed using wired, wireless and smart wireless-based sensor networking. Wire-based sensor network systems are traditional only used for laboratory-based experiments; real-time applications of wire-based sensor networks are few in number. Thus, a detailed discussion of wire-based sensor networks is omitted in this paper. Wireless-based sensor networks include a number of essential features, such as on-board microprocessors, sensing capability, wireless communication, and data storage, amongst other features, and are battery powered and inexpensive (Nagayama 2007). On-board microprocessors can be used for digital signal processing, self-diagnostics, self-identification and self-adaptation functions (Cho *et al*. 2008). Ever since the first studies were performed, numerous researchers have developed smart sensing platforms (Taylor *et al*. 2016). Lynch and Loh (2006) cite a number of papers on smart wireless sensor networks for infrastructure health monitoring conducted worldwide at a number of research institutes. However, detail of sensors and systems are needed to be explaining for future SHM applications. Table 2 provides details on sensor network systems in terms of their networking features, range, size and power for wireless and smart wireless sensor networks.

5.1 Wireless-based sensor networks

Pioneering efforts to develop wireless sensors for application to civil engineering structures were presented by Wang and Liao (2006) which is known as a Wireless Modular Monitoring System (WiMMS) consists of a microprocessor, radio modem, data storage, and batteries. To control this remote wireless sensor unit, a Motorola 68HC11 microprocessor, which consists of an 8-bit counter and a 16-bit timer with an asynchronous RS-232 serial communication port, is selected as the on-chip hardware, and C, a high-level programming language, is used for the embedded software (Lynch *et al*. 2003). However, this wireless sensor does not emphasize power minimization in its design (Cho *et al.* 2008). Hence, the remote intelligent monitoring system (RIMS) was designed in (Li *et al*. 2014) for the SHM of bridges and infrastructure. The RIMS employs a high-clock Renesas H8/4069 microcontroller, 3-axis MEMS piezoresistive accelerometer, and an internet-connected wireless modem to control the system via an ethernet protocol. To enhance the storage capabilities of this wireless sensor design, an additional 2 MB of externally interfaced dynamic random access memory (DRAM) is used to store the time-history data as well as to perform local computations to minimize the amount of data that must be transmitted wirelessly. A more recent version of the RIMS wireless sensor has been proposed that includes an improved computational core; the Renesas H8 microcontroller is replaced by a Rabbit 3000 microcontroller that offers a 12-bit analog-to-digital conversion resolution.

A wireless sensor platform known as DuraNode was developed by Chung *et al.* (2004) for the monitoring of bridges and buildings. DuraNode includes the special ability of enabling wired internet data communication for building structures that have a previously established Local Area Network (LAN) in addition to its wireless sensor platform. Basumallick *et al.* (2011) designed DuraNode using previously developed wireless sensors that had sensor-transparent interfaces. This proposed wireless sensor was designed around two types of MEMS-based accelerometers. Recognizing the limitations of battery power, they have also integrated a solar panel into DuraNode to recharge the lithium polymer battery.

To overcome the limitations imposed by batteries, Edward *et al.* (2004) designed a low-power, wireless intelligent sensor and actuator network (WISAN) using a 16-bit Texas Instruments MSP430F1611 microcontroller. For wireless communication, their unit employs the Chipcon CC2420 wireless transceiver, which is IEEE802.15.4 compliant and operates in the 2.4 GHz radio spectrum with a data rate of 250 kbps at ranges of 10–75 m. When fully assembled, this low-power wireless sensor uses 60 mW while receiving and 52 mW while transmitting.

The WiMMS platform was further improved upon by Wang and Liao (2006) and Shen and Giurgiutiu (2014) by implementing software that allows multiple computational threads, such as processing or transmitting data while collecting data, to be executed simultaneously to fully utilize the computational power of the wireless sensor. A four-channel Texas Instrument ADS8341 16-bit ADC is used to convert the analog signal to a digital signal for transmission by a MaxStream 9XCite wireless modem. This radio operates in the 900 MHz radio band and is capable of maximum data rates of up to 38.4 kbps with ranges in outdoor and indoor environments of approximately 300 m and 100 m, respectively.

5.2 Smart wireless-based sensor networks

A smart wireless sensor prototype that emphasizes the design of a powerful computational core to minimize power consumption throughout the entire sensing period was developed by Lynch *et al.* (2003) for improving on the WiMMS system (Lynch *et al*. 2003). Their unit consists of an 8-bit Atmel AVR8515 microcontroller and includes internal oscillators, serial communication transceivers, timers, and pulse width modulators. This microcontroller is capable of fully utilizing its 8 kB of programmable flash memory, 512 bytes of SRAM, and 512 bytes of EEPROM to perform local processing and data storage tasks. A low-noise, single-channel, 16-bit, 100 kHz, ADS7821 Texas Instrument ADC is used to convert the analog signal to a digital signal for transmission by a Proxim RangeLane2 wireless modem. The radio operates in the 2.4 GHz radio band and is capable of maximum data rates of 1.6 Mbps with ranges in outdoor and indoor environments of approximately 300 m and 150 m, respectively. When fully assembled, the smart wireless sensor is 10 x 10 x 15 cm3 and is powered by six AA batteries. An ADXL210 accelerometer is used as a sensing unit to measure the vibrational response of the structure.

Farrar *et al.* (2006) designed a smart wireless sensor platform known as Husky for SHM based on the damage detection algorithms using an Intel Pentium Motorola microprocessor with 256 MB of programmable flash memory, i.e., RAM, and a 512 MB compact flash card serving as a hard drive. Husky also includes serial, ethernet and USB interfaces for communication. A Motorola DSP56858 processor is used to sample data from six single-channel Maxim ADCs. To transmit the sensor data, they considered a Motorola neuRFon IEEE802.15.4 transceiver that operates in the 2.4 GHz ISM radio band and has a data rate of 230 kbps with an indoor range of 10 m. When fully assembled, the total unit volume of the Husky is 1750 cm3 and uses 6 W.

Table 2 Existing sensor networks and their applications

Sensor Networks	Networking Features	Range, Size and power
Wireless sensor network: WiMMS	• Motorola 8-bit 68HC11 microprocessor • 16-bit Harris H171881P ADC • 32 kB RAM and 6 kB ROM • 900 MHz radio band and 19.6 kbps data rate	• Outdoor and indoor range of 300 m and 150 m, respectively • 15×13×10 cm^3 fully assembled • Six AA batteries
Wireless sensor network: RIMS	• Renesas H8/4069 microcontroller • 20 MHz, 10-bit ADC • 2 MB DRAM • 120 Flash Memory	• Outdoor and indoor range of 50 m • 30×6×8 cm^3 fully assembled
Wireless sensor network: DuraNode	• Local area network (LAN) • 2.4 GHz 802.11b wireless network • MEMS accelerometer • Analog device ADXL202 and silicon design SD1221	• Outdoor and indoor range of 200 m and 150 m, respectively • Solar panel with rechargeable lithium polymer battery • 6×9×3.1 cm^3 fully assembled
Wireless sensor network: WISAN	• 16-bit Texas instrument MSP430F1611 microcontroller • 2 MB non-volatile EPROM • 6-channel, 12-bit ADC and 2-channel, 12-bit DAC • Chipcon CC2420 wireless transceiver • IEEE802.15.4-compliant 2.4 GHz radio spectrum and 250 kbps data rates	• Computational range of 10-75 m • Fully assembled sensor uses 60 mW at receiving and 52 mW for transmitting
Wireless sensor network: WiMMS	• 8-bit Atmel ATmega128 microcontroller • 128 Kb Flash memory • 4 kB SRAM and 4 kB EEPROM • Texas instrument ADS8341 ADC • 900 MHz radio band and 38.4 kbps data rate	• Outdoor and indoor range of 300 m and 150 m, respectively • 10×6×4 cm^3 fully assembled • Five AA batteries
Smart wireless sensor network: WiMMS	• 8-bit Atmel AVR8515 microcontroller • 8 Kb Flash memory • 512 bytes SRAM and 512 EEPROM • Texas instrument ADS7821 ADC • 2.4 GHz radio band and 1.6 Mbps data rate	• Outdoor and indoor range of 300 m and 150 m, respectively • 10×10×15 cm^3 fully assembled • Six AA batteries
Smart wireless sensor network: Husky	• Intel Pentium Motorola microprocessor • Motorola DSP56858 processor communication • 256 MB RAM • 512 MB flash card • Six-channel Maxim ADC • IEEE802.15.4 transceiver operates 2.4 GHz ISM radio band and 230 Kbps data rate	• Indoor range of 10 m • 1750 cm^3 fully assembled • Uses 6 W

A smart wireless sensor basically WSN, plays an outstanding role in the area of designing core, minimizing power consumption, remote monitoring and enabling real-time processing of demand-side management (Lynch *et al.* 2003). Though the different companies produced different specified WSN, however, in general smart WSN radio band and data rate are higher than that of conventional WSN. Indoor and outdoor ranges of smart WSN is shorter than WSN, however in some platform, the ranges are almost same like in WiMMS platform. When fully assembled, the total unit volume of the smart WSN is bit higher than that of WSN as shown in Table 2.

6. Current challenges and limitations

The application of sensor technology to civil infrastructure has become an important issue worldwide because of the associated long service life, high maintenance requirements and high costs when compared to other commercial products (Akyildiz and Stuntebeck 2006, Zeng *et al*. 2011, Kamel and Juma 2011). However, the field faces significant challenges in performing accurate SHM, detection and analysis using global information. A number of extremely important structures have deteriorated because of the results of aging materials, continuous use, overloading, aggressive exposure conditions, lack of sufficient maintenance, and difficulties encountered in proper inspection methods (Sun *et al.* 2010). All of these factors contribute to material and structural degradation, while internal and external damages emerge, coalesce, evolve and progress. Moreover, the existing public infrastructure of Canada, the United States, Europe, and other developed countries have suffered from decades of neglect and overuse, leading to the accelerated deterioration of bridges, buildings, municipal and transportation systems (Sbarufatti *et al*. 2014). For example, in Canada, more than 40% of the bridges currently in use were built over 50 years ago, and a significant number of these structures need strengthening, rehabilitation, or replacement (Leng and Asundi 2003). A significant amount of the infrastructure is unsatisfactory in some respect, and public funds are not generally available for the replacement of existing structures or construction of new structures. A detailed summary of the challenges and problems is given in the following.

6.1 Advanced sensor technologies and limitations

Available sensors applicable to SHM for the evaluation of real-time structural conditions are mostly in the experimental stage under laboratory conditions. Sensors that can potentially be used in SHM and detection analysis include strain gauge sensors, accelerometer sensors, ultrasonic sensors, acoustic emission sensors and impact echo sensors (Rivera *et al*. 2007). However, a majority of these sensors are ineffective for long-term SHM except strain gauges and accelerometers. Strain sensors are versatile tools in bridge health monitoring for the detection of displacements, vibrations, cracks, and corrosion and can perform in a harsh natural environment while having a large sensing scope, wide operating temperature range, low transmission losses, distributed sensing abilities as well as a number of other advantages (Park *et al*. 2008, Feng and Jia 2017). However, the long-term sensing ability of the strain sensor is not acceptable because of electromagnetic interference (EMI) and other problems related to the endurance of the sensors. The change in the long-term sensing ability of fiber optic sensors caused by aging under in-the-field experimental conditions has not been fully established and must be investigated further. The long-term sensing ability of the vibrating-wire strain gauge sensor is better than that of the other strain gauge sensors because of its use of frequency rather than voltage as the output of the gauges (Kerrouche *et al.* 2010). Fiber optic sensors are fragile in a number of configurations and are difficult to repair when they become damaged. The optical connections to the outer data recording system are weak elements of the FOS system. In addition, a deformation in the infrastructural component generates tension in the steel wire that is measured by plucking a wire that induces a resonant frequency of the vibration in the electromagnetic coil. These frequencies are transmitted over long cable lengths and can become degraded by variations in the cable resistance, contact resistance, or leakage to the ground. Thus, advance sensor technologies are needed to address the above issues as well as to provide a very stable system for the long-term monitoring of infrastructure behavior under environmental, physical and mechanical load actions.

Accelerometers such as piezoelectric, piezoresistive or capacitive accelerometers are used in modal analyses that measure the motion of a structure via the induced current caused by inertial forces acting on the material. The response of these sensors is typically processed by a signal amplifier or an internal electronic circuit and converted to a voltage difference for detection and acquisition. This technology has proven useful in a number of applications (Yi *et al.* 2015, Tondreau and Deraemaeker 2013). However, these accelerometers have a number of limitations in regards to sensor placement techniques, data acquisition and computation, temperature, harsh environments etc. Recently, however, MEMS accelerometers have become advanced candidates for the evaluation of infrastructure condition or crack detection in infrastructure based on frequency changes (Currano et al. 2008). Modal parameters such as frequency can be easily and inexpensively acquired by MEMS accelerometers to be used in SHM, detection and analysis. This approach could provide for an inexpensive structural assessment technique.

6.2 Wireless sensor limitations

A number of researchers have developed wireless and smart wireless sensor networks, emphasizing identification and adaptation, integration of a microcontroller with a wireless radio, minimizing power consumption and the use of remote intelligent systems for SHM (Cho *et al.* 2008, Lynch *et al.* 2004). However, difficulties remain such as high power consumptions, higher installation costs, data distortion caused by cable temperatures, hard-to-eliminate noise and difficulties in repairing or replacing sensors as well as sensors not being commercially available (Hassan *et al.* 2011). Sensor networks are particularly useful in a wide range of applications because they possess sensing capabilities without the need to implement a centralized infrastructure (Kominami *et al.* 2010). However, a number of critical technical problems must be resolved in wireless sensor networks, such as the energy efficiency of sensor nodes with limited battery life. A number of approaches exist for improving energy efficiency; for example, miniaturizing sensor nodes, media access control (MAC) with sleep control, and multi-hop routing (Almeida et al. 2015) have been proposed. Self-organization in Wireless Mesh Networks (WMN) is an emergent research area that is becoming important because of the increasing number of nodes in a network (Guardalben *et al.* 2010, Bao *et al.* 2017). Consequently, the manual configuration of nodes is either impossible or expensive. Thus, it is desirable for the nodes to be able to configure themselves. In this context, adaptive routing is essential to ensure safe and timely data delivery in building evacuation and fire-fighting resource applications. Existing routing mechanisms for wireless sensor networks are not well suited for building fires, especially because they do not consider critical and dynamic network scenarios (Zeng *et al.* 2011). Thus, to overcome these issues, innovative sensor and sensor technologies must be developed for construction materials to facilitate analyses of risk assessments and design processes by monitoring the structures.

7. Conclusions

This article outlined the various types of sensors, sensor technologies and sensor networks and their suitability for SHM and management. Civionics technology provides the necessary feedback to engineers in optimizing design techniques, understanding infrastructure performance, behavioral condition etc. for SHM. A detailed overview of SHM research on damage detection and location or degradation of infrastructural components has been given and includes systems, data processing and structural health evaluation. Significant SHM research from Canada, USA, Australia and Japan has been conducted to introduce innovations in design and construction to build, repair and monitor the health of infrastructure. Several types of existing sensor technologies and sensor categories and their applications in SHM have been reviewed and are listed in Tables 1 and 2. Wireless and smart wireless sensor networks related to SHM have been discussed in terms of networking features, data storage, range, cost, size and power. This review investigated and observed that the quality of the sensing devices and their reliability depend on the sensor technologies used and their networks in terms of data transmission, operating frequency, power consumption etc. The main challenges of the existing SHM sensors and their networks are related to sensor placement techniques, data acquisition and computation, temperatures, harsh environments, EMI, sensor endurance, high power consumption, installation cost, data distortion caused by cable temperature, hard-to-eliminate noise, difficulty in replacing or repairing, respectively. Thus, properly choosing a sensor and sensor network for a specific application is crucial to the development of highly efficient systems with minimum errors to achieve high data transfer rates throughout the life cycle of the structure for SHM. This article discussed a number of issues on the existing SHM sensors and sensor networks, such as their characteristics, challenges and problems in developing advanced techniques, low power consumption, high data rates, efficient data acquisition, low cost, long-term sensing ability and reliability in future applications. To achieve these goals, advanced sensor technology can be used to provide a stable wireless signal and offers flexibility for updating the data to the sensing system and network using automated control programs. Thus, the highlighted background on the challenges and problems will lead to increasing development of new, improved and appropriate solutions for reliable SHM.

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References

Akyildiz, I.F. and Stuntebeck, E.P. (2006), “Wireless underground sensor networks: Research challenges”, *Ad Hoc Networks*, **4**, 669-686.

Almeida, V.A.D., Baptista, F.G. and Aguiar, P.R. (2015), “Piezoelectric transducers assessed by the pencil lead break for impedance-based structural health monitoring”, *IEEE Sensor. J.*, **15**, 693- 702.

Annamdas, V.G.M., Bhalla, S. and Soh C.K. (2017), “Applications of structural health monitoring technology in Asia”, *Struct. Health Monit*., **16**, 324-346.

Aszkler, C. (2005), “Chapter 5: Acceleration, Shock and Vibration Sensors,” from Sensor Technology Handbook.

Bai, Z., Chen, S., Xiao, Q., Jia, L., Zhao, Y. and Zeng, Z. (2017), “Compressive sensing of phased array ultrasonic signal in defect detection: Simulation study and experimental verification”, *Struct. Health Monit.*, doi: 10.1177/1475921717701462.

Baifeng, J. and Weilian, Q. (2008), “The research of acoustic emission techniques for non destructive testing and health monitoring on civil engineering structures”, *Proceedings of the International Conference on Condition Monitoring and Diagnosis*, 21-24 April 2008, Beijing.

Bao, Y., Beck, J.L. and Li, H. (2011), “Compressive sampling for accelerometer signals in structural health monitoring”, *Struct. Health Monit*., **10**, 235-246.

Bao, Y., Shi, Z., Wang, X. and Li, H. (2017), “Compressive sensing of wireless sensors based on group sparse optimization for structural health monitoring”, *Struct. Health Monit*., doi: 10.1177/1475921717721457.

Barbezat, M., Brunner, A., Flüeler, P., Huber, C. and Kornmann, X. (2004), “Acoustic emission sensor properties of active fibre composite elements compared with commercial acoustic emission sensors”, *Sensor. Actuat. A: Phys*., **114**, 13-20.

Basumallick, N., Chatterjee, I., Biswas, P. and Dasgupta, K.B.S. (2012), “Fiber Bragg grating accelerometer with enhanced sensitivity”, *Sensor. Actuat. A: Phys.*, **173**(1), 108-115.

Bhuiyan, M.Z.A., Wang, G., Cao, J. and Wu, J. (2015), “Deploying wireless sensor networks with fault- tolerance for structural health monitoring”, *IEEE T. Comput*., **64**, 382-395.

Binici, B. (2005), “An analytical model for stress–strain behavior of confined concrete”, *Eng. Struct*., **27**, 1040-1051.

Bogdabovic, B.A., Mufti, A.A., Bagchi, A. (2005), "SHM data interpretation and structural condition assessment of the Manitoba Golden Boy", Proceedings of the SPIE 5767, 213-224.

Capoluongo, P., Ambrosino, C., Campopiano, S., Cutolo, A., Giordano, M., Bovio, I., Lecce, L. and Cusano, A. (2007), “Modal analysis and damage detection by Fiber Bragg grating sensors”, *Sensor. Actuat. A: Phys.*, **133**, 415-424.

Casas, J.R. (2003), “Fiber optic sensors for bridge monitoring”, *J. Bridge Eng*., **8**(6), 362-373.

Casciati, S., Chassiakos, A.G. and Masri, S.F. (2014), “Toward a paradigm for civil structural control”, *Smart Struct. Syst*., **14**(5), 981-1004.

Cazzulani, G., Moschini, S., Resta, F. and Ripamonti, F. (2013), “A diagnostic logic for preventing structural failure in concrete displacing boom”, *Automat. Constr*., **35**, 499-506.

Chen, J., Cheng, F., Xiong, F., Ge, Q. and Zhang, S. (2017), “An experimental study: Fiber Bragg grating–hydrothermal cycling integration system for seepage monitoring of rockfill dams”, *Struct. Health Monit*., **16**, 50-61.

Chen, Z., Li, H. and Bao, Y. (2018), “Analyzing and modeling inter-sensor relationships for strain monitoring data and missing data imputation: a copula and functional data-analytic approach”, *Struct. Health Monit*., doi: 10.1177/1475921718788703.

Chen, Z., Bao, Y., Li, H. and Spencer, B.F. (2017), “A novel distribution regression approach for data loss compensation in structural health monitoring”, *Struct. Health Monit*., doi: 10.1177/1475921717745719.

Cheng, L., Zhang, H. and Li, Q. (2007), “Design of a capacitive flexible weighing sensor for vehicle WIM system”, *Sensors*, **7**, 1530-1544.

Cho, S., Yun, C.B., Lynch, J.P., Zimmerman, A.T., Spencer, B.J. and Nagayama, T. (2008), “Smart wireless sensor technology for structural health monitoring of civil structures”, *J. Steel Struct*., **8**, 267-275.

Choi, M., Shrestha, M.M., Lee J. and Park, C. (2017), “Development of a laser-powered wireless ultrasonic device for aircraft structural health monitoring”, *Struct. Health Monit*., doi: 10.1177/1475921716686963.

Civionics (2009), Custom wireless sensing and control solutions.

Available on: http://Civionics.com/uncategorized/about-Civionics (accessed on 22 December 2011).

Currano, L.J., Bauman, S., Churaman, W., Peckerar, M., Wienke, J., Kim, S., Yu, M. and Balachandran, B. (2008), "Latching ultra-low power MEMS shock sensors for acceleration monitoring", *Sensor. Actuat. A: Phys.*, **147**, 490-497.

Daly, P. (1993), "Navstar GPS and GLONASS: Global satellite navigation systems", *Electro Commun. Eng. J*., **5**(6), 349-357.

Edward, S., Kerop, J. and Ratan, J.C. (2004), "Wireless intelligent sensor network for autonomous", *Struct. Health Monit.*, Available on: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.99.4283.

Fang, K., Liu, C. and Teng, J. (2017), "Cluster-based optimal wireless sensor deployment for structural health monitoring", *Struct. Health Monit*., doi: 10.1177/1475921717689967.

Farrar, C.R., Allen, D.W., Park, G., Ball, S. and Masquelier, M.P. (2006), "Coupling sensing hardware with data interrogation software for structural health monitoring", *Shock Vib*., **13**, 519-530.

Feng, S. and Jia, J. (2017), "Acceleration sensor placement technique for vibration test in structural health monitoring using microhabitat frog-leaping algorithm", *Struct. Health Monit*., doi: 10.1177/1475921717689967.

Guardalben, L., Villalba, L.J.G., Buiati, F., Sobral, J.B.M. and Camponogara, E. (2010), "Self- configuration and self-optimization process in heterogeneous wireless networks", *Sensor*, **11**, 425-454.

Guemes, J.A. and Menendez, J.M. (2002), "Response of Bragg grating fiber-optic sensors when embedded in composite laminates", *Compos. Sci. Technol*., **62**, 959-966.

Guy, K. and Jeff, S. (2011), "Principles of piezoelectri accelerometers", *Sensors*, Available on: http://www.sensorsmag.com › Sensors › Acceleration/Vibration (accessed on 10 December 2011).

Ha, D.W., Park, H.S., Choi, S.W. and Kim, Y. (2013), "A wireless MEMS-based inclinometer sensor node for structural health monitoring", *Sensors*, **13**, 16090-16104.

Hackmann, G., Guo, W., Yan, G., Sun, Z., Lu, C. and Dyke, S. (2014), "Cyber-physical codesign of distributed structural health monitoring with wireless sensor networks", *IEEE T. Para. Distr. Sys*., **25**, 63-72.

Han, B., Yu, Y. and Ou, J. (2008), "Development of a wireless stress/strain measurement system integrated with pressure-sensitive nickel powder-filled cement-based sensors", *Sensor. Actuat. A: Phys.*, **147**, 536-543.

Hassan, M.K., Zain, M.F.M, Hannan, M.A. and Jamil, M. (2010), "Sensor placement technique and GUI system for bridge girder monitoring", *Int. J. Civil Struct. Eng.*, **1**, 583-590.

Hassan, M.K., Zain, M.F.M., Jamil, M. and Hannan, M.A. (2011), "Sensor network for bridge girder crack identification and monitoring system", *Proceedings of the IEEE Int. Conf. Intelligent Computing and Intelligent System (ICIS2011)*, Kuala Lumpur.

Hong, K., Lee, J., Choi, S.W., Kim, Y. and Park, H.S. (2013), "A strain-based load identification model for beams in building structures", *Sensors*, **13**, 9909-9920.

Hu, Y., Rieutort-Louis, W.S., Sanz-Robinson, J., Huang, L., Glisic, B., Sturm, J.C., Wagner, S. and Verma, N. (2014), "Large-scale sensing system combining large-area electronics and CMOS ICs for structural-health monitoring", *IEEE J. Solid-State Circuits*, **49**, 513-523.

Huang, Y., Beck, J.L., Wu, S. and Li, H. (2014), "Robust Bayesian compressive sensing for signals in structural health monitoring", *Comput.-Aided Civil Infrastruct. Eng*., **29**, 160-179.

Hyeonseok, L., Hyun-Jun, P., Sohn, H. and Il-Bum, K. (2010), "Integrated guided wave generation and sensing using a single laser source and optical fibers", *Meas. Sci. Technol*., **21**, 105207-11.

Jang, W.S., Healy, W.M. and Skibniewski, M.J. (2008), "Wireless sensor networks as part of a web-based building environmental monitoring system", *Automat. Constr.*, **17**, 729-736.

Jo, H., Sim, S.H., Tatkowski, A., Spencer, B.F. and Nelson, M.E. (2013), "Feasibility of displacement monitoring using low-cost GPS receivers", *Struct. Control Health Monit*., **20**, 1240-1254.

Kamel, I. and Juma, H. (2011), "A lightweight data integrity scheme for sensor networks", *Sensors*, **11**, 4118- 4136.

Karantonis, D.M., Narayanan, M.R., Mathie, M., Lovell, N.H. and Celler, B.G. (2006). "Implementation of a real-time human movement classifier using a triaxial accelerometer for ambulatory monitoring", *IEEE. T. Inf. Technol. Biomed*., **10**, 156-167.

Kareem, A., Kijewski-Correa, T. and Bashor, R. (2005), "GPS: A new tool for structural health monitoring", APT Bulletin: *J. Preservation Technol*., **36**(1), 13-18. .

Kerrouche, A., Boyle, W., Sun, T. and Grattan, K. (2010), "Design and in-the-field performance evaluation of compact FBG sensor system for structural health monitoring applications", *Sensor. Actuat. A: Phys.*, **151**, 107-112.

Kim, J.T., Nguyen, K.D. and Huynh, T.C. (2013), "Wireless health monitoring of stay cable using piezoelectric strain response and smart skin technique", *Smart Struct. Syst*., **12**(3), 381-397.

Kinet, D., Mégret, P., Goossen, W., Heider, D. and Caucheteur, C. (2014), "Fiber Bragg grating sensors toward structural health monitoring in composite materials: Challenges and solutions", *Sensors*, **14**, 7394-7419.

Kominami, D., Sugano, M., Murata, M. and Hatauchi, T. (2010), "Energy-efficient receiver- driven wireless mesh sensor networks", *Sensors*, **11**, 111-137.

Lee, D., Jeon, H. and Myung, H. (2014), "Pose-graph optimized displacement estimation for structural displacement monitoring", *Smart Struct. Syst*., **14**(5), 943-960. •

Lei, Q., Shenfang, Y., Xiaoling, S. and Tianxiang, H. (2012), "Design of piezoelectric transducer layer with electromagnetic shielding and high connection reliability", *Smart Mater. Struct*., **21**, 075032-14.

Leng, J. and Asundi, A. (2003), "Structural health monitoring of smart composite materials by using EFPI and FBG sensors", *Sensor. Actuat. A: Phys.*, **103**, 330-340.

Li, H.N., Yi, T.H., Ren, L., Li, D.S. and Huo, L.S. (2014), "Reviews on innovations and applications in structural health monitoring for infrastructures", *Struct. Monit. Maint*., **1**(1), 1-45.

Liu, P., Lim, H.J., Yang, S., Sohn, H., Lee, C.H., Yi, Y., Kim, D., Jung, J. and Bae, I. (2017), "Development of a "stick-and-detect" wireless sensor node for fatigue crack detection", *Struct. Health Monit*., **16**, 153-163.

Liu, Z., Yu, Y., Liu, G., Wang, J. and Mao, X. (2014), "Design of a wireless measurement system based on WSNs for large bridges", *Measurement*, **50**, 324-330.

Lynch, J.P., Law, K.H., Kiremidjian, A.S., Carryer, E., Farrar, C.R., Sohn, H., Allen, D.W., Nadler, B. and Wait, J.R. (2004), "Design and performance validation of a wireless sensing unit for structural monitoring applications", *Struct. Eng. Mech*., **17**(3), 393-408.

Lynch, J.P. and Loh, K.J. (2006), "A summary review of wireless sensors and sensor networks for structural health monitoring", *Shock Vib. Digest*, **38**, 91-130.

Lynch, J.P., Partridge, A., Law, K.H., Kenny, T.W., Kiremidjian, A.S. and Carryer, E. (2003), "Design of piezoresistive MEMS-based accelerometer for integration with wireless sensing unit for structural monitoring", *J. Aerosp. Eng.*, **16**, 108-114.

Maheshwari, M., Tjin, S.C. and Asundi, A. (2016), "Combined fiber Bragg grating and fiber optic polarimetric sensors on a

single fiber for structural health monitoring of two-dimensional structures", *Struct. Health Monit.*, **15**, 599-609.
Malekzadeh, M., Gul, M., Kwon, I.B. and Catbas, N. (2014), "An integrated approach for structural health monitoring using an in-house built fiber optic system and non-parametric data analysis", *Smart Struct. Syst.*, **14**(5), 917-942.
Mufti, A.A. (2003), "Integration of sensing in civil structures: development of the new discipline of Civionics", *Struct. Health Monit. Intel. Infrastruct.*, **1**, 119-129.
Mufti, A.A., Bakht, B., Tadros, G., Horosko, A.T. and Sparks, G. (2007), "Civionics-a new paradigm in design, evaluation, and risk analysis of civil structures", *J. Int. Mat. Syst. Str.*, **18,** 757-763.
Mufti, A.A. and Neale, K.W. (2008), "State-of-the-art of FRP and SHM applications in bridge structures in Canada", *Compos. Res.*, **2**, 60-69.
Nagayama, T. (2007), Structural Health Monitoring Using Smart Sensors, PhD Dissertation, University of Illinois Urbana-Champaign, Urbana, IL USA.
Nasrollahi, A., Deng, W., Ma, Z. and Rizzo, P. (2017), "Multimodal structural health monitoring based on active and passive sensing", *Struct. Health Monit.*, 10.1177/1475921717699375 .
Grady, A. (2000), "Transducer/sensor excitation and measurement techniques", *Analog Dialogue,* **34**, 1-6.
Omega (2012), The Thermosistor. http://www.princeton.edu/~cavalab/tutorials/public/Thermocouples.pdf (accessed on 11 December 2016).
Park, G., Rosing, T., Todd, M.D., Farrar, C.R. and Hodgkiss, W. (2008), "Energy harvesting for structural health monitoring sensor networks", *J. Infrastruct. Syst.*, **14**, 64-79.
Peng, C., Fu, Y. and Spencer, B.F. (2017), Sensor Fault Detection, Identification, and Recovery Techniques for Wireless Sensor Networks: A Full-scale Study. In ANCRiSST2017.
Peng-hui, L., Hong-ping, Z., Hui, L. and Shun, W. (2015), "Structural damage identification based on genetically trained ANNs in beams", *Smart Struct. Syst.*, **15**(1), 227-244.
Rivera, E., Mufti, A.A. and Thomson, D.J. (2007), "Civionics for structural health monitoring", *Can. J. Civil Eng.*, **34**, 430-437.
Roberts, G.W., Meng, X. and Dodson, A.H. (2004). "Integrating a global positioning system and accelerometers to monitor the deflection of bridges", *J. Surv. Eng.*, **130**(2), 65-72.
Sadeghian, V. and Vecchio, F. (2015), "A graphical user interface for stand-alone and mixed-type modelling of reinforced concrete structures", *Comput. Concrete*, **16**(2), 287-309.
Sbarufatti, C., Manes, A. and Giglio, M. (2014), "Application of sensor technologies for local and distributed structural health monitoring", *Struct. Control Health Monit.*, **21**, 1057-1083.
Seok, B.I., Stefan, H. and Young, J.K. (2013), "Summary review of GPS technology for structural health monitoring", *J. Struct. Eng.*, **139**, 1653-1664.
Shen, Y. and Giurgiutiu, V. (2014), "Predictive modeling of nonlinear wave propagation for structural health monitoring with piezoelectric wafer active sensors", *J. Int. Mat. Syst. Str.*, **25**, 506-520.
Shih, J.L., Kobayashi, M. and Jen, C.K. (2010), "Flexible ultrasonic transducers for structural health monitoring of pipes at high temperatures", *IEEE T. Ultrason. Ferr.*, **57**(9), 2103-2110.
Soil (2011), Vibrating wire crack meter. https://www.bsil.com.cn/Downloads/DataSheets/J2_VW%20Crackmeter_ds.pdf (accessed on 11 January 2011).
Stabile, T.A., Giocoli, A., Perrone, A., Palombo, A., Pascucci, S. and Pignatti, S. (2012), "A new joint application of non-invasive remote sensing techniques for structural health monitoring", *J. Geophys. Eng*,. **9**, 53-63.
Sun, M., Staszewski, W. and Swamy, R. (2010), "Smart sensing technologies for structural health monitoring of civil engineering structures", *Adv. Civil Eng.*, 2010(2010), Article ID 724962, 13 pages.
Tastani, S. and Pantazopoulou, S. (2008), "Detailing procedures for seismic rehabilitation of reinforced concrete members with fiber reinforced polymers", *Eng. Struct.*, **30**, 450-461.
Taylor, S.G., Raby, E.Y., Farinholt, K.M., Park, G. and Todd, M. (2016), "Active-sensing platform for structural health monitoring: Development and deployment", *Struct. Health Monit.*, **15**, 413-422.
Teng, J., Lu, W., Wen, R. and Zhang, T. (2015), "Instrumentation on structural health monitoring systems to real world structures", *Smart Struct. Syst.*, **15**(1), 151-167.
Tensometer (2012), http://en.wikipedia.org/ wiki/Tensometer (accessed on 14 December 2012).
Ting-Hua, Y., Hong-Nan, L. and Xu-Dong, Z. (2012), "A modified monkey algorithm for optimal sensor placement in structural health monitoring", *Smart Mater. Struct.*, **21**, 105033-9.
Tondreau, G. and Deraemaeker, A. (2013), "Local modal filters for automated data-based damage localization using ambient vibrations", *Mech. Syst. Signal Pr.*, **39**, 162-180.
Ubertini, F., Laflamme, S., Ceylan, H., Materazzi, L., Cerni, G., Saleem, H., Alessandro, A. and Corradini, A. (2014), "Novel nanocomposite technologies for dynamic monitoring of structures: a comparison between cement-based embeddable and soft elastomeric surface sensors", *Smart Mater. Struct.*, **23**, 045023.
Venugopalan, T., Sun, T. and Grattan, K. (2008), "Long period grating-based humidity sensor for potential structural health monitoring", *Sensor. Actuat. A: Phys.*, **148**, 57-62.
Wang, D.H. and Liao, W.H. (2006), "Wireless transmission for health monitoring of large structures", *IEEE T. Instrum. Meas.*, 55, 972-981.
Wang, Y.H., Lee, C.Y. and Chiang, C.M.A. (2007), "MEMS-based air flow sensor with a free-standing micro-cantilever structure", *Sensors*, **7**, 2389-2401.
Watson, C., Watson, T. and Coleman, R. (2007), "Structural monitoring of cable-stayed bridge: Analysis of GPS versus modeled deflections", *J. Surv. Eng.*, **133**(1), 23-28.
Wong, L., Chiu, W.K. and Kodikara, J. (2017), "Using distributed optical fibre sensor to enhance structural health monitoring of a pipeline subjected to hydraulic transient excitation", *Struct. Health Monit.*, doi: 10.1177/1475921717691036.
Xiao, H., Li, H. and Ou, J. (2011), "Strain sensing properties of cement-based sensors embedded at various stress zones in a bending concrete beam", *Sensor. Actuat. A: Phys.*, **167**, 581-587.
Yang, C.C. and Hsu, Y.L. (2009), "Development of a wearable motion detector for tele-monitoring and real-time identification of physical activity", *Telemed. J. E. Health*, **15**, 62-72.
Yang, Y. and Nagarajaiah, S. (2016), "Harnessing data structure for recovery of randomly missing structural vibration responses time history: Sparse representation versus low-rank structure", *Mech.Syst. Signal Pr.*, **74**, 165-182.
Ye, X. W., Su, Y. H. and Han, J.P. (2014), "Structural health monitoring of civil infrastructure using optical fiber sensing technology: A comprehensive review", *Scientific World J.*, 2014 (2014), Article ID 652329, 11 pages. http://dx.doi.org/10.1155/2014/652329.
Yi, TH., Li, H.N. and Zhang, XD. (2015), "Sensor placement optimization in structural health monitoring using distributed monkey algorithm", *Smart Struct. Syst.*, **15**(1), 191-207.
Yu, L. and Tian, Z. (2013), "Lamb wave structural health monitoring using a hybrid PZT-laser vibrometer approach", *Struct. Health Monit.*, **12**, 469-483.
Zeng, Y., Sreenan, C.J., Sitanayah, L., Xiong, N., Park, H. and Zheng, G. (2011), "An emergency-adaptive routing scheme for

wireless sensor networks for building fire hazard monitoring", *Sensors*, **11**, 2899-2919.

Zhang, J., Zhou, Y. and Li, P.J. (2015), "Practical issues in signal processing for structural flexibility identification", *Smart Struct. Syst.*, **15**(1), 209-225.

Zhang, Y., Liu, W., Zhang, H., Yang, J. and Zhao, H. (2011), "Design and analysis of a differential waveguide structure to improve magnetostrictive linear position sensors", *Sensors*, **11**, 5508-5519.

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