Title
Recent Advances in Skin-Inspired Sensors Enabled by Nanotechnology

Journal
JOM, 64(7)

ISSN
1047-4838

Authors
Loh, Kenneth J
Azhari, Faezeh

Publication Date
2012-07-01

DOI
10.1007/s11837-012-0358-5

Peer reviewed

Recent Advances in Skin-inspired Sensors Enabled by Nanotechnology

Kenneth J. Loh[1,*] and Faezeh Azhari[1]

[1]Department of Civil & Environmental Engineering
University of California, Davis, 95616-5294, USA
[*]E-mail: kjloh@ucdavis.edu

Abstract

The highly optimized performance of nature's creations and biological assemblies has inspired the development of their bio-inspired artificial counterparts that can potentially outperform conventional systems. In particular, the skin of humans, animals, and insects exhibit unique functionalities and properties and has subsequently led to active research in developing skin-inspired sensors. This paper presents a summary of selected work related to skin-inspired tactile, distributed strain, and artificial hair cell flow sensors, with a particular focus on technologies enabled by recent advancements in the nanotechnology domain. The purpose is not to present a comprehensive review on this broad subject matter but rather to use selected work for outlining the diversity of current research activities.

Keywords: bio-inspired sensors; flow sensors; nanocomposite; nanotechnology; sensing; skin; smart materials; tactile sensors.

1. Introduction

Nature's creations, ranging from the most common household plants to large mammals such as dolphins or humans, are complex designs optimized to survive and adapt to its surrounding environment. Proteins, cells, microorganisms, and other functional structures are intricately weaved together to perform specific purposes while working collectively to enable autonomous behaviors such as motor function (*e.g.*, swimming, running, and flying) and decision making for the living creature. It is the unique functionalities performed by many living organisms that have historically inspired humans to mimic their behavior for engineering applications [1].

Modern technology has enabled the design of complex and high performance biologically-inspired systems such as morphing aircrafts [2], dynamic materials [3], control methodologies [4], algorithms [5], and solar energy devices [6], among many others. Despite numerous attempts of biomimicry, most artificial systems remain inferior to its natural counterparts and require expensive and tedious materials processing. In addition, bio-inspired technology reaches beyond mimicking biological functionalities and entails learning how nature assembles, organizes, and communicates with one another (*e.g.*, ranging from cellular activity at nano-/micro-scales to whale songs that can be received many miles away). It is not until recently where the advent of nanotechnology has permitted the "bottom-up" assembly of molecules similar to biological processes to form macro-scale devices. In addition, nanomaterials often possess unique physical, mechanical, chemical, and electronic properties that greatly differ than their bulk state [7]. Unlike micro-fabrication and micro-electromechanical systems (MEMS) that miniaturize macro-scale designs, nano-fabrication mimics biological processes and assembles materials starting at the molecular length scale, one building block at a time, thereby permitting intricate designs that can outperform current-generation devices [8].

In the specific case of sensors, nature has perfected biological assemblies and functionalities to enable touch, visual, auditory, olfactory, and taste sensing among its diverse creations. A recent review by Bar-Cohen [9] has highlighted important advancements in sensor technologies inspired by the aforementioned biological senses. These bio-inspired sensors have the potential to revolutionize and find applications for structural health monitoring/damage detection [10], environmental monitoring [11], tactile sensing [12], and artificial muscles [13, 14], to name a few [15-17]. Equally high interests from funding agencies have also driven research productivity in bio-inspired sensors (*e.g.*, from the National Science Foundation (NSF), United States Department of Defense (DoD), and Defense Advanced Research Projects Agency (DARPA)). For example, NSF's dedication to advancing bio-inspired research and promoting international collaboration has led to several joint workshops (*e.g.*, US-Taiwan in 2009, US-China in 2011, and US-Japan in 2011) [18].

The purpose of this summary paper is to highlight recent advances in sensors research inspired by the skin of living creatures. In particular, the human dermatological system is an incredible and highly optimized multifunctional material, where it is capable of protecting bodily organs, absorb nutrients, regulate temperature, and sense the external environment [19]. While many existing technologies have been inspired by the skin or surfaces of living creatures, this paper will showcase recent developments and technological breakthroughs that have been made possible by materials and tools derived from the nanotechnology domain. Topics that will be covered range from skin-inspired distributed sensors to functional or smart surfaces. This paper is not meant to serve as an exhaustive review on the subject matter but is rather intended to provide the reader with a broad overview by highlighting selected work.

2. Tactile and Distributed Sensing using Microelectronics

A unique and impressive functionality of human skin is its ability to perform densely distributed and multi-modal sensing. Approximately 640,000 sensory receptors are distributed throughout the skin for sensing bodily interactions with the outside world, such as changes in temperature and deformation [19]. In particular, human skin has inspired extensive research in developing biomimetic tactile sensors that can measure contact pressure and shear strain, while simultaneously possessing skin-like mechanical flexibility. Lee and Nicholls [12] has compiled a comprehensive review on tactile sensor state-of-art research up to 1999. These tactile sensors can find applications for robotics, biomedical prosthetics, and industrial automation, among others [12]. Investigations of biomimetic tactile sensors have focused on incorporating discrete piezoresistive [20], piezoelectric [21], capacitive [22], or micro-electronic elements [23] in a flexible and compliant matrix. An updated review has been presented by Yousef *et al.* [24] in 2011, and the review showcases new technological advancements in conductive fluids [25], polymers [26], elastomer composites [27, 28], and micro-electromechanical systems (MEMS)-based devices [29], among others, for tactile sensing. An overview of the diverse types of tactile sensors is presented in this section.

One of the most actively studied types of tactile sensors involves the embedment of miniaturized microelectronic systems within a flexible skin-like membrane or film. Xu *et al.* [23] has fabricated a shear stress sensor skin for monitoring flow separation on the leading edge of unmanned aerial vehicles. The sensing element is based on resistive heating of poly-silicon/nitride diaphragms (using constant current mode) that are embedded in a flexible polyimide matrix. A 36-channel array of the skin has been implemented on the leading edge of a delta-wing structure during wind tunnel and flight tests, and the results confirm the measurement of shear stress topography and flow separation. Someya *et al.* [30] has also developed flexible electronic artificial skins (E-skin) that feature thermal (*i.e.*, organic diodes) and pressure sensors (*i.e.*, organic transistors) distributed throughout its net-like structure. Each type of sensor can be assembled to form 12 x 12 transistor arrays and then laminated over one another to form a multi-modal distributed sensor. The test results confirm mapping of the temperature and pressure distributions due to a heated copper block placed diagonally on the E-skin. Technologies like the E-skin and flexible films with embedded piezoresistor micro-sensors for force sensing are suitable for use in artificial or robotic hands [31]. Arrays of MEMS force sensors have also been embedded in a patterned polymer robotic fingertip for sensing different surface textures and roughness [32]. Flexible tactile sensors have also been implemented on the RI-MAN human-interactive robot's chest and arms for sensing and manipulating a dummy human load [33].

Tactile sensing has also been achieved with capacitive micro-sensor elements such as sensor arrays based on silicon diaphragm-based capacitive transducers [22]. Cheng *et al.* [34] has also used micromachining for fabricating pseudo-parallel-plate capacitive normal and shear sensor arrays with floating electrodes that rest on a flexible poly(dimethyl siloxane) (PDMS) structure. Prototypes featuring 8 x 8 sensor arrays have been fabricated and tested in the laboratory; the system features a force sensing resolution of 26 mN and a maximum sensitivity of 1.67%-mN^{-1}. Similarly, MEMS-based capacitive tactile sensor arrays have also been packaged in PDMS [35], and bare and PDMS-packaged sensors exhibit force sensitivities of 0.035 pF-mN^{-1} and 0.068 fF-mN^{-1}, respectively [29]. On the other hand, Tiwana *et al.* [36] has presented a different capacitive tactile sensor that uses vertical pillars encased in pinkysil silicone elastomer for sensing shear. Lateral displacement of the protruding pillar causes measureable changes in device capacitance, and the sensor exhibits near-linear sensitivity to applied force, as have been verified experimentally and via numerical modeling using *COMSOL*. In addition to capacitive-based sensors, tactile sensing elements based on piezoelectric polymers like poly(vinylidene fluoride) (PVDF) have also been successfully demonstrated, as have been done by Dahiya *et al.* [21], Jamali and Sammut [26], and Drimus and Bilberg [37], to name a few. Maheshwari and Saraf [38] has also developed an electro-optical thin film tactile sensor based on gold and cadmium sulfide (CdS) nanoparticles. The multilayered thin film's electro-luminescence and current density are linearly related to applied stress. It has also been shown that a charge-coupled device (CCD) camera can capture the electro-luminescent light of the thin film tactile sensor to achieve direct pressure/stress imaging of different objects (*e.g.*, a penny) [38].

3. Distributed Strain Sensing using Nanocomposites

Among the wide selection of nanomaterials, carbon nanotubes (CNT) [39] have attracted significant research interest due to their unique material properties [40] and diverse applications [41, 42]. Khare and Bose [43] and Kang *et al.* [44] have compiled comprehensive reviews of CNT synthesis methodologies, their impressive material properties, and applications for sensing [45]. Despite their advantages, their nano-scale physical properties and tendency to agglomerate make them inherently challenging to use as is [46]. Thus, numerous methods have been used to incorporate carbon nanotubes in flexible matrices for achieving nanocomposite-based skin-like distributed sensors. Examples of fabrication methods include polymer casting [47], epoxy molding [48], spin coating [49], buckypaper [50], layer-by-layer [51], evaporation [52], and spraying [53], among many others [54]. The incorporation of CNTs within a nanocomposite architecture permits tuning of material properties [55], encoding of electro-mechanical sensing capabilities [56], while simultaneously achieving mechanical flexibility similar to skin. In fact, Sinha *et al.* [57], Mahar *et al.* [58], and Li *et al.* [59] have assembled comprehensive reviews of CNT-based nanocomposite sensors and actuators.

An effective way of taking advantage of carbon nanotube's unique material properties is to embed them in the flexible epoxy matrices as part of fiber-reinforced polymer (FRP) composites. Park *et al.* [60] has compared the electro-mechanical response of carbon nanotube-, carbon nanofiber-, and carbon black-based epoxy composites. The mechanical response (*i.e.*, tensile strength and modulus) and damage sensitivity of CNT/epoxy is the highest among the three different sample sets tested (*i.e.*, given the same concentration of nanomaterials embedded, which is 2.0 *vol.*%). Thostenson and Chou [48, 61, 62] has shown that effective dispersions of CNTs in epoxy can produce conductive epoxy-based composites, and even the incorporation of 0.1 *wt.*% CNTs has resulted in a percolated composite structure with deformation/strain sensing capabilities. In addition to demonstrating linear strain sensing performance [61], CNT-modified epoxy composites can also be used for monitoring delamination and micro-cracks, as have also been found by Böger *et al.* [63], Nofar *et al.* [64], and Kostopoulous *et al.* [65]. Li and Chou [66] has also used two-dimensional finite element models to validate the CNT/epoxy's electrical resistance sensitivity to deformation and damage. On the other hand, Anand and Mahapatra [67] has used models and experiments to show that CNT/epoxy composites that also incorporate carbon black nanoparticles possess nonlinear strain sensitivity under quasi-static loading. Strain sensitivity has been shown to be dependent on the oscillation frequency during dynamic testing. Epoxy resins modified with carbon black alone have also been validated for their piezoresistivity [68]. Besides sensing, Rajoria and Jalili [69] has shown that CNT/epoxy composites can also possess improved energy dissipation characteristics (*i.e.*, multi-walled carbon nanotube (MWNT)-based epoxy composites possess damping ratios up to 700% higher than pristine epoxy-based specimens). Yun *et al.* [70] has also demonstrated CNT/epoxy composites for actuation.

Another very active research area is to enable skin-like strain sensing capabilities using CNT-based thin films. Early investigation by Dharap *et al.* [71] has shown that single-walled carbon nanotube (SWNT) mats or buckypapers possess linear piezoresistivity (*i.e.*, thin film electrical resistivity changes due to applied strain) up to 0.04% strain. Kang *et al.* [72] has also assembled SWNT-based buckypaper as well as SWNT/polymethyl methacrylate (PMMA)-casted films. Quasi-static and dynamic cantilevered beam tests have been conducted, and the results show that both types of films are capable of monitoring strain and possess high strain sensitivities (or gage factors up to ~5 and ~7 for the PMMA-based films and buckypapers, respectively). This study has also been extended for crack detection and corrosion monitoring using a sprayed-on CNT-neuron thin film [53], although even higher strain sensitivities of PMMA-based films (up to ~15) has been achieved by Pham *et al.* [47]. Loh *et al.* [51, 73] has also shown that SWNT-based films assembled using layer-by-layer self-assembly exhibit linear piezoresistivity up to 1% strains, and its strain sensitivity can also be readily controlled by modifying carbon nanotube concentrations during fabrication [74]. These layer-by-layer films have also been embedded in FRP composites for embedded strain monitoring and damage detection [75]. Park *et al.* [76] has shown that CNT/polyethylene oxide films change their resistance linearly to applied strains up to 0.8%, and the film can be used to monitor strains up to 7%. However, it is Chang *et al.* [77] that has achieved gage factors of up to 269 by growing and suspending individual nanotubes over patterned trenches on a flexible substrate. Films fabricated with other techniques such as epoxy mixing [67, 78], in situ polymerization [79-81], compression molding [82], vacuum filtration [83-85], casting [86], and heat treatment [87], or ones based on different polymer matrices [88-91], have also been validated for their piezoresistivity. It should be mentioned that since CNTs are embedded in polymeric thin films, their mechanical response may be viscoelastic by nature, as have been characterized by Suhr *et al.* [92] and Zhao *et al.* [93]. These CNT/polymer-based thin films have also been demonstrated for actuation [94-102].

Skin-like distributed strain sensing has been achieved by Hou *et al.* [103] and Loh *et al.* [104], where piezoresistive carbon nanotube-based thin films (fabricated using layer-by-layer assembly) have been coupled with an electrical impedance tomography (EIT) algorithm. In short, EIT utilizes boundary electrical measurements for solving the inverse problem that enables mapping of a conductive body's two- or three-dimensional electrical conductivity (or resistivity) map [105, 106]. Since the electrical properties of layer-by-layer films have been shown to be linearly correlated to strain [51, 74], the spatial conductivity maps directly reveal the strain distributions as measured by the carbon nanotube-based thin films. Hou *et al.* [103] has validated these "sensing skin's" ability of measuring the location of etched regions on a film surface and has applied EIT for sensing changes in pH on a carbon nanotube/polyaniline-based film (Fig. 1). Continued work by Loh *et al.* [104] has demonstrated that this technique can effectively identify the location and severity of impact damage on a sensing skin-coated aluminum plate (Fig. 2). Spatial corrosion monitoring and wireless data acquisition has also been achieved [107]. Similarly, Alirezaei *et al.* [108] has designed and fabricated a pressure-sensitive conductive knitted fabric, and the fabric has been applied onto a physical model of a human face. The fabric and EIT algorithm has been validated for sensing pressure applied to different locations on the fabric and human face. Continued research has also shown that the system is able to measure dynamic pressure and deformation [109]. The advantage of using EIT is that spatial information can be obtained from boundary electrical measurements instead of probing every location on the sensor surface. While EIT for bio-inspired skin sensors is still in its early stages of development, it should be noted that EIT has been long used for biomedical applications such as lung disorders [110] and breast cancer [111] diagnosis. Also, EIT is not the only method for spatial sensing; researchers such as Zunino [112] has developed multilayered smart coatings and nanocomposites that change their color in response to deformation or corrosion.

Instead of using continuous sensing materials and techniques like EIT, an alternative approach to create bio-inspired sensing skins is to use densely distributed sensors with wireless data acquisition and transmission capabilities. For instance, Tata *et al.* [113] has designed strain-sensitive patch antennas and has fabricated them on flexible polyimide/Kapton substrates. Applied strain changes the geometry of the patch antenna, which ultimately causes a shift in the antenna's resonant frequency, and the backscattered signal can be interrogated and measured wirelessly using a horn antenna (Fig. 3). The results demonstrate linear variations in sensor resonant frequency with applied strains, and the sensor's in-plane strain sensitivity is ~15 kHz-$\mu\varepsilon^{-1}$ for both orthogonal directions. Yi *et al.* [114] has fabricated and tested a radio frequency identification (RFID)-based folded patch antenna for strain monitoring. Again, sensor resonant frequency varies linearly with strain, and the sensitivity is approximately -750 Hz-$\mu\varepsilon^{-1}$. These sensors can be interrogated as far as 24 in (or 61 cm) away. Other RFID-based wireless strain sensors have also been validated by integrating SWNT-based thin films with an inductive coil antenna [115, 116].

4. Flow Sensing

Nature also offers many examples where organisms (such as fish, insects, and humans) are capable of monitoring fluid flow fields in their vicinity using hairy surface structures. For instance, the spatially-distributed lateral line system in various aquatic species can detect slow, uniform motions as well as rapidly changing motions and is able to integrate and segregate spatial information through velocity-sensitive superficial sensory organs (neuromasts) and acceleration- or pressure-gradient-sensitive canal neuromasts, respectively [117]. The lateral line system not only can provide information on both large-scale stimuli and fine spatial details, but it has also evolved to ensure improved signal-to-noise ratios in different unexpected and expected behavioral contexts. Coombs [117] has reviewed the information processing capabilities of the lateral line mechanosensory system with the objective of potentially applying its design features and neural processing algorithms to aquatic robots to enhance their ability in maneuvering, surveying, and manipulating objects in foreign, dark, and turbulent environments. Another example is human hairs (cilia) which have the capability to detect minute changes in the direction and magnitude of fluid flow [118]. Similarly, crickets are naturally equipped with sensory filiform hairs for monitoring slight changes in low frequency acoustic signals and for detecting movements (*i.e.*, displacements) of nearby predators [119]. Inspired by natural hair cells and their diversity, recent studies have aimed at developing flow sensors that mimic the mechanisms evolved and perfected in sensory hairs. Artificial hair cells (AHCs) perform electro-mechanical transduction [120] in response to air or fluid flow similar to the way tilting of biological hair cells results in neuronal electrical signals [121].

Natural sensory hairs are small and exist in arrays, which make them ideal for flow sensing; their small size enables them to optimally interact with their surroundings without creating any interference, while their abundance enhances their spatial flow detection. Only recently has technology advanced in micro- and nano-scale materials and circuits that have provided researchers with the tools for fabricating artificial hair cells with dimensions comparable to those of biological species. The trajectory of these developments will likely lead to flow sensors almost as robust and sensitive as those found in nature. For instance, whiskers are effectively used by animals for sensing their environment and surroundings. Recognizing this ability, Scholz and Rahn [122] has developed flexible actuated whiskers that can be used for shape identification of swept objects. These sensors can potentially be used for obstacle avoidance and object identification in unstructured environments such as harsh and murky underwater conditions [122].

While Scholz and Rahn [122] has developed active artificial whiskers, Liu [123] has developed various generations of passive AHC sensors. One rendition of their AHC sensors can detect two-axis deflection and consists of a polyurethane hair sitting over carbon-impregnated polyurethane force sensitive resistors (FSRs), the conductivity of which changes as a function of mechanical stress [124]. In another study, AHC sensors using photo-definable SU-8 epoxy as the cilium have been introduced. Through piezoresistive sensing, these highly directional sensors can detect flow velocities in water and air with high accuracy and sensitivity [121]. A recent review by Nawi *et al.* [125] presents the broad spectrum of AHC-based flow sensors.

Comparable studies have also been performed by various researchers focusing on the sensory capabilities of the filiform hairs of crickets as inspiration for developing next-generation biomimetic flow sensors. Dijkstra *et al.* [126] and Wiegerink *et al.* [119] have designed and realized 1 mm-long arrays of SU-8 photoresist hairs and have successfully demonstrated their viability and sensitivity as flow sensors through capacitive measurements. Viscous drag acting on the artificial hair causes tilting in a membrane, which in turn induces capacitance change. To date, an array of 144 columns each supported on an individual membrane and connected in parallel has been successfully fabricated to increase the sensor's flow sensitivity. The flow can thus be measured by differentially determining the changes in capacitance and acquiring the corresponding displacement angle [119]. Similar hair structures on flexible SU-8 membranes inspired by lateral lines in fish have also been studied for distributed flow sensing [127]. Sarles *et al.* [120] have used a gel-supported lipid bilayer as the transduction element in their AHC sensors, which is inspired by membrane structures in mammalian hearing. The physical structure incorporates a polymeric hydrogel synthetic fiber (as the hair structure). The properties of the measured current across the bilayer, induced by cilia vibration due to air flow, can be directly correlated to the trans-membrane voltage, flow rate, and hair dimensions [120]. On the hand, the stimuli-responsive dermis of sea cucumbers have been the inspiration for developing a new series of mechanically dynamic nanocomposites, using cotton cellulose whiskers, that change their mechanical properties when exposed to thermal and chemical stimuli [128].

While polymer-based sensors are more mechanically robust, silicon-based sensors provide superior sensitivity [123]. Silicon nanowire sensors have been configured as field-effect sensor by Kim *et al.* [129] for flow velocity measurements. Nanowire conductance changes in response to modifications in the streaming potential, which is due to changes in the flow velocity. These sensors can not only probe flow velocity but can also distinguish different electrolytic solutions and their ionic strength [129]. Tonisch *et al.* [130] have drawn on a bottom-up approach in their proposal and development of nanowire nano-electromechanical flow sensors, in which freestanding nanowires on top of a AlGaN/GaN heterostructure are deflected due to flow, causing strain, and thus resistance change. On the other hand, inspired by inner ear's cochlea and cilia, McGary *et al.* [131] has fabricated artificial cilia transducers using magnetostrictive nanowires that magnetically respond to bending loads. Special attention has been given to Galfenol nanowires as they are able to retain appreciable magnetostriction in both tension and compression [131]. These Galfenol nanowires have been coupled with giant magnetoresistive sensors for acoustic sensing [132]. Alternatively, Lin *et al.* [133] has adopted a hydrothermal synthesis method and has successfully grown vertically-aligned piezoelectric lead zirconate titanate (PZT) nanowire forests. The aligned nanowires exhibit potential for flow sensing or even actuation applications, particularly because PZT nanowire strain coupling coefficients are two orders of magnitude higher as compared to ones based on zinc oxide. In fact, Yu *et al.* [134] has shown that piezoelectric micro-fibers have the potential for use as real-time flow sensors. Research is ongoing for developing higher performance flow sensors and to apply these technologies for various applications [135-137].

Similar to Section 4, carbon nanotubes have also attracted attention and have been applied for fabricating novel flow sensors. Early studies by Ghosh *et al.* [138] has revealed that SWNT bundles respond to water flow by a corresponding flow-induced voltage. A logarithmic relationship between laminar flow velocity and generated voltage has been experimentally [138] and theoretically confirmed [139]. Liu *et al.* [140] has conducted an extended study investigating SWNT and MWNT arrays as well as how their relative alignment with respect to flow affects the measured flow-induced voltages. It has been found that aligned nanotubes can generate up to 70 times higher voltage (*i.e.*, for a sample subjected to water flowing at 0.0005 m-s^{-1}), and SWNTs have generated higher voltages versus MWNTs. In addition, these nanotubes have also been subjected to NaCl solutions flowing at different velocities, and it has been found that there is a linear relationship between flow-induced voltages and NaCl concentrations (*i.e.*, for a fixed flow velocity). Instead of using pristine nanotubes, Cao *et al.* [141] has verified that flow sensing is possible using SWNT/PDMS composite thin films. Pinto *et al.* [142] has also studied the flow sensing response of PDMS-based films embedded with SWNTs and single-walled nanohorns (SWNH). Electrical impedance spectroscopy has been conducted for characterizing sample response to air and fluid exposure, and small changes in sensor voltage has been measured due to varying flow conditions.

5. Smart Surfaces

In addition to the aforementioned skin- and cilia-inspired sensors, a plethora of other bio-inspired "smart" surfaces have been developed, as have been summarized by Singh *et al.* [143] and Xia and Jiang [144]. For example, the ability of lizards and geckos to climb and attach to various surfaces has inspired the development of reversible and highly adhesive functional surfaces [145]. The ability of biological creatures to attach and detach from surfaces is due to their unique nano-/micro-hair structures, which has subsequently inspired the investigation of artificial hair structures for smart adhesives [146]. Bhushan and

Sayer [147] has fabricated polyvinylsilaxane micro-pillars and has shown that such structured surfaces are characterized by enhanced static and kinetic coefficients of friction and roughness for greater surface adhesion. Similarly, the adhesion response of polyurethane microfiber arrays have also been studied by Aksak *et al.* [148]. Murphy *et al.* [149] has demonstrated that arrays of angled "mushroom-tipped" microfibers exhibit anisotropic adhesive properties. Enhanced adhesion can be achieved from a particular orientation, whereas peeling can be attained in the opposite direction, which is similar to the repeatable and reversible adhesive properties of gecko's feet. A numerical approach using the classical JKR model for investigating the reversible adhesion and detachment of a rigid cylinder in contact with an isotropic elastic surface at different angles has been performed by Chen and Gao [150]. More recently, polymeric nanohairs have also been investigated [151]. Continued future research in smart adhesives can lead to the development of gecko-inspired robots, such as the mobile wireless sensing robot (which is equipped with magnetic wheels rather than smart adhesives) that has been designed by Zhu *et al.* [152]. While this section has only presented selected work relevant to smart reusable adhesive surfaces, it should be mentioned that countless other bio-inspired surfaces are also being actively studied. For examples, lotus leaf-inspired super-hydrophobic and/or self-cleaning surfaces have gained widespread attention [153-155]. Other examples include, anti-reflective [156], self-healing [157], ultra-strong [158], adaptive [159], and other functional surfaces [160].

6. Conclusions

In summary, this paper has highlighted recent research on skin-inspired sensors that take advantage of nanotechnology derived materials and fabrication tools. The scope of this paper has been limited to presenting an overview of tactile sensors for robotic systems, distributed strain sensors for strain monitoring and damage detection, flow sensors for environmental sensing, and smart adhesive surfaces. In general, a wealth of other skin-inspired sensors have also been investigated, namely systems that are capable of achieving self-cleaning, self-healing, actuation, and ones that can morph/adapt due to various external applied stimuli. It is expected that bio-inspired sensors research will continue to expand, especially with the discovery of new materials, fabrication methodologies, and enhanced understanding of fundamental nano-scale physics and chemistry. In parallel to these engineering advancements, a more in-depth understanding of biological systems and their assemblies will be just as important for creating new opportunities for scientific and technological breakthroughs in bio-inspired sensor research.

7. References

[1] Bar-Cohen, Y., ed., *Biomimetics: Biologically Inspired Technologies*, CRC Press: Boca Raton, FL (2006).

[2] Barbarino, S., Bilgen, O., Ajaj, R.M., Friswell, M.I. and Inman, D.J., "A Review of Morphing Aircraft," Journal of Intelligent Material Systems and Structures, **22**(9), 823-877 (2011).

[3] Mohammed, J.S. and Murphy, W.L., "Bioinspired Design of Dynamic Materials," Advanced Materials, **21**(23), 2361 -2374 (2009).

[4] Siddique, N.H. and Amavasai, B.P., "Bio-Inspired Behaviour-Based Control," Artificial Intelligence Review, **27**(2), 131-147 (2007).

[5] Potvin, J.-Y., "A Review of Bio-Inspired Algorithms for Vehicle Routing," Studies in Computational Intelligence, **161**, 1-34 (2009).

[6] Boghossain, A.A., Ham, M.-H., Choi, J.H. and Strano, M.S., "Biomimetic Strategies for Solar Energy Conversion: A Technical Perspective," Energy and Environmental Science, **4**(10), 3834-3843 (2011).

[7] Devreese, J.T., "Importance of Nanosensors: Feynman's Vision and the Birth of Nanotechnology," MRS Bulletin, **32**(9), 718-724 (2007).

[8] Hierold, C., "From Micro- to Nanosystems: Mechanical Sensors Go Nano," Journal of Micromechanics and Microengineering, **14**(9), S1-S11 (2004).

[9] Bar-Cohen, Y., "Biological Senses as Inspiring Model for Biomimetic Sensors," IEEE Sensors Journal, **11**(12), 3194-3201 (2011).

[10] Ou, J. and Li, H., "Structural Health Monitoring in Mainland China: Review and Future Trends," Structural Health Monitoring, **9**(3), 219-231 (2010).

[11] Krantz-Rulcker, C., Stenberg, M., Winquist, F. and Lundstrom, I., "Electronic Tongues for Environmental Monitoring Based on Sensor Arrays and Pattern Recognition: A Review," Analytica Chimica Acta, **426**(2), 217-226 (2001).

[12] Lee, M.H. and Nicholls, H.R., "Review Article Tactile Sensing for Mechatronics—a State of the Art Survey," Mechatronics, **9**(1), 1-31 (1999).

[13] Bar-Cohen, Y., "Artificial Muscles Based on Electroactive Polymers as an Enabling Tool in Biomimetics " Journal of Mechanical Engineering Science, **221**(10), 1149-1156 (2007).

[14] Shahinpoor, M., Bar-Cohen, Y., Simpson, J.O. and Smith, J., "Ionic Polymer-Metal Composites (Ipmcs) as Biomimetic Sensors, Actuators and Artificial Muscles - a Review," Smart Materials and Structures, **7**(6), R15-R30 (1998).

[15] Stroble, J.K., Stone, R.B. and Watkins, S.E., "An Overview of Biomimetic Sensor Technology," Sensor Review, **29**(2), 112-119 (2009).

[16] Kindschy, L.M. and Alocija, E.C., "A Review of Molecularly Imprinted Polymers for Biosensor Development for Food and Agricultural Applications," Transactions of the ASABE, **47**(4), 1375-1382 (2004).

[17] Bogue, R., "Inspired by Nature: Developments in Biomimetic Sensors," Sensor Review, **29**(2), 107-111 (2009).

[18] Baba, Y., Kitamori, T., Lynch, J.P. and Tomizuka, M., "Us-Japan Workshop on Bio-Inspired Engineering of Next-Generation Sensors and Actuators," Proceedings of US-Japan Workshop on Bio-inspired Engineering of Next-Generation Sensors and Actuators, (2011).

[19] Schmidt, R.F., *Fundamentals of Sensory Physiology*, *edn.*, Springer: New York, NY (1986).

[20] Beebe, D.J., Hsieh, A.S., Denton, D.D. and Radwin, R.G., "A Silicon Force Sensor for Robotics and Medicine," Sensors and Actuators A: Physical, **50**(1-2), 5-65 (1995).

[21] Dahiya, R.S., Valle, M., Metta, G. and Lorenzelli, L., "Bio Inspired Tactile Sensing Arrays," Proceedings of SPIE Bioengineered and Bioinspired Systems IV, **7365**, 73650D/73651-73659 (2009).

[22] Muhammad, H.B., Oddo, C.M., Beccai, L., Adams, M.J., Carrozza, M.C., Hukins, D.W. and Ward, M.C., "Development of a Biomimetic Mems Based Capacitive Tactile Sensor," Procedia Chemistry, **1**(1), 124-127 (2009).

[23] Xu, Y., Jiang, F., Newbern, S., Huang, A., Ho, C.-M. and Tai, Y.-C., "Flexible Shear-Stress Sensor Skin and Its Application to Unmanned Aerial Vehicles," Sensors and Actuators A: Physical, **105**(3), 321-329 (2003).

[24] Yousef, H., Boukallei, M. and Althoefer, K., "Tactile Sensing for Dexterous in-Hand Manipulation in Robotics - a Review," Sensors and Actuators A: Physical, **167**(2), 171-187 (2011).

[25] Wettels, N., Santos, V.J., Johansson, R.S. and Loeb, G.E., "Biomimetic Tactile Sensor Array," Advanced Robotics, **22**(8), 829-849 (2008).

[26] Jamali, N. and Sammut, C., "Material Classification by Tactile Sensing Using Surface Textures," Proceedings of 2010 IEEE Conference on Robotics and Automation, 2336-2341 (2010).

[27] Ventrelli, L., Beccai, L., Mattoli, V., Menciassi, A. and Dario, P., "Development of a Stretchable Skin-Like Tactile Sensor Based on Polymeric Composites," Proceedings of 2009 IEEE International Conference on Robotics and Biomimetics, 123-128 (2009).

[28] Wang, L., Ding, T. and Wang, P., "Effects of Instantaneous Compression Pressure on Electrical Resistance of Carbon Black Filled Silicone Rubber Composite During Compressive Stress Relaxation," Composites Science and Technology, **68**, 3448-3450 (2008).

[29] Muhammad, H.B., Oddo, C.M., Beccai, L., Recchiuto, C., Anthony, C.J., Adams, M.J., Carrozza, M.C., Hukins, D.W.L. and Ward, M.C.L., "Development of a Bioinspired Mems Based Capacitive Tactile Sensor for a Robotic Finger," Sensors and Actuators A: Physical, **165**(2), 221-229 (2011).

[30] Someya, T., Kato, Y., Sekitani, T., Iba, S., Noguchi, Y., Murase, Y., Kawaguchi, H. and Sakurai, T., "Conformable, Flexible, Large-Area Networks of Pressure and Thermal Sensors with Organic Transistor Active Matrixes," Proceedings of the National Academy of Sciences of the United States of America, **102**(35), 12321-12325 (2005).

[31] Beccai, L., Roccella, S., Ascari, L., Valdastri, P., Sieber, A., Carrozza, M.C. and Dario, P., "Development and Experimental Analysis of a Soft Compliant Tactile Microsensor for Anthropomorphic Artificial Hand," IEEE/ASME Transactions on Mechatronics, **13**(2), 158-168 (2008).

[32] Oddo, C.M., Beccai, L., Muscolo, G.G. and Carrozza, M.C., "A Biomimetic Mems-Based Tactile Sensor Array with Fingerprints Integrated in a Robotic Fingertip for Artificial Roughness Encoding," Proceedings of 2009 IEEE International Conference on Robotics and Biomimetics, 894-900 (2009).

[33] Mukai, T., Onishi, M., Odashima, T., Hirano, S. and Luo, Z., "Development of the Tactile Sensor System of a Human-Interactive Robot "Ri-Man"," IEEE Transactions on Robotics, **24**(2), 505-512 (2008).

[34] Cheng, M.-Y., Lin, C.-L., Lai, Y.-T. and Yang, Y.-J., "A Polymer-Based Capacitive Sensing Array for Normal and Shear Force Measurement," Sensors, **10**(11), 10211-10225 (2010).

[35] Muhammad, H.B., Recchiuto, C., Oddo, C.M., Beccai, L., Anthony, C.J., Adams, M.J., Carrozza, M.C. and Ward, M.C.L., "A Capacitive Tactile Sensor Array for Surface Texture Discrimination," Microelectronic Engineering, **88**(8), 1811-1813 (2011).

[36] Tiwana, M.I., Shashank, A., Redmond, S.J. and Lovell, N.H., "Characterization of a Capacitive Tactile Shear Sensor for Applications in Robotic and Upper Limb Prostheses," Sensors and Actuators A: Physical, **165**, 164-172 (2011).

[37] Drimus, A. and Bilberg, A., "Novel Approaches for Bio-Inspired Mechano-Sensors," Intelligent Robotics and Applications, **7102**, 12-23 (2011).

[38] Maheshwari, V. and Saraf, R.F., "High-Resolution Thin-Film Device to Sense Texture by Touch," Science, **312**(5779), 1501-1504 (2006).

[39] Iijima, S., "Helical Microtubules of Graphitic Carbon," Nature, **354**(6348), 56-58 (1991).

[40] Saito, R., Dresselhaus, G. and Dresselhaus, M.S., *Physical Properties of Carbon Nanotubes*, *edn.*, Imperial College Press: London (1998).

[41] Baughman, R.H., Zakhidov, A.A. and De Heer, W.A., "Carbon Nanotubes-the Route toward Applications," Science, **297**(5582), 787-792 (2002).

[42] Harris, P.J.F., *Carbon Nanotube Science : Synthesis, Properties and Applications*, *[Rev. and updated edn.*, Cambridge University Press: Cambridge, UK ; New York (2009).

[43] Khare, R. and Bose, S., "Carbon Nanotube Based Composites - a Review," Journal of Minerals & Materials Characterization & Engineering, **4**(1), 31-46 (2005).

[44] Kang, I., Heung, Y.Y., Kim, J.H., Lee, J.W., Gollapudi, R., Subramaniam, S., Narasimhadevara, S., Hurd, D., Kirikera, G.R., Shanov, V., Schulz, M.J., Shi, D., Boerio, J., Mall, S. and Ruggles-Wren, M., "Introduction to Carbon Nanotubes and Nanofiber Smart Materials," Composites: Part B, **37**(6), 382-394 (2006).

[45] Fam, D.W.H., Palaniappan, A., Tok, A.I.Y., Liedberg, B. and Moochhala, S.M., "A Review on Technological Aspects Influencing Commercialization of Carbon Nanotube Sensors," Sensors and Actuators B: Chemical, **157**(1), 1-7 (2011).

[46] Mackay, M.E., Tuteja, A., Hawker, P.M.D.C.J., Van Horn, B., Guan, Z., Chen, G. and Krishman, R.S., "General Strategies for Nanoparticle Dispersion," Science, **311**(5768), 1740-1743 (2006).

[47] Pham, G.T., Park, Y.-B., Liang, Z., Zhang, C. and Wang, B., "Processing and Modeling of Conductive Thermoplastic/Carbon Nanotube Films for Strain Sensing," Composites Part B, **39**, 209-216 (2008).

[48] Thostenson, E.T. and Chou, T.-W., "Aligned Multi-Walled Carbon Nanotube-Reinforced Composites: Processing and Mechanical Characterization," Journal of Physics D, **35**(16), L77-80 (2002).

[49] Yim, J.H., Kim, Y.S., Koh, K.H. and Lee, S., "Fabrication of Transparent Single Wall Carbon Nanotube Films with Low Sheet Resistance," Journal of Vacuum Science & Technology B, **26**(2), 851-855 (2008).

[50] Vemuru, S.M., Wahi, R., Nagarajaiah, S. and Ajayan, P.M., "Strain Sensing Using a Multiwalled Carbon Nanotube Film," Journal of Strain Analysis for Engineering Design, **44**(7), 555-562 (2009).

[51] Loh, K.J., Kim, J.H., Lynch, J.P., Kam, N.W.S. and Kotov, N.A., "Multifunctional Layer-by-Layer Carbon Nanotube-Polyelectrolyte Thin Films for Strain and Corrosion Sensing," Smart Materials and Structures, **16**(2), 429-438 (2007).

[52] Dinh-Trong, N., Steitz, J., Lei, B. and Kanoun, O., "Influence of the Composition of Mwcnts Layers on the Properties of Strain Gauges," Proceedings of 9th IEEE Conference on Nanotechnology, 477-480 (2009).

[53] Kang, I., Lee, J.W., Choi, G.R., Jung, J.Y., Hwang, S.-H., Choi, Y.-S., Yoon, K.J. and Schulz, M.J., "Structural Health Monitoring Based on Electrical Impedance of a Carbon Nanotube Neuron," Key Engineering Materials, **321-323**, 140-145 (2006).

[54] Breuer, O. and Sundararaj, U., "Big Returns from Small Fibers: A Review of Polymer/Carbon Nanotube Composites," Polymer Composites, **5**(6), 630-645 (2004).

[55] Coleman, J.N., Khan, U. and Gun'ko, Y.K., "Mechanical Reinforcement of Polymers Using Carbon Nanotubes," Advanced Materials, **18**(6), 689-706 (2006).

[56] Winey, K.I., Kashiwagi, T. and Mu, M., "Improving Electrical Conductivity and Thermal Properties of Polymers by the Addition of Carbon Nanotubes as Fillers," MRS Bulletin, **32**(4), 348-353 (2007).

[57] Sinha, N., Ma, J. and Yeow, J.T.W., "Carbon Nanotube-Based Sensors," Journal of Nanoscience and Nanotechnology, **6**(3), 573-590 (2006).

[58] Mahar, B., Laslau, C., Yip, R. and Sun, Y., "Development of Carbon Nanotube-Based Sensors—a Review," IEEE Sensors Journal, **7**(2), 266-284 (2007).

[59] Li, C., Thostenson, E.T. and Chou, T.-W., "Sensors and Actuators Based on Carbon Nanotubes and Their Composites: A Review," Composites Science and Technology, **68**(6), 1227-1249 (2008).

[60] Park, J.-M., Kim, D.-S., Kim, S.-J., Kim, P.-G., Yoon, D.-J. and Devries, L., "Inherent Sensing and Interfacial Evaluation of Carbon Nanofiber and Nanotube/Epoxy Composites Using Electrical Resistance Measurement and Micromechanical Technique," Composites Part B, **38**(7-8), 847-861 (2007).

[61] Thostenson, E.T. and Chou, T.-W., "Carbon Nanotube Networks: Sensing of Distributed Strain and Damage for Life Prediction and Self Healing," Advanced Materials, **18**(21), 2837-2841 (2006).

[62] Thostenson, E.T. and Chou, T.-W., "Real-Time in Situ Sensing of Damage Evolution in Advanced Fiber Composites Using Carbon Nanotube Networks," Nanotechnology, **19**(21), 215713/215711-215716 (2008).

[63] Böger, L., Wichmann, M.H.G., Meyer, L.O. and Schulte, K., "Load and Health Monitoring in Glass Fibre Reinforced Composites with an Electrically Conductive Nanocomposite Epoxy Matrix," Composites Science and Technology, **68**(7-8), 1886-1894 (2008).

[64] Nofar, M., Hoa, S.V. and Pugh, M.D., "Development of Novel Single-Wall Carbon Nanotube–Epoxy Composite Ply Actuators," Composites Science and Technology, **69**(10), 1599-1606 (2009).

[65] Kostopoulos, V., Vavouliotis, A., Karapappas, P., Tsotra, P. and Paipetis, A., "Damage Monitoring of Carbon Fiber Reinforced Laminates Using Resistance Measurements. Improving Sensitivity Using Carbon Nanotube Doped Epoxy Matrix System," Journal of Intelligent Material Systems and Structures, **20**(9), 1025-1034 (2009).

[66] Li, C. and Chou, T.-W., "Modeling of Damage Sensing in Fiber Composites Using Carbon Nanotube Networks," Composites Science and Technology, **68**(15-16), 3373-3379 (2008).

[67] Anand, S.V. and Mahapatra, D.R., "Quasi-Static and Dynamic Strain Sensing Using Carbon Nanotube/Epoxy Nanocomposite Thin Films," Smart Materials and Structures, **18**(4), 045013/045011-045013 (2009).

[68] Aldraihem, O.J., Akl, W.N. and Baz, A.M., "Nanocomposite Functional Paint Sensors for Vibration and Noise Monitoring," Sensors and Actuators A: Physical, **149**(2), 233-240 (2009).

[69] Rajoria, H. and Jalili, N., "Passive Vibration Damping Enhancement Using Carbon Nanotube-Epoxy Reinforced Composites," Composites Science and Technology, **65**(14), 2079-2093 (2005).

[70] Yun, Y.-H., Shanov, V., Schulz, M.J., Narasimhadevara, S., Subramaniam, S., Hurd, D. and Boerio, F.J., "Development of Novel Single-Wall Carbon Nanotube–Epoxy Composite Ply Actuators," Smart Materials and Structures, **14**(6), 1526-1532 (2005).

[71] Dharap, P., Li, Z., Nagarajaiah, S. and Barrera, E.V., "Nanotube Film Based on Single-Wall Carbon Nanotubes for Strain Sensing," Nanotechnology, **15**(3), 379-382 (2004).

[72] Kang, I., Schulz, M.J., Kim, J.H., Shanov, V. and Shi, D., "A Carbon Nanotube Strain Sensor for Structural Health Monitoring," Smart Materials and Structures, **15**(3), 734-748 (2006).

[73] Loh, K.J., Lynch, J.P. and Kotov, N.A., "Conformable Single-Walled Carbon Nanotube Thin Film Strain Sensors for Structural Monitoring," Proceedings of 5th International Workshop on Structural Health Monitoring, **2**, 686-694 (2005).

[74] Loh, K.J., Lynch, J.P., Shim, B.S. and Kotov, N., "Tailoring Piezoresistive Sensitivity of Multilayer Carbon Nanotube Composite Strain Sensors," Journal of Intelligent Material Systems and Structures, **19**(7), 747-764 (2008).

[75] Loyola, B.R., La Saponara, V. and Loh, K.J., "In Situ Strain Monitoring of Fiber-Reinforced Polymers Using Embedded Piezoresistive Nanocomposites," Journal of Materials Science, **45**(24), 6786-6798 (2010).

[76] Park, M., Kim, H. and Youngblood, J.P., "Strain-Dependent Electrical Resistance of Multi-Walled Carbon Nanotube/Polymer Composite Films," Nanotechnology, **19**(5), 055705/055701-055707 (2008).

[77] Chang, N.-K., Su, C.-C. and Chang, S.-H., "Fabrication of Single-Walled Carbon Nanotube Flexible Strain Sensors with High Sensitivity," Applied Physics Letters, **92**(6), 063501/063501-063503 (2008).

[78] Yin, G., Hu, N., Karube, Y., Liu, Y., Li, Y. and Fukunaga, H., "A Carbon Nanotube/Polymer Strain Sensor with Linear and Anti-Symmetric Piezoresistivity," Journal of Composite Materials, **45**(12), 1315-1323 (2011).

[79] Hu, N., Karube, Y., Yan, C., Masuda, Z. and Fukunaga, H., "Tunneling Effect in a Polymer/Carbonnanotube Nanocomposite Strain Sensor," Acta Materialia, **56**(13), 2929-2936 (2008).

[80] Kang, J.H., Park, C., Scholl, J.A., Brazin, A.H., Holloway, N.M., High, J.W., Lowther, S.E. and Harrison, J.S., "Piezoresistive Characteristics of Single Wall Carbon Nanotube/Polyimide Nanocomposites," Polymer Physics, **47**(10), 994-1003 (2009).

[81] Hu, N., Masuda, Z., Yamamoto, G., Fukunaga, H., Hashida, T. and Qiu, J., "Effect of Fabrication Process on Electrical Properties of Polymer/Multi-Wall Carbon Nanotube Nanocomposites," Composites Part A: Applied Science and Manufacturing, **39**(5), 893-903 (2008).

[82] Abdel Chafy, R.R. and Esawi, M.H.a.a.M.K., "Fabrication of Carbon Nanotube/Low Density Polyethylene Composites for Strain Sensing," Key Engineering Materials, **495**, 33-36 (2012).

[83] Lee, K., Lee, S.S., Lee, J.A., Lee, K.-C. and Ji, S., "Carbon Nanotube Film Piezoresistors Embedded in Polymer Membranes," Applied Physics Letters, **96**(1), 013511/013511-013513 (2010).

[84] Li, Z., Dharap, P., Nagarajaiah, S., Barrera, E.V. and Kim, J.D., "Carbon Nanotube Film Sensors," Advanced Materials, **16**(7), 640-643 (2004).

[85] Li, X., Levy, C. and Elaadil, L., "Multiwalled Carbon Nanotube Film for Strain Sensing," Nanotechnology, **19**(4), 045501/045501-045507 (2008).

[86] Bautista-Quijano, J.R., Aviles, F., Aguilar, J.O. and Tapia, A., "Strain Sensing Capabilities of a Piezoresistive Mwcnt-Polysulfone Film," Sensors and Actuators A: Physical, **159**(2), 135-140 (2010).

[87] Zhang, R., Baxendale, M. and Peijs, T., "Universal Resistivity–Strain Dependence of Carbon Nanotube/Polymer Composites," Physical Review B, **76**(19), 195433/195431-195435 (2007).

[88] Knite, M., Tupureina, V., Fuith, A., Zavickis, J. and Teteris, V., "Polyisoprene-Multi-Wall Carbon Nanotube Composites for Sensing Strain," Materials Science and Engineering C, **27**(5-8), 1125-1128 (2007).

[89] Jung, S., Ji, T., Xie, J. and Varadan, V.K., "Flexible Strain Sensors Based on Pentacene-Carbon Nanotube Composite Thin Films," Proceedings of 7th IEEE Conference on Nanotechnology, 375-378 (2007).

[90] Zhang, W., Suhr, J. and Koratkar, N., "Carbon Nanotube/Polycarbonate Composites as Multifunctional Strain Sensors," Journal of Nanoscience and Nanotechnology, **6**(4), 960-964 (2006).

[91] Song, X., Liu, S., Gan, Z., Lv, Q., Cao, H. and Yan, H., "Controllable Fabrication of Carbonnanotube-Polymer Hybrid Thinfilm for Strainsensing," Microelectronic Engineering, **86**(11), 2330-2333 (2009).

[92] Suhr, J., Koratkar, N., Keblinski, P. and Ajayan, P., "Viscoelasticity in Carbon Nanotube Composites," Nature Materials, **4**, 134-137 (2005).

[93] Zhao, Y., Loyola, B.R. and Loh, K.J., "Characterizing the Viscoelastic Properties of Layer-by-Layer Carbon Nanotube-Polyelectrolyte Thin Films," Smart Materials and Structures, **20**, 075020/075021-075011 (2011).

[94] Mukai, K., Asaka, K., Sugino, T., Kiyohara, K., Takeuchi, I., Terasawa, N., Futaba, D.N., Hata, K., Fukushima, T. and Aida, T., "Highly Conductive Sheets from Millimeter-Long Single-Walled Carbon Nanotubes and Ionic Liquids: Application to Fast-Moving, Low Voltage Electromechanical Actuators Operable in Air," Advanced Materials, **21**(16), 1582-1585 (2009).

[95] Geier, S., Riemenschneider, J., Mahrholz, T., Wierach, P. and Sinapius, M., "Investigations of the Key Mechanism of Carbon-Nanotube Actuators and Their Dependencies," Proceedings of SPIE - Behavior and Mechanics of Multifunctional Materials and Composites, **7644**, 76441G/76441-76449 (2010).

[96] Zhang, Z., Liu, Y. and Leng, J., "Effects of Conductive Particles on the Actuating Behavior of Dielectric Elastomer Actuator," Proceedings of SPIE - Electroactive Polymer Actuators and Devices, **7642**, 76420S/76421-76428 (2010).

[97] Chen, I.-W.P., Liang, Z., Wang, B. and Zhang, C., "Charge-Induced Asymmetrical Displacement of an Aligned Carbon Nanotube Buckypaper Actuator," Carbon, **48**(4), 1064-1069 (2010).

[98] Yun, Y.-H., Miskin, A., Kang, P., Jain, S., Narasimhadevara, S., Hurd, D., Shinde, V., Schulz, M.J., Shanov, V., He, P., Boerio, F.J., Shi, D. and Srivinas, S., "Carbon Nanofiber Hybrid Actuators: Part Ii - Solid Electrolyte-Based," Journal of Intelligent Material Systems and Structures, **17**(3), 191-197 (2006).

[99] Baughman, R.H., Cui, C., Zakhidov, A.A., Iqbal, Z., Barisci, J.N., Spinks, G.M., Wallace, G.G., Mazzoldi, A., De Rossi, D., Rinzler, A.G., Jaschinski, O., Roth, S. and Kertesz, M., "Carbon Nanotube Actuators," Science, **284**(5418), 1340-1344 (1999).

[100] Landi, B.J., Raffaelle, R.P., Heben, M.J., Alleman, J.L., Vanderveer, W. and Gennett, T., "Development and Characterization of Singe Wall Carbon Nanotube-Nafion Composite Actuators," Materials Science and Engineering B, **116**, 359-362 (2005).

[101] Ramaratnam, A. and Jalili, N., "Reinforcement of Piezoelectric Polymers with Carbon Nanotubes: Pathway to Next-Generation Sensors," Journal of Intelligent Material Systems and Structures, **17**(3), 199-208 (2006).

[102] Kang, I., Choi, G.R., Jung, J.Y., Chang, Y.H., Choi, Y.-S. and Schulz, M.J., "A Carbon Nanotube Film for Power Harvesting," Key Engineering Materials, **326-328**, 1447-1450 (2006).

[103] Hou, T.C., Loh, K.J. and Lynch, J.P., "Spatial Conductivity Mapping of Carbon Nanotube Composite Thin Films by Electrical Impedance Tomography for Sensing Applications," Nanotechnology, **18**(31), 315501/315501-315509 (2007).

[104] Loh, K.J., Hou, T.-C., Lynch, J.P. and Kotov, N.A., "Carbon Nanotube Sensing Skins for Spatial Strain and Impact Damage Identification," Journal of Nondestructive Evaluation, **28**(1), 9-25 (2009).

[105] Holder, D.S., ed., *Electrical Impedance Tomography Methods, History and Applications*, The Institute of Physics: London (2005).

[106] Borcea, L., "Electrical Impedance Tomography," Inverse Problems, **18**(6), (2002).

[107] Pyo, S., Loh, K.J., Hou, T.-C., Jarva, E. and Lynch, J.P., "A Wireless Impedance Analzyer for Automated Tomographic Mapping of a Nanoengineered Sensing Skin," Smart Structures and Systems, **8**(1), 137-153 (2011).

[108] Alirezaei, H., Nagakubo, A. and Kuniyoshi, Y., "A Highly Stretchable Tactile Distribution Sensor for Smooth Surfaced Humanoids," Proceedings of 7th IEEE-RAS International Conference on Humanoid Robots, 167-173 (2007).

[109] Alirezaei, H., Nagakubo, A. and Kuniyoshi, Y., "A Tactile Distribution Sensor Which Enables Stable Measurement under High and Dynamic Stretch," Proceedings of IEEE Symposium on 3D User Interfaces, 87-93 (2009).

[110] Frerichs, I., "Electrical Impedance Tomography (Eit) in Applications Related to Lung and Ventilation: A Review of Experimental and Clinical Activities," Physiological Measurement, **21**(2), R1 (2000).

[111] Zou, Y. and Guo, Z., "A Review of Electrical Impedance Techniques for Breast Cancer Detection," Medical Engineering & Physics, **25**(2), 79-90 (2003).

[112] Zunino Iii, J.L., "Development of Materials and Sensors for the U.S. Army's Active Coatings Technology Program," Sensors & Transducers, **84**(10), 51-59 (2007).

[113] Tata, U., Deshmukh, S., Chiao, J.C., Carter, R. and Huang, H., "Bio-Inspired Sensor Skins for Structural Health Monitoring," Smart Materials and Structures, **18**(10), 104026/104021-104028 (2009).

[114] Yi, X., Wu, T., Wang, Y., Leon, R.T., Tentzeris, M.M. and Lantz, G., "Passive Wireless Smart-Skin Sensor Using Rfid-Based Folded Patch Antennas," International Journal of Smart and Nano Materials, **2**(1), 22-38 (2011).

[115] Loh, K.J., Lynch, J.P. and Kotov, N.A., "Inductively Coupled Nanocomposite Wireless Strain and Ph Sensors," Smart Structures and Systems, **4**(5), 531-548 (2008).

[116] Loh, K.J., Lynch, J.P. and Kotov, N.A., "Passive Wireless Sensing Using Multifunctional Carbon Nanotube Composite Thin Film Patches," International Journal of Applied Electromagnetics and Mechanics, **28**(1-2), 87-94 (2008).

[117] Coombs, S., "Smart Skins: Information Processing by Lateral Line Flow Sensors," Autonomous Robots, **11**(3), 255-261 (2001).

[118] Pfatteicher, S.K.A. and Tongue, M.P., "What Drives Diversity? [Engineering Education and Underrepresentation of Minority Groups]," Proceedings of 32nd Annual Frontiers in Education, **3**, S1C-1-6 (2002).

[119] Wiegerink, R.J., Floris, A., Jaganatharaja, R.K., Izadi, N., Lammerink, T.S.J. and Krijnen, G.J.M., "Biomimetic Flow-Sensor Arrays Based on the Filiform Hairs on the Cerci of Crickets," Proceedings of IEEE Sensors 2007 Conference, 1073-1076 (2007).

[120] Sarles, S.A., Madden, J.D.W. and Leo, D.J., "Hair Cell Inspired Mechanotransduction with a Gel-Supported, Artificial Lipid, Membrane," Soft Matter, **7**(10), 4644-4653 (2011).

[121] Chen, N., Tucker, C., Engel, J.M., Yang, Y., Pandya, S. and Liu, C., "Design and Characterization of Artificial Haircell Sensor for Flow Sensing with Ultrahigh Velocity and Angular Sensitivity," Journal of Microelectromechanical Systems, **16**(5), 999-1014 (2007).

[122] Scholz, G.R. and Rahn, C.D., "Profile Sensing with an Actuated Whisker," IEEE Transactions on Robotics and Automation, **20**(1), 124-127 (2004).

[123] Liu, C., "Micromachined Biomimetic Artificial Haircell Sensors," Bioinspiration and Biomimetics, **2**(4), S162-S169 (2007).

[124] Engel, J.M., Chen, J. and Liu, C., "Polyurethane Rubber All-Polymer Artificial Hair Cell Sensor," Journal of Microelectromechanical Systems, **15**(4), 729-736 (2006).

[125] Nawi, M.N.M., Manaf, A.A., Arshad, M.R. and Sidek, O., "Review of Mems Flow Sensors Based on Artificial Hair Cell Sensor," Microsystem Technologies, **17**(9), 1417-1426 (2011).

[126] Dijkstra, M., Barr, J.J.V., Wiegerink, R.J., Lammerink, T.S.J., Boer, J.H.D. and Krijnen, G.J.M., "Artificial Sensor Hairs Based on the Flow Sensitive Receptor Hairs of Crickets," Journal of Micromechanics and Microengineering, **15**(7), S132-S138 (2005).

[127] Izadi, N., De Boer, M.J., Berenschot, J.W. and Krijnen, G.J.M., "Fabrication of Superficial Neuromast Inspired Capacitive Flow Sensors," Journal of Micromechanics and Microengineering, **20**(8), 085041/085041-085049 (2010).

[128] Shanmuganathan, K., Capadona, J.R., Rowan, S.J. and Weder, C., "Bio-Inpsired Mechanically-Adaptive Nanocomposites Derived from Cotton Cellulose Whiskers," Journal of Materials Chemistry, **20**(1), 180-186 (2010).

[129] Kim, D.R., Lee, C.H. and Zheng, X., "Probing Flow Velocity with Silicon Nanowire Sensors," Nano Letters, **9**(5), 1984-1988 (2009).

[130] Tonisch, K., Cimalla, V., Will, F., Weise, F., Stubenrauch, M., Albrecht, A., Hoffmann, M. and Ambacher, O., "Nanowire-Based Electromechanical Biomimetic Sensor," Physica E, **37**(1-2), 208-211 (2007).

[131] Mcgary, P.D., Tan, L., Zou, J., Stadler, B.J.H., Downey, P.R. and Flatau, A.B., "Magnetic Nanowires for Acoustic Sensors," Journal of Applied Physics, **99**(8), 08B310/311-316 (2006).

[132] Jain, R., Mccluskey, F.P. and Flatau, A.B., "Mems Package for an Iron-Gallium Nanowire-Based Acoustic Sensor," IEEE Transactions on Components, Packaging and Manufacturing Technology, **PP**(99), 1-9 (2011).

[133] Lin, Y., Liu, Y. and Sodano, H.A., "Hydrothermal Synthesis of Vertically Aligned Lead Zirconate Titanate Nanowire Arrays," Applied Physics Letters, **95**(12), 122901/122901-122903 (2009).

[134] Yu, X., Tao, J. and Berilla, J., "A Bio-Inspired Flow Sensor," Proceedings of SPIE - Nanosensors, Biosensors, and Info-Tech Sensors and Systems, **7646**, (2010).

[135] Pinto, P.A., Sarles, S.A. and Leo, D.J., "Bio-Inspired Flow Sensors Fabricated from Carbon Nanomaterials," Proceedings of ASME 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, **2**, 725-732 (2011).

[136] Eberhardt, W.C., Shakhsheer, Y.A., Calhoun, B.H., Paulus, J.R. and Appleby, M., "A Bio-Inspired Artificial Whisker for Fluid Motion Sensing with Increased Sensitivity and Reliability," Proceedings of 2011 IEEE Sensors, 982-985 (2011).

[137] Tao, J., Yu, X.B. and Berrilla, J., "Bio-Inspired Flow and Acoustic Sensor," Proceedings of SPIE Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense X, **8019**, 80190R/80191-80110 (2011).

[138] Ghosh, S., Sood, A.K. and Kumar, N., "Carbon Nanotube Flow Sensors," Science, **299**(5609), 1042-1044 (2003).

[139] Sood, A.K. and Ghosh, S., "Flow Driven Electronic Transport in Carbon Nanotubes," International Journal of Nanoscience, **4**(5-6), 839-848 (2005).

[140] Liu, J., Dai, L. and Baur, J.W., "Multiwalled Carbon Nanotubes for Flow-Induced Voltage Generation," Journal of Applied Physics, **101**(6), 064312/064311-064316 (2007).

[141] Cao, H., Gan, Z., Lv, Q., Yan, H., Luo, X., Song, X. and Liu, S., "Single-Walled Carbon Nanotube Network/Poly Composite Thin Film for Flow Sensor," Microsystem Technologies, **16**(6), 955-959 (2010).

[142] Pinto, P.A., Sarles, S.A., Leo, D.J., Philen, M., Champion, H.A., Black, S.B. and Dorn, H.C., "Bio-Inspired Flow Sensors Fabricated from Carbon Nanomaterials," Proceedings of ASME 2011 Conference on Smart Materials, Adaptive Structures & Intelligent Systems, 1-8 (2011).

[143] Singh, A.V., Rahman, A., Sudhir Kumar, N.V.G., Aditi, A.S., Galluzzi, M., Bovio, S., Barozzi, S., Montani, E. and Parazzoli, D., "Bio-Inspired Approaches to Design Smart Fabrics," Materials and Design, **36**, 829-839 (2012).

[144] Xia, F. and Jiang, L., "Bio-Inspired, Smart, Multiscale Interfacial Materials," Advanced Materials, **20**(15), 2842-2858 (2008).

[145] Irschick, D.J., Austin, C.C., Petren, K., Fisher, R.N., Losos, J.B. and Ellers, O., "A Comparative Analysis of Clinging Ability among Pad-Bearing Lizards," Biological Journal of the Linnean Society, **59**(1), 21-35 (1996).

[146] Spolenak, R., Gorb, S. and Arzt, E., "Adhesion Design Maps for Bio-Inspired Attachment Systems," Acta Biomaterialia, **1**(1), 5-13 (2005).

[147] Bhushan, B. and Sayer, R.A., "Surface Characterization and Friction of a Bio-Inspired Reversible Adhesive Tape," Microsystem Technologies, **13**(1), 71-78 (2007).

[148] Aksak, B., Murphy, M.P. and Sitti, M., "Adhesion of Biologically Inspired Vertical and Angled Polymer Microfiber Arrays," Langmuir, **23**(6), 3322-3332 (2007).

[149] Murphy, M.P., Aksak, B. and Sitti, M., "Gecko-Inspired Directional and Controllable Adhesion," Small, **5**(2), 170-175 (2009).

[150] Chen, S. and Gao, H., "Bio-Inspired Mechanics of Reversible Adhesion: Orientation-Dependent Adhesion Strength for Non-Slipping Adhesive Contact with Transversely Isotropic Elastic Materials," Journal of the Mechanics and Physics of Solids, **55**, 1001-1015 (2007).

[151] Kwak, M.K., Jeong, H.-E., Kim, T.-I., Yoon, H. and Suh, K.Y., "Bio-Inspired Slanted Polymer Nanohairs for Anisotropic Wetting and Directional Dry Adhesion," Soft Matter, **6**(9), 1849-1857 (2010).

[152] Zhu, D., Yi, X., Wang, Y., Lee, K.-M. and Guo, J., "A Mobile Sensing System for Structural Health Monitoring: Design and Validation," Smart Materials and Structures, **19**(5), 055011/055011-055011 (2010).

[153] Erbil, H.Y., Demirel, A.L., Avci, Y. and Mert, O., "Transformation of a Simple Plastic into a Superhydrophobic Surface," Science, **299**(5611), 1377-1380 (2003).

[154] Jiang, L., Zhao, Y. and Zhai, J., "A Lotus-Leaf-Like Superhydrophobic Surface: A Porous Microsphere/Nanofiber Composite Film Prepared by Electrohydrodynamics," Angewandte Chemie, **116**(33), 4438–4441 (2004).

[155] Ma, M. and Hill, R.M., "Superhydrophobic Surfaces," Current Opinion in Colloid & Interface Science, **11**(4), 193-202 (2006).

[156] Boden, S.A. and Bagnall, D.M., "Optimization of Moth-Eye Antireflection Schemes for Silicon Solar Cells," Progress in Photovoltaics: Research and Applications, **18**(3), 195-203 (2010).

[157] Toohey, K.S., Sottos, N.R., Lewis, J.A., Moore, J.S. and White, S.R., "Self-Healing Materials with Microvascular Networks," Nature Materials, **6**(581-585), (2007).

[158] Bonderer, L.J., Studart, A.R. and Gauckler, L.J., "Bioinspired Design and Assembly of Platelet Reinforced Polymer Films," Science, **319**(5866), 1069-1073 (2008).

[159] Zhang, Z., Philen, M. and Neu, W., "A Biologically Inspired Artificial Fish Using Flexible Matrix Composite Actuators: Analysis and Experiment," Smart Materials and Structures, **19**(9), 094017/094011-094011 (2010).

[160] Liu, K. and Jiang, L., "Bio-Inspired Design of Multiscale Structures for Function Integration," Nanotoday, **6**(2), 155-175 (2011).

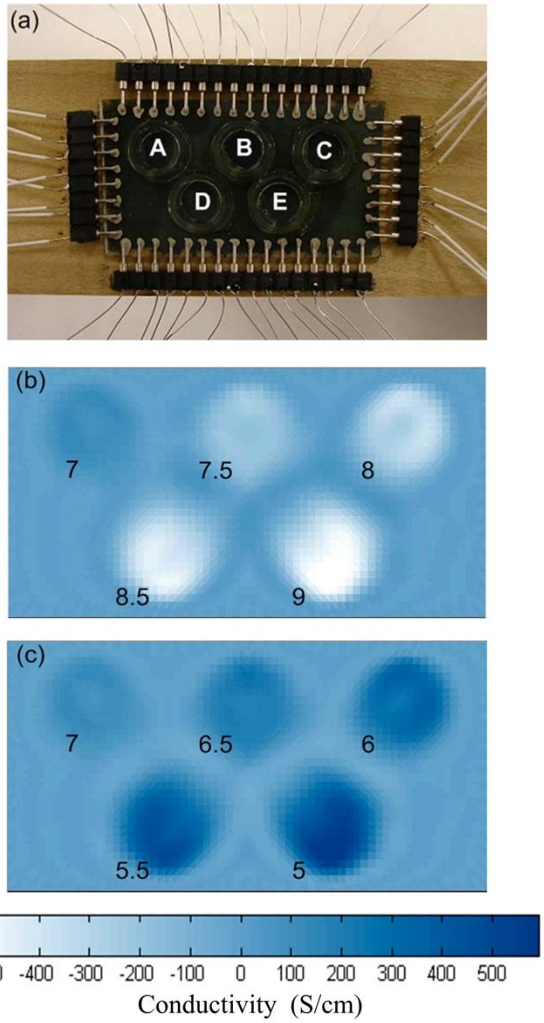
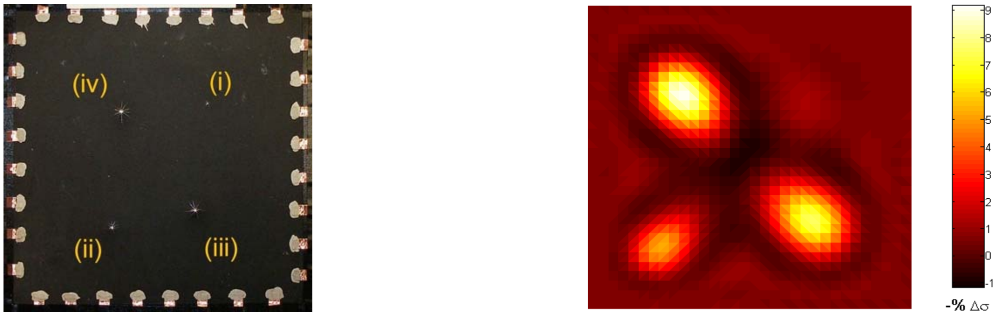


Fig. 1. (a) A pH-sensitive layer-by-layer film is mounted with plastic wells and exposed to different pH buffer solutions. EIT has been used to map the thin film's spatial conductivity distribution for identifying localized changes in film conductivity due to different pH buffers, namely (b) from pH 7 to 9 and (c) from pH 7 to 5. Image provided courtesy of the Institute of Physics Publishing.



(a) (b)

Fig. 2. (a) An aluminum plate has been coated with a piezoresistive layer-by-layer carbon nanotube-based thin film, and the plate has been impacted at four different locations, each with different impact energies. (b) The EIT spatial conductivity map of the sensing skin clearly identifies the location and severity of impact damage. Image provided courtesy of Springer.

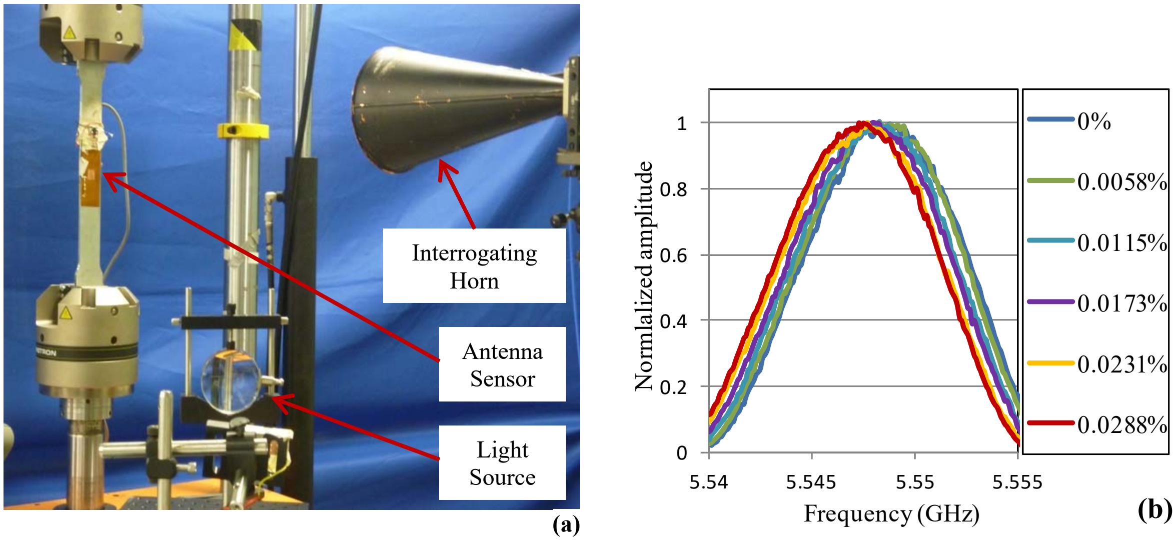


Fig. 3. (a) A sensor skin patch antenna is mounted in a testing coupon for strain sensing validation testing. (b) Wireless sensor readout plots clearly show that sensor resonant frequency increases in tandem with induced structural strains. Image provided courtesy of Prof. Haiying Huang, University of Texas-Arlington.