Chapter 11
Bio-inspired Sensors for Structural Health Monitoring

Kenneth J. Loh, Donghyeon Ryu and Bo Mi Lee

Abstract Structural systems are susceptible to damage throughout their operational lifetime. Thus, structural health monitoring technologies and, in particular, sensors that could monitor structural performance and detect damage are needed. While there exist a variety of different sensing platforms, this continues to be an active area of research due to the many challenges associated with identifying and quantifying structural damage, which is inherently very complex. This chapter discusses an emerging area of sensors research in which sensor design or functionality is inspired by biological systems. By borrowing concepts from and learning how nature's creations sense and interact with its environment, the goal is to create novel sensors with unparalleled performance as compared to the current state-of-art. This chapter is not meant to be an exhaustive literature review on this topic. Rather, only a small selection of published work is sampled and presented to showcase different ideas and the breadth of research. Topics ranging from bio-inspired algorithms, creature-like robots, and skin-like sensors are presented.

11.1 Introduction

Infrastructure systems, such as bridges, buildings, cranes, dams, and pipelines, among others, could incur damage throughout their service lifetime. Natural disasters, excessive loads, accidents, and/or environmental degradation could cause various types of damage. Damage (e.g., corrosion or fatigue cracks) could escalate over different time- and length-scales and while the structure remains in service. If left undetected, accumulated damage could diminish structural performance, serviceability, and safety.

K.J. Loh (✉) · D. Ryu · B.M. Lee
Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA
e-mail: kjloh@ucdavis.edu

F. Pacheco Torgal et al. (eds.), *Biotechnologies and Biomimetics for Civil Engineering*,
DOI 10.1007/978-3-319-09287-4_11

For example, a fatal rupture and explosion of a natural gas pipeline in Carlsbad, NM in 2000 was a result of deterioration caused by corrosion and other factors (NTSB 2003, Peekema 2013). Another example is cracking in steel girders of the Interstate I-794 Daniel Webster Hoan Bridge (Milwaukee, WI) in 2000 that caused one of its spans to sag by more than 1.2 m (4 ft); as a result, a total of US$7.8 million was invested for repair and retrofit (Fisher et al. 2001). The catastrophic collapse of the Sgt. Aubrey Cosens V.C. Memorial Bridge (Latchford, ON, Canada) in 2003 was due to fatigue rupture of hanger connections within the arch bridge's enclosed steel boxes (Biezma and Schanack 2007). As evident from these historic events, the timely detection of damage is crucial for facilitating the necessary structural repairs, ensuring optimal performance of structures, and enhancing public safety.

Routine visual inspection by trained technicians continues to be the predominant methodology adopted for evaluating the performance and safety of existing structural systems. For instance, the National Bridge Inspection Standards, set forth by the U.S. Federal Highway Administration, mandates that all highway bridges be inspected every 24 months (FWHA 2004). Due to their inherent time-, labor-, and cost-intensiveness (Hartle et al. 1990; Moore et al. 2001), tethered sensing systems are sometimes used to supplement visual inspection (Zhang et al. 2007; Sumitro et al. 2005; Celebi 2006). While simple sensors such as accelerometers and strain gages offer quantitative measures of structural response, their high costs to install and maintain the great lengths of coaxial cables have limited the number and density of sensors installed per structure (Celebi 2006). The end result is a sparsely distributed monitoring system (relative to the size of the structure) that is, at times, poorly scaled with structural damage, which is inherently highly localized.

On the other hand, structural health monitoring (SHM) integrates structural response data collected from distributed sensors with feature extraction algorithms for identifying the presence of damage relative to its *healthy* or pristine state. Statistical analysis is then required for relating accumulated damage to structural functionality, resistance to various loading scenarios, and overall safety (Farrar and Worden 2007). According to Farrar and Worden (2007) and Rytter (1993), damage detection involves a five-step process of increasing complexity, namely: (1) existence; (2) location; (3) type; (4) extent; and (5) prognosis. One of the major considerations in which any or all of these five steps could be achieved relies on the careful selection and deployment of sensors. These sensors need to be strategically instrumented and need to provide high signal-to-noise data that are indicative of damage, where damage and detection threshold is defined based on the end-user's needs.

In fact, a plethora of emerging technologies have been proposed over the past few decades for autonomous SHM and damage detection. Examples include fiber optics and fiber Bragg gratings for distributed strain and temperature measurements (Tsuda et al. 1999; Kersey 1996), wireless sensors for densely distributed system identification (Lynch and Loh 2006; Spencer Jr. et al. 2004), and piezoelectric sensor and actuator arrays for active sensing and acoustic emissions

(Tadigadapa and Mateti 2009; Yu et al. 2008; Zhao et al. 2007), among others (Boller 2000). Despite these advancements, these SHM systems possess certain limitations that sometimes make it challenging for them to diagnose a structure's *health*. While limitations vary between sensor platforms, in most cases, sensors are discrete transducers that only measure data at instrumented locations. Spatial structural response is usually obtained using a dense network of sensors and interpolation. Most sensors only measure structural response, and physics-based models or statistical methods are needed for inferring information about damage.

Unlike the aforementioned manmade sensing technologies, nature and its diverse creations have perfected biological assemblies and functionalities to enable the five senses of touch, visual, auditory, olfactory, and taste. In fact, humans have historically relied on biological inspirations to create artificial systems that mimicked the functionalities of many creatures. For example, camouflage tactics used in the military (i.e., planes, ships, and tanks) have been motivated by an octopus' ability to match its colors to its surroundings (Bar-Cohen 2006). With the advent of modern computing technology, electronics, and nanotechnology, these bio-inspired systems have become increasingly more complex and higher performance. For example, McGary et al. (2006) and Liu (2007) have fabricated artificial hair cell arrays for magnetostrictive acoustic sensing and fluid flow drag force sensing, respectively. Other examples include bio-inspired auto-adaptive and autonomous engineering systems (Tomizuka et al. 2007), plant-inspired actuators (Philen et al. 2007), phospholipids, and microfluidic membranes (Horsley et al. 2008), among many others (Loh et al. 2009; Li et al. 2004; Kao et al. 2007; Lin and Sodano 2009).

Instead of presenting an exhaustive review of bio-inspired sensing systems, this book's chapter uses select examples of published works to highlight the breadth of cutting-edge research. In particular, this chapter focuses on three different types of bio-inspired sensors for SHM. First, Sect. 11.2 presents bio-inspired algorithms for SHM. These algorithms could be used with current sensor networks for detecting damage or sensor faults. Second, Sect. 11.3 discusses robotic sensors that mimic the functionality of various creatures. Like geckos, these sensors could crawl on various structural surfaces and collect information from locations inaccessible to inspectors. Then, Sect. 11.4 highlights recent advances in designing conformable sensors based on nanotechnology. These thin films could be coated onto structural surfaces, and like skin, be able to detect damage over large spatial areas. This chapter concludes with a brief summary and discussion of future trends and needs.

11.2 Bio-Inspired Computational Tools

The development of various data management, signal processing, and damage detection algorithms has been inspired by biology. One particular prominent area is computational methods inspired by the biological immune system (BIS). In particular, BIS has provided a conceptual basis for deriving an artificial immune system (AIS) to improve the reliability and security of sensor networks for SHM (Drozda et al. 2011a; Twycross and Aickelin 2009; Dasgupta 2006).

One of the interesting features of the BIS is homeostasis, which helps maintain a normal operation level in environments where errors and changes could occur (Drozda et al. 2011a). One should know that BIS consists of two components (i.e., innate and adaptive immune systems) to protect the biological host from threatening pathogens. Here, the innate immune system immediately responds to the known pathogen, and the system does not change. On the other hand, the adaptive immune system involves learning and memory that take place over relatively longer periods of time (e.g., over several days). When unknown pathogens affect the host, the adaptive immune system recognizes and memorizes the new threat or change.

The detailed mechanism that enables the adaptive immune system response is that lymphocytes experience either positive or negative selection processes with a minimum self-reactivity or autoimmunity. When autoimmunity happens, the host cells undergo self-attack. It should be noted that first generation AIS considered only one type cell (i.e., B cell) for stabilization of the network (Hunt et al. 1999). When antigens were presented to B cells, and if affinities between B cells were strong, the B cells were cloned and contributed to stabilization of the network.

A second generation AIS was proposed by introducing different cell types (e.g., B and T cells) to the conventional AIS to enhance performance of error detection (Twycross and Aickelin 2009). Research focused on the communication between the different cell types. The innate immune system took part in error detection, which involves classifying the error and providing context on errors triggering damage. AIS' error detection structure was composed of adaptive and context classification modules. The two modules interacted in a feedback loop. By mimicking biological adaptive immunity, the structure offered functions of selection, memory, and learning for detecting new errors and changes in existing errors in the monitored sensor network.

The context classification module, inspired by innate immunity, evaluates the quality of service, and provides feedback to the adaptive module after error detection. Using the immune system-inspired error detection algorithm, it was shown that various objectives, such as energy efficiency, final false positives rate, adaptivity, and novel error detection, could be taken into account. By simulating the experiments conducted by Drozda et al. (2011b), improvements in the adaptive strategy-based error detection method were validated with minimum impact on energy efficiency and intact false positives control (Drozda et al. 2011a).

Bio-inspiration has also been adopted to improve the performance of complicated sensor networks for SHM. In addition, as these sensor networks evolve, they become even more complicated, with increasing number of sensors and dimensions. In particular, complex sensor networks with large number of sensors require the use of novel algorithms and strategies for optimum sensor placement to avoid coverage holes and unbalanced data flows.

For instance, genetic algorithms (GA) were investigated by numerous researchers for fault detection, as well as for monitoring spatial lattice structures and large space structures (Worden and Burrows 2001; Liu et al. 2008; Yao et al. 1993).

Javadi et al. (2005) developed a hybrid GA by integration of back-propagation neural network to improve convergence performance and the quality of the solution. Inspired by natural evolution, evolutionary algorithms (EA) have been used for optimizing mobile sensor deployment with optimum sensor coverage in a randomly distributed wireless sensor network (Abbasi et al. 2014). To simulate social behavior, particle swarm optimization (PSO) was implemented, which was suggested by Kennedy and Eberhart (1995). PSO was further enhanced by introducing chaos into an accelerated PSO by Gandomi et al. (2013). An overview of sensor node movement methodologies was provided by Abbasi et al. (2014) to improve network coverage as well as network lifetime, and the bio-inspired algorithms were shown to enhance data details, timeline, and reliability.

To shorten computational run-time and improve convergence performance in complicated sensor networks, Yi et al. (2012) developed an asynchronous-climb monkey algorithm (AMA) for optimizing sensor placement. The AMA mainly consists of monkeys' mountain-climbing process (i.e., climb, watch, jump, and somersault) (Fig. 11.1). In particular, AMA mimics monkeys' social behavior to find the optimum positions of sensors, in which monkeys exchange information with neighbor monkeys and were guided by the monkey king (i.e., the first step of AMA). This procedure was repeated until the best objective value (in this case the binary vector of sensor location) was obtained. The objective value was continuously updated with the position vector of monkeys by considering each monkey's own experience and the social experience from neighbor monkeys. The best objective value was designated as a "monkey king," and the Darwinian principle of natural selection was incorporated to accommodate replacing the monkey king with the next best one.

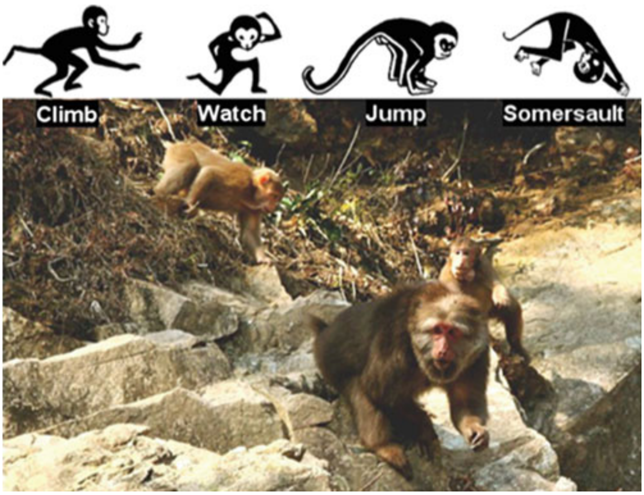

Fig. 11.1 The process by which monkeys climb, watch, jump, and somersault provides the conceptual basis for the asynchronous-climb monkey algorithm (Yi et al. 2012). (Image provided courtesy of IOP publishing)

Furthermore, AMA was improved by combining PSO, which was expected to be useful for civil infrastructures instrumented with large number of sensors. The proposed AMA was verified through a trial involving different sensor placements for characterizing the vibrational behavior of the Canton Tower (Shanghai, China). Modal assurance criterion (MAC) was chosen to yield two types of objective functions, and for comparison with AMS, a conventional monkey algorithm (MA) was used with a dual-structure coding method. Two simplified finite element (FE) models of the Canton Tower were established with and without the antenna mast. For all cases of objective functions and FE models, AMA exhibited the best performance in optimizing sensor placement.

Data processing and transferring techniques have also been developed by adopting biological concepts with the purposes of improving accuracy in data detection and realizing real-time data processing for large-scale civil infrastructures (Lin et al. 2010; Peckens and Lynch 2013). A new damage extraction and classification method for SHM based on the concept of a deoxyribonucleic acid (DNA) array was implemented (Lin et al. 2010). The purpose was to improve damage detection accuracy. Damage characteristics were extracted using a double-tier regression model to establish the autoregressive (AR)-autoregressive exogeneous (ARX) database, which was regarded as analogous to DNA of biological creatures. Just as how DNA arrays are classified based on DNA patterns using naïve Bayesian (NB) algorithm for detecting cancer cells, AR-ARX arrays could also be classified using an NB algorithm and further improved through optimization using a likelihood selection method. The novel DNA-inspired SHM system was verified through experiments involving a six-story building under ambient vibration. It was shown that the optimized SHM system achieved 90–95 % accuracy in terms of damage identification. To enable real-time data processing, the auditory signal compression and transferring concepts were used (Peckens and Lynch 2013). Inspired by the cochlea, high signal compression ratio was achieved with a reasonable reconstruction error as compared to two other conventional compressive techniques, namely wavelet transforms and compressed sensing (Fig. 11.2) (Peckens and Lynch 2013).

There have been other efforts in using bio-inspired concepts for improving damage detection and SHM (Loh and Azhari 2012; Salowitz et al. 2013; Kirikera et al. 2008). Fatigue monitoring has been considered challenging, particularly due to its long time-scales and high-frequency signals. Inspired by the concept of tree ring data tracking, an intelligent fatigue monitoring system was developed (Bai et al. 2014). Fatigue characteristics (i.e., the amplitude of strain, the number of cycles, and the stress state) were acquired with a high degree of accuracy, which could be transmitted in real-time via a wireless network. The wireless fatigue monitoring system was validated using cantilever bending fatigue tests. Maximum strain of the test specimen was tracked using either strain gage or polyvinylidene fluoride, and the obtained digital signals were processed to extract the number of loading cycles, among other fatigue characteristics. Feature extraction was performed using digital

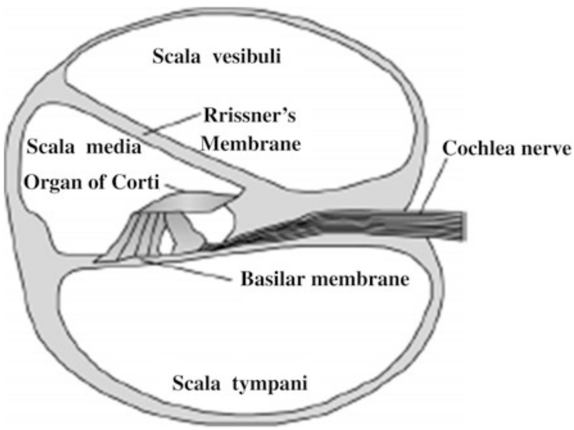

Fig. 11.2 A cross-section of the cochlea is shown. The cochlea is a part of the mammalian inner ear and plays an important role in processing and transmitting auditory signals (Peckens and Lynch 2013). (Image provided courtesy of IOP publishing)

signal processing technology integrated with a rain-flow counting method. It was shown that loading cycles were accurately measured with <5 % error, and fatigue life was calculated.

11.3 Creature-like Robotic Sensors

While bio-inspired algorithms offer the possibility of optimizing sensor instrumentations, in many cases, large structures still require densely distributed sensors for SHM. It has already been shown by Celebi (2002) that the cost to install sensors in tall buildings could exceed US$5,000 per channel. Although one of the major goals (and advantages) of wireless sensors was to lower costs by eliminating sensor dependence on a tethered connection (Lynch and Loh 2006), the need for a dense sensor instrumentation could make a wireless SHM system cost prohibitive for many end-users and applications.

Mobile or robotic sensors that are inspired by different creatures' ability to navigate around the natural world offer unique benefits for SHM. In particular, the fundamental benefit is that mobile sensors are no longer tied to their instrumented locations, as is the case for static sensor networks. Instead, a small number of mobile sensors could crawl around a bridge or building and record structural response data at many measurement points. The robotic sensor could be wirelessly commanded, collect data at a variety of measurement points over large spatial domains, and as frequently as desired (given the limitations of onboard power). The end result would be the possibility of obtaining densely distributed structural response data using only a handful of sensors. These robots could also navigate to

Fig. 11.3 A mobile sensor prototype (developed by researchers at the Georgia Institute of Technology, USA) is crawling on a steel pedestrian bridge. (Photo courtesy of Prof. Yang Wang, Georgia Institute of Technology, USA)

hard-to-reach areas that an inspector or engineer would otherwise not be able to access conveniently.

A prime example of a bio-inspired mobile sensor for SHM is work by Zhu et al. (2010). The mobile sensor was fabricated by connecting two two-wheeled vehicles with a flexible beam (Fig. 11.3). The wheels were made with magnets so that it could climb ferromagnetic structures. The design of the robot also included infrared sensors and Hall effect sensors for the purposes of detecting boundaries and for locomotion, respectively. For SHM, a Silicon Designs 2260-010 accelerometer was located on the center of the robot's center flexible beam, and the mobile sensor could control the attachment and detachment of the accelerometer onto the structure (i.e., by moving the two two-wheeled cars closer or farther away from each other, respectively). Two different experimental laboratory tests were conducted in the laboratory for validating their performance. The mobile sensors successfully crawled around a steel portal frame, and two robots collected structural vibration response (excited using impact hammer strikes) at 11 different measurement points. Damage was simulated by adding a mass block or by loosening bolts at connections. By analyzing the transmissibility function, damage location was successfully identified. Other research groups have also developed various types of crawling robots (Huston et al. 2005; Akiba et al. 2013; Oh et al. 2009).

While the aforementioned mobile sensor was more mechanical and resembled that of a car, the design of the Geckobot was inspired by the gecko's ability to climb almost any type of surface (Unver et al. 2006). In particular, the Geckobot featured synthetic dry adhesive feet, made with polydimethyl siloxane (PDMS) elastomer that mimicked the gait and climbing mechanism of real geckos. Like a real gecko, when the PDMS toe was controlled to detach from the surface, the PDMS was bent and peeled off in a way that minimized the detaching force. Another unique design was its active tail that enhanced the robot's mobility during climbing. With the existence of a tail, it could provide additional force that secured

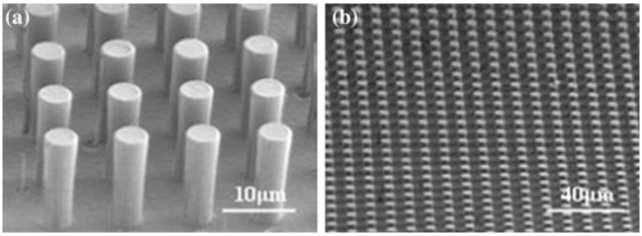

Fig. 11.4 Polyurethane micro-hair arrays mimic the hairs (or setae) on a gecko's feet that enable vertical climbing (Wu et al. 2013). (Images provided courtesy of Springer)

Fig. 11.5 A gecko-inspired robot is shown climbing vertical walls of different materials. Vertical climbing is enabled with the robot's polyurethane micro-hair array on its wheels (Wu et al. 2013). (Images provided courtesy of Springer)

the Geckobot to the surface. Experimental studies demonstrated that the mobile sensor could walk at a speed of up to 5 and 1 cm/s on a flat and inclined surface, respectively. However, one limitation was that the robot could not climb a normal or 90° surface.

In contrast, Wu et al. (2013) proposed a climbing robot with two pedrails, in lieu of individual wheels or robotic feet. A unique feature of the pedrail was that it featured dry adhesive pedrails modeled after the gecko's feet. The surface of the pedrail was patterned with micro-fiber hair arrays, very much similar to the spatulae that populates setae found on Gecko's feet. The micro-fiber hair array was fabricated using polyurethane and is shown in Fig. 11.4. The prototype gecko-inspired robot successfully climbed surface materials and of different inclinations (Fig. 11.5).

Robots inspired by other creatures, including snakes, have also been explored. For example, Enner et al. (2012, 2013) proposed a snake-like robot for monitoring pipeline systems. The main function of the snake-inspired robot was to measure the pipe's diameter, since its diameter could change as a result of corrosion or damage. The robot could wrap itself inside the pipe or along the outer surface.

Fig. 11.6 The ability of a worm to shrink and extend its own body to propel itself forward has inspired the creation of artificial counterparts that mimic this behavior (Balaguer et al. 2005). (Images provided courtesy of Springer)

For both cases, the geometry of the robot was related to the pipe radius (or diameter), assuming that the centerline of the robot coincided with that of the pipe. Therefore, information about the pipe diameter could be obtained directly for SHM applications.

It should be mentioned that other climbing robots have also been developed. Examples include the ROMA I that was inspired by the locomotion of caterpillars that shrink and extend its body to move (Fig. 11.6) (Balaguer et al. 2005). Another example is the ROMA II that utilized vacuum suction for climbing on different surfaces (Balaguer et al. 2005). In fact, the mobile sensor consisted of two arms and 10 vacuum cups. By controlling suction on either arm and by moving and/or rotating the unattached arm, motion could be achieved. Bio-inspired mobile sensors continue to be an important area of research with commercial prototypes emerging in the marketplace.

11.4 Skin-Inspired Sensors

The human skin is another prime example of an impressive biological system that is capable of densely distributed sensing. The sensing and monitoring of changes in temperature, deformation, flow, pressure, and damage (i.e., injuries) is achieved by the 640,000 sensory receptors distributed throughout the entire system (Schmidt 1986). Unlike mobile sensors that need to navigate to different locations and collect data at different points in time, the skin is able to resolve changes throughout the entire system simultaneously.

In fact, the skin has inspired the development of various tactile sensors, as have been described in review articles by Lee and Nicholls (1999) and Yousef et al. (2011). These tactile sensors are particularly important considerations for the development of next-generation human-interactive robotic systems as an example Mukai et al. (2008). In the context of SHM, Loh and Azhari (2012) have presented a review of skin-inspired sensors.

Extensive research in flow sensors inspired by, for instance, human hairs and the lateral line system in fish, has been conducted. Velocity-, acceleration-, or pressure-sensitive neuromasts in the lateral line allow these creatures to measure flow and changes in motion (Coombs 2001). Hairs on the skin or on the surface of insects (like crickets) also enable biological systems to monitor changes in fluid flow (Pfatteicher and Tongue 2002) or acoustic signals (Wiegerink et al. 2007). Hairs or whiskers on mice are also used for object identification and avoidance.

Research by Dijkstra et al. (2005) and Wiegerink et al. (2007) have shown that biomimetic filiform hairs could be used for sensing flow. Viscous flow would tilt these micro-machined hairs and induce measureable capacitance changes. These artificial hairs have also been organized into a large array for enhanced sensitivity and performance. An array is also useful for enhancing sensing resolution, as well as differentiating flow direction. Besides measuring capacitance changes, others have used the measurement of changes in electrical current (Sarles et al. 2011), field-effect response (Kim et al. 2009), piezoelectricity (Yu et al. 2010), or magnetostriction (McGary et al. 2006). These bio-inspired flow sensors have been proposed for various applications (Pinto et al. 2011; Eberhardt et al. 2011; Tao et al. 2011).

A specific application in which bio-inspired flow sensors have been used for SHM is the case of bridge scour monitoring. Bridge scour is the disruption of marine structure's foundations (e.g., overwater bridge piers and abutments) due to rapid water flow, flooding, or severe weather events, among others (Whitehouse 1998). For instance, (Swartz et al. 2014) proposed a wireless smart scour sensing post that consisted of bio-inspired magnetostrictive flow sensors attached to the post surface (Fig. 11.7). When scour advances and exposes these Galfenol whiskers at different buried depths, the sensors would deflect due to fluid flow and drag. A giant magnetostrictive sensor mounted at the base of the whisker would detect such a change, and the response would be transmitted wirelessly to a base station. A similar concept was also proposed by Wang et al. (2012), Loh et al. (2014), and Azhari et al. (2014) but with piezoelectric sensors.

While hair-like structures that protrude from the surface of the skin could be used for sensing flow, it is well known that the skin itself is a highly effective distributed sensor. In fact, the skin has inspired the development of thin films and coatings that are sensitive to different damage features. One particular technique for creating artificial skin sensors is to incorporate randomly distributed carbon nanotubes (CNT) in a thin, flexible, polymer matrix. Numerous techniques have been developed, and they include examples such as evaporation (Dinh-Trong et al. 2009), spin coating (Yim et al. 2008), layer-by-layer (Loh et al. 2007), and spraying (Kang et al. 2006), just to name a few.

In particular, Loh et al. (2007, 2005) demonstrated strain sensing using layer-by-layer thin films assembled with single-walled carbon nanotubes (SWNT) and various polyelectrolyte species. It was observed that the film's electrical properties (e.g., resistivity) varied linearly with applied strains up to at least 1 % strains, and strain sensitivity could be controlled by modifying the concentration of the CNT solution used during layer-by-layer fabrication (Loh et al. 2008). Like skin, these materials could be applied onto the surfaces of structures for SHM. However, for detecting damage within structural materials, these SWNT-based films were also

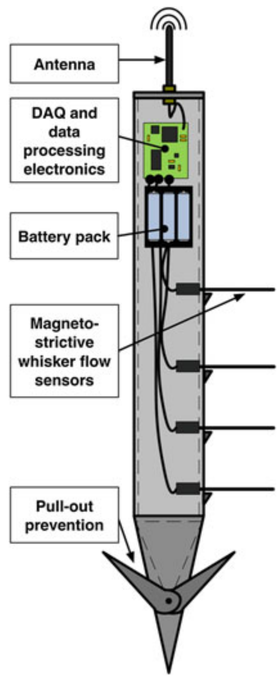

Fig. 11.7 A smart scour sensing post incorporates bio-inspired magnetostrictive whisker sensors for measuring fluid flow and bridge scour. (Image courtesy of Prof. R. Andrew Swartz, Michigan Technological University, USA)

embedded in structures like fiber-reinforced polymer (FRP) composites for embedded strain monitoring and damage detection (Fig. 11.8) (Loyola et al. 2010).

It should also be mentioned that another method for achieving embedded sensing was to modify the FRP composite's epoxy matrix, again, using conductive fillers like carbon nanotubes. Strain sensing, as well as monitoring delamination and micro-cracks, were validated by Thostenson and Chou (2006), Böger et al. (2008),

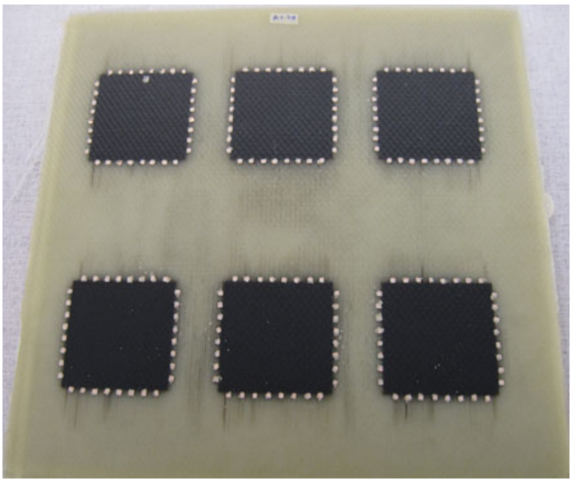

Fig. 11.8 Multiple carbon nanotube-based sensing skins are embedded underneath the surface of a large GFRP panel during the manufacturing process for achieving in situ damage detection and SHM

Nofar et al. (2009), and Kostopoulos et al. (2009). CNT concentrations as low as 0.1 w% was sufficient for producing electrically conductive, epoxy-based composites (Thostenson and Chou 2002; Thostenson and Chou 2006; Thostenson and Chou 2008).

Despite these advances in creating skin-like thin films that are piezoresistive, strain sensing could only be accomplished in an average sense. A resistivity measurement was directly correlated to strains being experienced by the underlying structure (i.e., at least on the surface). However, this strain measurement was averaged over the entire surface area or measurement area of the film. Yet, structural damage including cracks, corrosion, and impact were localized phenomena. An "averaged" strain measurement may not be able to detect such damage (i.e., depending on the size of damage and measurement area).

Instead, one could leverage the fact that the electrical resistivity (or equivalently conductivity) of every location in the film is calibrated to strain. Work by Hou et al. (2007b) and Loh et al. (2009) showed that an electrical impedance tomography (EIT) algorithm (Brown 2003) could be used for mapping the spatial conductivity distribution of CNT-based thin films. To produce this conductivity map without having to probe every location in the film, EIT relied on a set of instrumented electrodes along the boundaries of the thin film. This defined the sensing area. Then, EIT utilized boundary current input and voltage measurements for reconstructing the spatial conductivity distribution of the thin film (Borcea 2002; Brown 2003). By nature, the EIT inverse problem is an ill-posed problem, and one set of boundary voltage measurements would be insufficient for determining the spatial conductivity map of the sensing area (Holder 2005). Thus, electrical current was applied to numerous boundary electrodes, and sets of boundary voltage measurements were obtained for each current injection case. Since thin film conductivity (or resistivity) was correlated to applied strain, pH, or other damage phenomena (Loh et al. 2007, 2008; Loh 2008), the spatial conductivity maps were directly related to spatial damage in the underlying structure.

Previous works by Hou et al. (2007a, b) validated the EIT technique for spatial conductivity mapping of the aforementioned layer-by-layer CNT-based thin films. Square 25×25 mm^2 SWNT-based thin films were instrumented with boundary electrodes, and EIT was used to obtain baseline conductivity maps of these films. Then, selected regions on the film surface were intentionally etched and removed so as to create straight, diagonal, and L-shaped cuts (Hou et al. 2007b). These cuts formed regions of zero conductivity in the film and were used for simulating some change or extreme damage. After mechanical etching, EIT was conducted again to obtain the relative change in thin film spatial conductivities. It was found that the spatial conductivity maps visually represented that of the actual films, and they could be used for identifying the locations of these cuts (Hou et al. 2007a, b). It was also shown that the EIT-estimated spatial conductivities were within 2 % error as compared to experimental measurements of the same film and sensing area.

With the EIT algorithm validated, these carbon nanotube *sensing skins* were then used for SHM and laboratory tests. For example, sensing skins were coated onto aluminum plates and mounted in an impact testing apparatus. It was shown

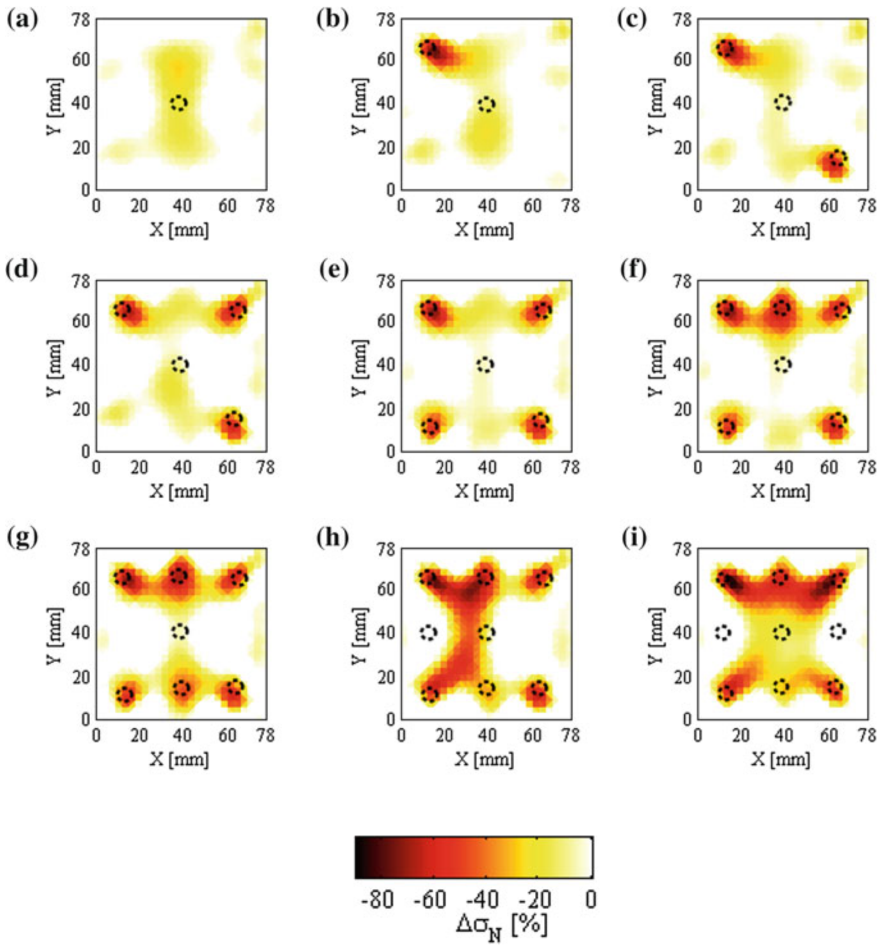

Fig. 11.9 The sensing skins and EIT algorithm are tested by verifying that this method could detect the location of drilled holes in sensing skin-enhanced GFRP panels. Each EIT image is obtained after a new hole is drilled in the **a** *center*, **b** *upper-left*, **c** *lower-right*, **d** *upper-right*, **e** *lower-left*, **f** *upper-center*, **g** *lower-center*, **h** *center-left*, and **i** *center-right* of the composite specimen (Loyola et al. 2013a). (Images provided courtesy of Sage publications)

that EIT was able to resolve the severity and location of four different magnitude impact damage sites (Loh et al. 2009). The monitoring of spatial variations in pH (i.e., as a precursor of corrosion) (Hou et al. 2007b) and changes in film conductivity due to corrosion/rust formation (Pyo et al. 2011) were also validated.

More recently, an airbrushing technique for spray deposition of these CNT-based sensing skins was developed for achieving rapid fabrication and field applications (Mortensen et al. 2013). In short, an ink solution was created by dispersing multi-walled carbon nanotubes (MWNT) in poly(sodium 4-styrene-sulfonate) (PSS) and the mixing it with a latex solution. The ink and latex mixture could then be sprayed onto virtually any substrate including metals, glass, concrete, and plastic. In particular, sensing skins were sprayed and embedded in glass fiber-reinforced polymer (FRP) composites during fabrication. Laboratory characterization tests were conducted, and the results verified the detection of spatially distributed impact damage (Loyola et al. 2013b) and drilled holes (Fig. 11.9) (Loyola et al. 2013a), again, using EIT. While these bio-inspired sensing skins demonstrated promise for SHM, more in-depth studies and larger-scale validation tests are needed for transitioning this technology to the commercial domain.

11.5 Summary

This chapter summarizes recent developments in bio-inspired computational tools and new technological developments for SHM. In particular, three specific areas have been discussed. First, computational methods inspired by the BIS have been shown to be applicable for distributed SHM sensing system. These computational tools can be used for detecting sensor faults in the network, optimizing sensor instrumentation strategy, or processing signals measured.

Second, mobile robotic sensors are inspired by different living being's ability to crawl or navigate around the world. These robotic devices offer the possibility of measuring densely distributed structural response by crawling around the host structure. Their small size and nimbleness allow them to navigate to inaccessible or dangerous places.

Finally, thin film-based sensors inspired by the human dermatological system (or skin) have also been proposed and validated in the laboratory. The skin is an extremely unique organ in which densely distributed and multi-modal sensing is accomplished in real-time. Recent developments in nanotechnology-enabled thin film sensors or coatings have permitted the design of artificial sensing skins. For instance, polymeric thin films that incorporate carbon nanotubes have been shown to be sensitive to strain. When combined with an electrical impedance tomographic spatial conductivity algorithm, spatial sensing and the detection of damage severity and location have been verified.

Despite numerous attempts of biomimicry, most artificial systems remain inferior to its natural counterparts and still require expensive and tedious materials processing. The authors expect that future trends in SHM will continue to see further developments in biologically inspired sensing systems. Not only will technological innovations mimic biological system behavior, but also, one could expect systems that are assembled in the same manner as in biology. This possibility is becoming more realistic, especially where the advent of nanotechnology has permitted the "bottom-up" assembly of molecules to form macro-scale devices. In addition, mechanisms ranging from actuation, healing, and energy transduction, among many others, would become integrated for advancing SHM and for achieving next-generation resilient infrastructure systems.

References

Abbasi M, Bin Abd Latiff MS, Chizari H (2014) Bioinspired evolutionary algorithm based for improving network coverage in wireless sensor networks. Sci World J 2014:8

Akiba T, Lee N, Mita A (2013) Sensor agent robot with servo-accelerometer for structural health monitoring. Key Eng Mater 558:289–296

Azhari F, Benassini J, Tom C, Loh KJ, Bombardelli FA (2014) Design and characterization of a piezoelectric sensor for monitoring scour hole evolution. In: SPIE—21st annual symposium on smart structures and materials and nondestructive evaluation and health monitoring, SPIE, San Diego, CA

Bai S, Li X, Xie Z, Zhou Z, Ou J (2014) A wireless fatigue monitoring system utilizing a bio-inspired tree ring data tracking technique. Sensors 14:4364–4383

Balaguer C, Gimenez A, Jardon A (2005) Climbing robots' mobility for inspection and maintenance of 3D complex environments. Auton Robots 18:157–169

Bar-Cohen Y (ed) (2006) Biomimetics: biologically inspired technologies. CRC Press, Boca Raton

Biezma MV, Schanack F (2007) Collapse of steel bridges. J Perform Constructed Facil 21:398–405

Boller C (2000) Next generation structural health monitoring and its integration into aircraft design. Int J Syst Sci 31:1333–1349

Borcea L (2002) Electrical impedance tomography. Inverse Problems, 18

Brown BH (2003) Electrical impedance tomography (EIT): a review. J Med Eng Technol 27:97–108

Böger L, Wichmann MHG, Meyer LO, Schulte K (2008) Load and health monitoring in glass fibre reinforced composites with an electrically conductive nanocomposite epoxy matrix. Compos Sci Technol 68:1886–1894

Celebi M (2002) Seismic instrumentation of buildings (with emphasis on federal buildings). United States Geological Survey, Menlo Park, CA

Celebi M (2006) Real-time seismic monitoring of the new Cape Giradeau bridge and preliminary analyses of recorded data: an overview. Earthq Spectra 22:609–630

Coombs S (2001) Smart skins: information processing by lateral line flow sensors. Auton Robots 11:255–261

Dasgupta D (2006) Advances in artificial immune systems. IEEE Comput Intell Mag 1:40–49

Dijkstra M, Barr JJV, Wiegerink RJ, Lammerink TSJ, Boer JHD, Krijnen GJM (2005) Artificial sensor hairs based on the flow sensitive receptor hairs of crickets. J Micromech Microeng 15:S132–S138

Dinh-Trong N, Steitz J, Lei B, Kanoun O (2009) Influence of the composition of MWCNTs layers on the properties of strain gauges. In: 9th IEEE conference on nanotechnology Genoa, Italy, pp 477–480

Drozda M, Schaust S, Schildt S, Szczerbicka H (2011b) Priming: making the reaction to intrusion or fault predictable. Nat Comput 10:243–274

Drozda M, Bate I, Timmis J (2011a) Bio-inspired error detection for complex systems. Dependable computing (PRDC), 2011. In: IEEE 17th Pacific rim international symposium, pp 154–163. 12–14 Dec 2011

Eberhardt WC, Shakhsheer YA, Calhoun BH, Paulus JR, Appleby MA (2011) Bio-inspired artificial whisker for fluid motion sensing with increased sensitivity and reliability. In: IEEE sensors, Limerick, pp 982–985

Enner F, Rollinson D, Choset H (2012) Simplified motion modeling for snake robots. In: IEEE International conference on robotics and automation, St. Paul, MN, pp 4216–4221

Enner F, Rollinson D, Choset H (2013) Motion estimation of snake robots in straight pipes. In: IEEE International conference on robotics and automation (ICRA), Karlsruhe, Germany, pp 5149–5153

Farrar CR, Worden K (2007) An introduction to structural health monitoring. Philos. Trans. R. Soc. A 365:(1851):303–315

Federal Highway Administration (FHWA) (2004) National bridge inspection standards
Fisher JW, Kaufmann EJ, Wright W, Xi Z, Tjiang H, Sivakumar B, Edberg W (2001) In: Hoan bridge forensic investigation failure analysis final report. Wisconsin Department of Transportation and the Federal Highway Administration, Madison, WI
Gandomi AH, Yun GJ, Yang X-S, Talatahari S (2013) Chaos-enhanced accelerated particle swarm optimization. Commun Nonlinear Sci Numer Simul 18:327–340
Hartle RA, Amrhein WJ, Iii KEW, Baughman DR, Tkacs JJ (1990) Bridge inspector's training manual/90. Federal Highway Administration, McLean
Holder DS (2005) Electrical impedance tomography—methods, history and applications. Institute of Physics Publishing, Bristol, UK
Horsley DA, Talin AA, Skinner JL (2008) Micromechanical and microfluidic devices incorporating metallic gratings fabricated using nanoimprint lithography. J Nanophotonics 2:021785/1-11
Hou T.-C, Loh KJ, Lynch JP (2007a) Electrical impedance tomography of carbon nanotube composite materials. SPIE, San Diego, CA 652926/1-10
Hou TC, Loh KJ, Lynch JP (2007b) Spatial conductivity mapping of carbon nanotube composite thin films by electrical impedance tomography for sensing applications. Nanotechnology 18:315501/1-9
Hunt J, Timmis J, Cooke E, Neal M, King C (1999) Jisys: the envelopment of an artificial immune system for real world applications. In: Dasgupta D (ed) Artificial immune systems and their applications. Springer, Berlin Heidelberg
Huston D, Esser B, Miller J, Wang X (2005) Robotic and mobile sensor systems for structural health monitoring. In: 5th International workshop on structural health monitoring, Stanford, CA, pp 1–8
Javadi AA, Farmani R, Tan TP (2005) A hybrid intelligent genetic algorithm. Adv Eng Inform 19:255–262
Kang I, Lee JW, Choi GR, Jung JY, Hwang S-H, Choi Y-S, Yoon KJ, Schulz MJ (2006) Structural health monitoring based on electrical impedance of a carbon nanotube neuron. Key Eng Mater 321–323:140–145
Kao I, Kumar A, Binder J (2007) Smart MEMS flow sensor: theoretical analysis and experimental characterization. IEEE Sens J 7:713–722
Kennedy J, Eberhart R (1995) Particle swarm optimization. In: Proceedings of IEEE international conference on neural networks, Perth, Australia, pp 1942–1948
Kersey AD (1996) A review of recent developments in fiber optic sensor technology. Opt Fiber Technol 2:291–317
Kim DR, Lee CH, Zheng X (2009) Probing flow velocity with silicon nanowire sensors. Nano Lett 9:1984–1988
Kirikera GR, Shinde V, Schulz MJ, Ghoshal A, Sundaresan MJ, Allemang RJ, Jong WL (2008) A structural neural system for real-time health monitoring of composite materials. Struct Health Monit 7:65–83
Kostopoulos V, Vavouliotis A, Karapappas P, Tsotra P, Paipetis A (2009) Damage monitoring of carbon fiber reinforced laminates using resistance measurements. improving sensitivity using carbon nanotube doped epoxy matrix system. J Intell Mater Syst Struct 20:1025–1034
Lee MH, Nicholls HR (1999) Review article tactile sensing for mechatronics—a state of the art survey. Mechatronics 9:1–31
Li Z, Dharap P, Nagarajaiah S, Barrera EV, Kim JD (2004) Carbon nanotube film sensors. Adv Mater 16:640–643
Lin T-K, Kiremidjian A, Lei C-Y (2010) A bio-inspired structural health monitoring system based on ambient vibration. Smart Mater Struct 19:115012
Lin Y, Sodano HA (2009) Fabrication and electromechanical characterization of a piezoelectric structural fiber for multifunctional composites. Adv Funct Mater 19:592–598
Liu C (2007) Micromachined biomimetic artificial haircell sensors. Bioinspiration Biomimetics 2:S162–S169

Liu W, Gao W-C, Sun Y, Xu M-J (2008) Optimal sensor placement for spatial lattice structure based on genetic algorithms. J Sound Vib 317:175–189

Loh KJ, Azhari F (2012) Recent advances in skin-inspired sensors enabled by nanotechnology. J Mater 64:793–801

Loh KJ, Hou T-C, Lynch JP, Kotov NA (2009) Carbon nanotube sensing skins for spatial strain and impact damage identification. J Nondestr Eval 28:9–25

Loh KJ, Kim JH, Lynch JP, Kam NWS, Kotov NA (2007) Multifunctional layer-by-layer carbon nanotube-polyelectrolyte thin films for strain and corrosion sensing. Smart Mater Struct 16:429–438

Loh KJ, Lynch JP, Shim BS, Kotov N (2008) Tailoring piezoresistive sensitivity of multilayer carbon nanotube composite strain sensors. J Intell Mater Syst Struct 19:747–764

Loh KJ, Tom C, Benassini J, Bombardelli F (2014) A distributed piezo-polymer scour net for bridge scour hole topography monitoring. Smart Struct Sys 1:183-195

Loh KJ (2008) Development of multifunctional carbon nanotube nanocomposite sensors for structural health monitoring. Ph.D., Department of Civil & Environmental Engineering, University of Michigan, Ann Arbor

Loh KJ, Lynch JP, Kotov NA (2005) Conformable single-walled carbon nanotube thin film strain sensors for structural monitoring. In: 5th International workshop on structural health monitoring, Stanford, CA, pp 686–694

Loyola BR, Briggs TM, Arronche L, Loh KJ, Saponara VL, O'Bryan G, Skinner JL (2013a) Detection of spatially distributed damage in fiber-reinforced polymer composites. Struct Health Monit 12:225–240

Loyola BR, la Saponara V, Loh KJ (2010) In situ strain monitoring of fiber-reinforced polymers using embedded piezoresistive nanocomposites. J Mater Sci 45:6786–6798

Loyola BR, la Saponara V, Loh KJ, Briggs TM, O'Bryan G, Skinner JL (2013b) Spatial sensing using electrical impedance tomography. IEEE Sens J 12:2357–2367

Lynch JP, Loh KJ (2006) A summary review of wireless sensors and sensor networks for structural health monitoring. Shock Vibr Digest 38:91–128

Mcgary PD, Tan L, Zou J, Stadler BJH, Downey PR, Flatau AB (2006) Magnetic nanowires for acoustic sensors. J Appl Phys 99:08B310/1-6

Moore M, Phares B, Graybeal B, Rolander D, Washer G (2001) Reliability of visual inspection for highway bridges. Federal Highway Administration, Washington

Mortensen LP, Ryu D, Zhao Y, Loh KJ (2013) Rapid assembly of multifunctional thin film sensors for wind turbine blade monitoring. Key Eng Mater 569–570:512–522

Mukai T, Onishi M, Odashima T, Hirano S, Luo Z (2008) Development of the tactile sensor system of a human-interactive robot "RI-MAN". IEEE Trans Rob 24:505–512

National Transportation Safety Board (NTSB) (2003) Natural gas pipeline rupture and fire near Carlsbad, New Mexico. In: Pipeline accident report, Washington DC

Nofar M, Hoa SV, Pugh MD (2009) Development of novel single-wall carbon nanotube–epoxy composite ply actuators. Compos Sci Technol 69:1599–1606

Oh J-K, Jang G, Oh S, Lee JH, Yi B-J, Moon YS, Lee JS, Choi Y (2009) Bridge inspection robot system with machine vision. Autom Constr 18:929–941

Peckens CA, Lynch JP (2013) Utilizing the cochlea as a bio-inspired compressive sensing technique. Smart Mater Struct 22:105027

Peekema RM (2013) Causes of natural gas pipeline explosive ruptures. ASCE J Pipeline Syst Eng Pract 4:74–80

Pfatteicher SKA, Tongue MP (2002) What drives diversity? Engineering education and underrepresentation of minority groups. In: 32nd Annual frontiers in education, Boston, MA, pp S1C-1-6

Philen MK, Shan Y, Prakash P, Wang KW, Rahn CD, Zydney AL, Bakis CE (2007) Fibrillar network adaptive structure with ion-transport actuation. J Intell Mater Syst Struct 18:323–334

Pinto, PA, Sarles SA, Leo DJ (2011) Bio-inspired flow sensors fabricated from carbon nanomaterials. In: ASME 2011 Conference on smart materials, adaptive structures and intelligent systems, Scottsdale, AZ, pp 725–732

Pyo S, Loh KJ, Hou T-C, Jarva E, Lynch JP (2011) A wireless impedance analzyer for automated tomographic mapping of a nanoengineered sensing skin. Smart Struct Syst 8:137–153

Rytter A (1993) Vibration based inspection of civil engineering structures. Aalborg University, Aalborg Ph.D. Ph.D

Salowitz N, Guo Z, Li Y-H, Kim K, Lanzara G, Chang F-K (2013) Bio-inspired stretchable network-based intelligent composites. J Compos Mater 47:97–105

Sarles SA, Madden JDW, Leo DJ (2011) Hair cell inspired mechanotransduction with a gel-supported, artificial lipid, membrane. Soft Matter 7:4644–4653

Schmidt RF (1986) Fundamentals of sensory physiology. Springer, New York

Spencer Jr BF, Ruiz-Sandoval ME, Kurata N (2004) Smart sensing technology: opportunities and challenges. J Struct Control Health Monit 11:349–368

Sumitro S, Kurokawa S, Shimano K, Wang ML (2005) Monitoring based maintenance utilizing actual stress sensory technology. Smart Mater Struct 14:S68–S78

Swartz RA, Flatau AB, Brooks CN, Barkdoll BD, NA S-M, Endsley KA (2014) Bio-inspired magnetostrictive whisker sensors for autonomous bridge scour sensing. In: Transportation research board 93rd annual meeting, Washington, DC, pp 1–12

Tadigadapa S, Mateti K (2009) Piezoelectric MEMS sensors: state-of-the-art and perspectives. Meas Sci Technol 20:1–30

Tao J, Yu XB, Berrilla J (2011) Bio-inspired flow and acoustic sensor. In: Proceedings of the Sensors, and command, control, communications, SPIE and intelligence (C3I) technologies for homeland security and homeland defense X, Orlando, FL, pp 80190R/1-10

Thostenson ET, Chou T-W (2002) Aligned multi-walled carbon nanotube-reinforced composites: processing and mechanical characterization. J Phys D 35:L77–L80

Thostenson ET, Chou T-W (2006) Carbon nanotube networks: sensing of distributed strain and damage for life prediction and self healing. Adv Mater 18:2837–2841

Thostenson ET, Chou T-W (2008) Real-time in situ sensing of damage evolution in advanced fiber composites using carbon nanotube networks. Nanotechnology 19:215713

Tomizuka M, Bergman LA, Shapiro B, Shoureshi R, Spencer BF, Taya M (2007) Bio-inspired autonomous engineered systems. Smart Struct Syst 3:495–505

Tsuda H, Takahashi J, Urabe K, Ikeguchi T (1999) Damage monitoring of carbon fiber-reinforced plastics with Michelson interferometric fiber-optic sensors. J Mater Sci 34:4163–4172

Twycross J, Aickelin U (2009) An Immune Inspired Approach to Anomaly Detection. arXiv preprint arXiv:0910.3117

Unver O, Uneri A, Aydemir A, Sitti M (2006) Geckobot: a gecko inspired climbing robot using elastomer adhesives. In: Proceedings of the IEEE International conference on robotics and automation, Orlando, FL. pp 2329–2335

Wang C-Y, Wang H-L, Ho C-C (2012) A piezoelectric film type scour monitoring system for bridge Pier. Adv Struct Eng 15:897–905

Whitehouse R (1998) Scour at Marine Structures. Thomas Telford, Heron Quay, London

Wiegerink RJ, Floris A, Jaganatharaja RK, Izadi N, Lammerink TSJ, Krijnen GJM (2007) Biomimetic flow-sensor arrays based on the filiform hairs on the cerci of crickets. In: IEEE sensors conference, pp 1073–1076

Worden K, Burrows AP (2001) Optimal sensor placement for fault detection. Eng Struct 23:885–901

Wu X, Wang D, Zhao A, Li D, Mei T (2013) A wall-climbing robot with biomimetic adhesive pedrail. In: Zhang D (ed) Advanced mechatronics and MEMS devices. Springer, New York

Yao L, Sethares WA, Kammer DC (1993) Sensor placement for on-orbit modal identification via a genetic algorithm. AIAA J 31:1922–1928

Yi T-H, Li H-N, Zhang X-D (2012) Sensor placement on canton tower for health monitoring using asynchronous-climb monkey algorithm. Smart Mater Struct 21:125023

Yim JH, Kim YS, Koh KH, Lee S (2008) Fabrication of transparent single wall carbon nanotube films with low sheet resistance. J Vac Sci Technol B 26:851–855

Yousef H, Boukallei M, Althoefer K (2011) Tactile sensing for dexterous in-hand manipulation in robotics—a review. Sens Actuators A 167:171–187

Yu L, Santoni-Bottai G, Xu B, Liu W, Giurgiutiu V (2008) Piezoelectric wafer active sensors for in situ ultrasonic-guided wave SHM. Fatigue Fract Eng Mater Struct 31:611–628

Yu X, Tao J, Berilla J (2010) A Bio-inspired flow sensor. In: Proceedings of SPIE—nanosensors, biosensors, and info-tech sensors and systems

Zhang G, Zhang Z, Ficher C (2007) Structural health monitoring of a long-span cable-stayed bridge. J Intell Mater Syst Struct 18:835–843

Zhao X, Qian T, Mei G, Kwan C, Zane R, Walsh C, Paing T, Popovic Z (2007) Active health monitoring of an aircraft wing with an embedded piezoelectric sensor/actuator network: II. wireless approaches. Smart Mater Struct 16:1218–1225

Zhu D, Yi X, Wang Y, Lee K-M, Guo J (2010) A mobile sensing system for structural health monitoring: design and validation. Smart Mater Struct 19:055011/1-11