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New Smart Materials to Address Issues of Structural Health Monitoring

Pavel M. Chaplya

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New Smart Materials to Address Issues of Structural Health Monitoring

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Abstract

Nuclear weapons and their storage facilities may benefit from *in-situ* structural health monitoring systems. Appending health-monitoring functionality to conventional materials and structures has been only marginally successful. The purpose of this project was to evaluate feasibility of a new smart material that includes self-sensing health-monitoring functions similar to that of a nervous system of a living organism. Reviews of current efforts in the fields of heath-monitoring, nanotechnology, micro-electro-mechanical systems (MEMS), and wireless sensor networks were conducted. Limitations of the current nanotechnology methods were identified and new approaches were proposed to accelerate the development of self-sensing materials. Wireless networks of MEMS sensors have been researched as possible prototypes of self-sensing materials. Sensor networks were also examined as enabling technologies for dense data collection techniques to be used for validation of numerical methods and material parameter identification.

Each grain of the envisioned material contains sensors that are connected in a dendritic manner similar to networks of neurons in a nervous system. Each sensor/neuron can communicate with the neighboring grains. Both the state of the sensor (on/off) and the quality of communication signal (speed/amplitude) should indicate not only a presence of a structural defect but the nature of the defect as well. For example, a failed sensor may represent a through-grain crack, while a lost or degraded communication link may

represent an inter-granular crack. A technology to create such material does not exist. While recent progress in the fields of MEMS and nanotechnology allows to envision these new smart materials, it is unrealistic to expect creation of self-sensing materials in the near future. The current state of MEMS, nanotechnology, communication, sensor networks, and data processing technologies indicates that it will take more than ten years for the technologies to mature enough to make self-sensing materials a reality.

Nevertheless, recent advances in the field of nanotechnology demonstrate that nanotubes, nanorods, and nanoparticles of carbon, boron and other materials have remarkable mechanical and electrical properties. This would provide for a plethora of potential applications including self-sensing materials. Record strength-to-weight ratios, ballistic conductivity, and sensing capabilities (i.e., piezo- resistance and piezoelectricity) have been reported for carbon nanotubes. The first transistors, sensors, and actuators have been made from the carbon nanotubes and other nanomaterials. However, nanomaterials are notoriously difficult to manipulate into useful geometries. Nano-manufacturing processes often produce bundles or random networks of nanostructured materials. Samples of the material are then manipulated with advanced microscopy tools to measure properties or to create a single device. This is a laborious and time consuming process. An often overlooked property of the manufactured nanotube bundles is their similarity to the dendritic structure of neural networks with a great quantity of interconnects that may serve as initiation sites for artificial neurons in a self-sensing material nervous system. To accelerate the development of self-sensing materials, future research should concentrate on naturally occurring dendritic nano-structures.

While self-sensing materials with subgrain size sensors (scale of micrometers) remain in the realm of basic research, meso-scale (millimeters to centimeters) sensors and their networks are in the state of mature research and have begun to find their way into commercial applications. Macro-scale (centimeters to decimeters) sensors and their networks are commercially available from various sources. The majority of applications that employ sensor networks are driven by the needs of the Department of Defense. Widespread adaptation of sensor networks has been limited by, on one hand, the sensor's high cost of design, development, and deployment, and on the other hand, a lack of reliable long-term power sources. Solutions to both of these drawbacks require significant investments driven by real-life applications. Possible applications for sensor networks at Sandia National Laboratories include dense data collection techniques for validation of numerical methods and material parameter identification. For example, an array of distributed wireless macro-scale sensors can record the structural response of soils and reinforced concrete during explosive loading. Another example is an array of surface mounted micro-sensors that can record the modal response of nuclear weapon components. The collected data would be used to validate existing numerical codes and to identify new physical mechanisms to improve Sandia's computational models.

A road toward self-sensing materials must include the following three research directions. The first direction is an investigation into properties and design of dendritic nanomaterials. This is a basic science research that will leverage existing nano-technology capabilities, will expand our expertise in new materials and processes, and will result in unexpected discoveries en-route toward self-sensing materials. The second direction is leveraging MEMS technology to a) fabricate interconnects between nano and macro scale for testing and integration, and b) develop sensor network prototypes that will expand expertise in hardware neural network implementation. Micromachined electrodes must be developed to address one of the biggest issues associated with using nano-structured materials which is their interconnectivity to macroscale systems. The sensor network prototype may provide the most immediate benefits of the project in an area of dense data collection techniques for validation of numerical methods and material parameter identification. The third direction is development of analytical and computational models to provide insights into physical mechanisms of the nano-fabricated materials. Numerical models must capture multi-physics and scale-dependent phenomena with multiple interacting failure modes.

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Motivation

A system that monitors a structure in order to detect damage or defects is referred to as a *health monitoring system*. Functional structural health monitoring (SHM) methods may prevent catastrophic failures such as space shuttle Colombia accident in 2003. An SHM system of nuclear weapons, nuclear storage facilities, or other Department of Energy owned structures can reduce maintenance costs, and optimize service and replacement schedules. Most importantly, structural health monitoring system can save lives with an advanced warning before catastrophic failure occurs or, if the structures were damaged due to a natural disaster or a terrorist attack, the system can provide safety/hazard assessment to facilitate rescue and recovery operations.

Even though structural health monitoring has been studied for more than thirty years, a robust, in-situ health monitoring technique is far from being designed and implemented. Most of the current SHM methods are based on a premise that a structure's vibration signature (e.g., natural frequency, mode shape, mode shape derivative, flexibility matrix, etc) will change in a presence of cracks or other structural defects (Doebling et al. 1996). Successful implementation of these vibration-based methods has been severely limited by the low sensitivity level of vibration parameters to small cracks and defects. The system's sensitivity will increase with an increased number of measurement sensors but the cost of the system will become prohibitive for practical implementation. Other methods of damage detection include ultrasonic techniques, acoustic emissions, radiography, thermography, and laser holography. While effective, these methods are based on local inspections that require sophisticated equipment and disassembly of a structure which makes them impractical for in-situ implementation (Liberatore 2003).

In summary, most notable structural damage detection methods that are based on changes in measured vibration response include:

- frequency changes (Doebling et al. 1996),
- mode shape changes (Doebling et al. 1996),
- stiffness changes (Burton et al. 1998),
- strain energy changes (Cornwell et al. 1997),
- state space geometry changes (Todd et al. 2001).

Disadvantages of vibration based methods are (Liberatore 2003):

- low sensitivity to damage,
- requirements of precise measurements or large level of damage,
- difficulty in damage location identification except at higher modal frequencies,
- higher modal frequency measurements requiring larger numbers of sensors to determine damage location uniquely.

Techniques to improve vibration based methods include:

- embedded multiple active sensors (Giurgiutiu et al. 2002),
- innovative algorithms such as chaotic excitation and attractor (Nichols et al. 2003) and artificial intelligence-based neural network programs (Asundi and Song 2003).

Nondestructive testing (NDT) methods for damage detection include:

- ultrasonic techniques,
- acoustic emissions,
- radiography,
- thermography,
- laser holography.

Disadvantages of nondestructive testing (NDT) methods are:

- limitation to local inspections,
- requirement of sophisticated equipment,
- requirement of disassembly of a structure,
- requirement of *a priori* knowledge of damage location,
- impracticality for in-situ implementation.

A number of detailed reviews of the existing methods' strengths and disadvantages have been published (Doebling et al. 1996; Doebling et al. 1998; Farrar et al. 2001; Farrar and Hemez 2002).

The cornerstone of the existing structural health monitoring methods' limitations is that the monitoring functions are appended to the conventional materials and structures. Therefore, a creation of a new structural self-sensing material that will incorporate health-monitoring functions as one of their properties similar to the nervous system of a living organism should be investigated.

Self-sensing materials - a concept

Suppose that each material grain contains a sensor that can communicate with the neighboring grains (see Figure 1). Both the state of the sensor (on/off) and the quality of communication signal (speed or amplitude) will indicate not only a presence of a structural defect, but its nature as well. That is, a failed sensor may represent a through-grain crack, while a lost or degraded communication link may represent an inter-granular crack. Moreover, the large number of embedded and distributed sensors may enable the existing SHM approaches to become viable and useful. A technology to create self-sensing materials does not exist. However, recent progress in the fields of micro-electro-mechanical systems and nanotechnology may lead to the development of these new smart materials.

The idea of smart materials with self-sensing and even self-healing properties has been around since the inception of the term nanotechnology. However, there has not been a comprehensive study directed toward creation of a material with embedded subgrain sensors with health monitoring functionality. The challenge of such a project is twofold. First, a creative combination of different existing technologies is required from the very early phases of the project. The development of self-sensing materials must bring together experts in sensor development, data processing, communication, manufacturing, power, and structural health monitoring fields (see Figure 2). Second, new methods and techniques are needed to close a gap between the macro and nano world. The most obvious challenges would arise in the areas of manufacturing and integration of nano-systems. The technical risk is high and includes the possible conclusion that a self-sensing material is not currently feasible either technically or economically. However, successful conclusion of such a project will lead to tremendous payoffs.

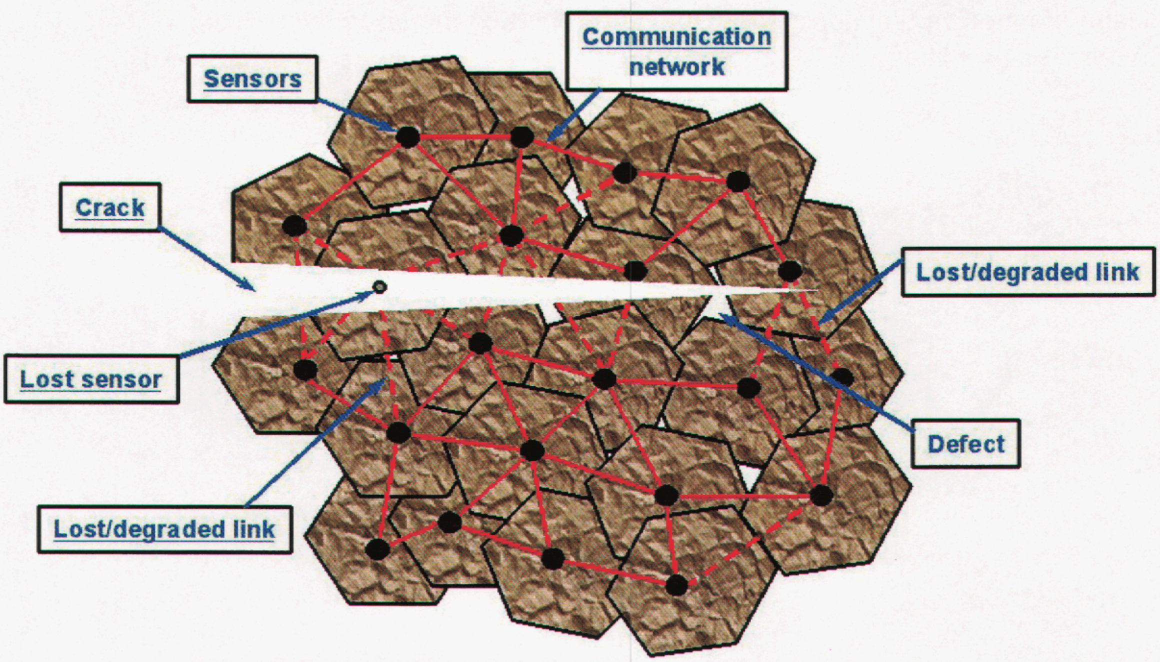

Figure 1 Diagram of a material with subgrain-sized sensors.

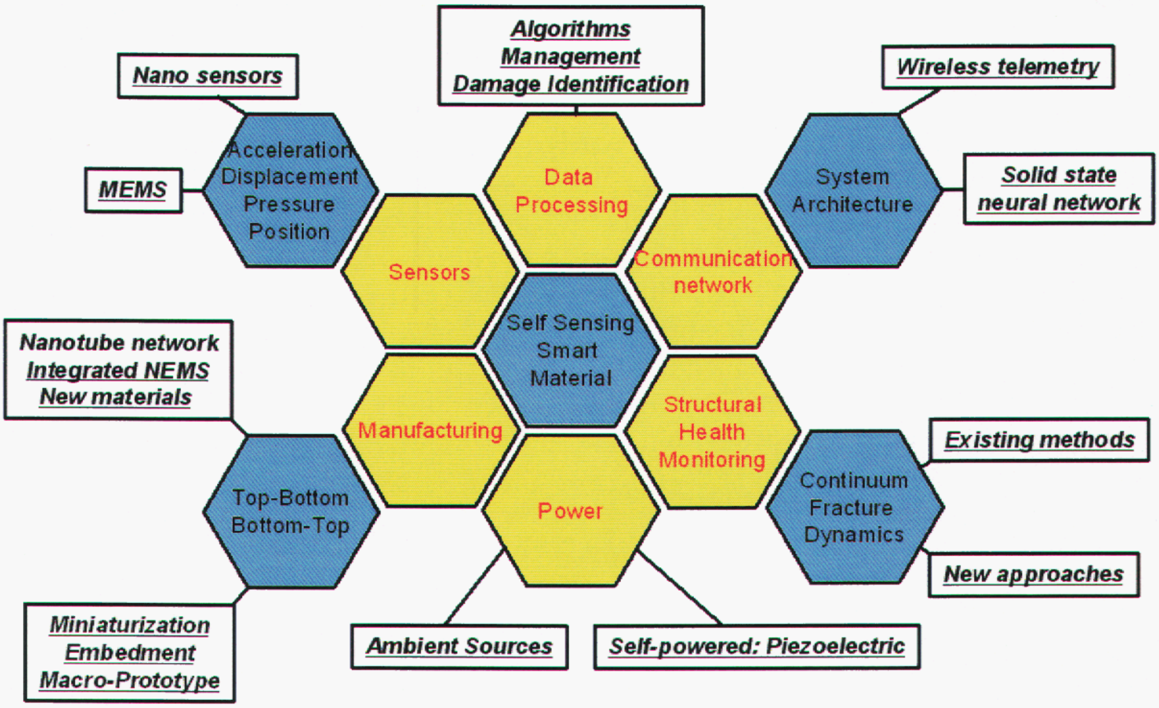

Figure 2 Multi-disciplinary collaboration to create self-sensing materials.

This report presents general research findings of a one-year feasibility study that was aimed at creation of a new smart material that incorporates self-sensing functionality. First, a summary of the current efforts in the field of nanotechnology is presented. Limitations of current manufacturing techniques are discussed. Next, MEMS sensors and sensor networks are discussed next. Finally, the report will outline a roadmap to create a new self-sensing smart material based on investigation into sensing capabilities of nano-structured materials with inherent dendritic configurations.

Nanomaterials as building blocks for self sensing materials

Recent nanotechnological advances enable development of self-sensing structural materials even though development of sensors that can sense at the nanoscale and of new methods to communicate with large numbers of these sensors remains the major challenge in developing a viable artificial neural system. Nanotubes, nanorods, and nanoparticles of carbon, boron and other materials show remarkable mechanical and electrical properties. Carbon nanotubes (CNTs), a unique graphene-based material, generate great excitement due to their intriguing physical properties and a plethora of potential applications. Single-walled CNTs can be electrically conducting, semi-conducting, and piezoresistive, depending upon the chirality of the cylindrical graphene sheet. Record strength-to-weight ratios, ballistic conductivity, and sensing capabilities have been reported for carbon nanotubes (Chengyu et al. 2002; Qingzhong et al. 2002; Chengyu et al. 2003a; b). The first transistors, sensors, and actuators have been fabricated from carbon nanotubes (Goldhaber Gordon et al. 1997; Baughman et al. 1999; Bachtold et al. 2001). Multiwall CNTs consist of several graphene sheets rolled into concentric cylinders. These are grown at lower chemical-vapor-deposition (CVD) temperatures directly onto substrates in useful configurations. Sandia researchers co-authored the first reports of CNT vertical arrays on glass and silicon substrates (Huang et al. 1998; Ren et al. 1998) with the CNT diameters precisely controlled by the CVD growth temperature (Siegal et al. 2002). For development of dendritic structures, it may be advantageous to grow unaligned CNTs. This can be accomplished simply by growing nanotubes without the use of a template.

Most promising areas of carbon nanotube application are vacuum microelectronics, energy storage media, fillers in polymer and ceramic composites, and field emission displays (Ajayan and Zhou 2000). Nanotube based sensors and actuators are also gaining visibility. Carbon nanotube electromechanical actuators with higher energy densities per cycle than any previously known technology have been developed (Baughman et al. 1999; Ahuwalia et al. 2001; Minett et al. 2001; Fraysse et al. 2002). Flow of a fluid along single wall carbon nanotube bundles induces a voltage in the sample along the direction of the flow showing a potential for sensor and energy conversion applications (Ghosh et al. 2003). Major barriers to widespread applications of carbon nanotubes are the availability of bulk quantities of well-defined samples, cost, polydispersity in the tube type (i.e., single- and multi-wall), limitations in processing, organizing, manipulating, and assembly methods (Baughman et al. 2002).

Many other materials have been studied at nanoscale. A well known piezoelectrics such as zinc oxide and barium titanate retain their properties at nanoscale. Zinc oxide nanowires, nanobelts, nanorings have been demonstrated (Jong-Su et al. 2003; Kong et al. 2004) and nanowires of barium titanate have been grown (Wan Soo et al. 2002; Yun et al. 2002). Boron-nitride nanotubes are also piezoelectric (Srivastava et al. 2001a; Nakhmanson et al. 2003). Gallium oxide (Ga_2O_3) nanowires and nanobelts are semiconducting and have photoluminescence – an emission of light under optical excitation – properties (Gundiah et al. 2002). Nickel nanowires are magnetic (Hultgren, Tanase et al. 2003). The variety of metallic, semiconducting, insulating, ferroelectric or piezoelectric nanomaterials provides for a rich variety of electrical, optical, and magnetic properties to construct a neural network.

Most of the progress in nanotechnology has been in the area of biomolecular and chemical diagnostics while development of accelerometers, linear/angular displacement, and stress sensors that are generally used in structural health monitoring has lagged behind. Various chemical sensors, biosensors and biochips have been developed at Oak Ridge National Laboratory (Vo-Dinh et al. 2001). Polymer nano-fibers, semiconductive nanobelts, boron-doped silicon nanowires, and porous silicon have shown potential for use in chemical and biological sensing applications (Gaburro et al. 2001; Kwoun et al. 2001; Yi et al. 2001; Gundiah et al. 2002). Magnetic nanowires were used to apply force to organic cells (Hultgren et al. 2003; Reich et al. 2003). Encouraging results in the development of nano-sized strain, stress, or pressure sensors were shown in layered magnetoresistive and magnetostrictive structures (Lohndorf et al. 2002a; Lohndorf et al. 2002b). Carbon and boron nitride nanotubes can exhibit piezoelectric effects (Nakhmanson et al. 2003). Even though the piezoelectricity in the nanotubes is small compared to conventional piezo-ceramics and polymers, these nanotubes have been proposed for use as sensors and actuators (Roth and Baughman 2002; Spinks et al. 2002).

Manufacturing and manipulation of nanotubes and nanorods may be the most challenging aspects of nanotechnology (Zhou et al. 2002). Manipulation and assembly at the nanoscale is often achieved by inefficient manipulation of the material samples with advanced microscopy tools. New and more efficient approaches have been proposed such as use of chemical reactions to guide the assembly of nanostructures similar to DNA replication mechanisms (Seeman 2001). Another approach uses fluidic alignment and surface patterning techniques to bring nanowires together. Using this method, nanowires have been assembled into parallel arrays with a controlled average separation and periodicity. Layer-by-layer assembly results in complex crossed parallel arrays of nanowires that form electrically conducting networks. Interconnects of the network may be individually addressed for data processing, and potentially, structural health monitoring applications (Huang et al. 2001).

The self-monitoring materials will have a dendritic structure similar to a network of neurons in a biological nervous system. An often overlooked property of the manufactured bundles of nanotubes is their similarity to a dendritic structure of neural networks with a great quantity of interconnects that may act/serve as initiation sites for artificial neurons in a self-sensing material nervous system. Carbon nanotube bundles usually contain both metallic and semi-conducting tubes. Pentagon-heptagon defects in carbon nanotubes result in Y- and T-type intersections that create metal-semiconductor or semiconductor-semiconductor junctions (see Figure 3). The Y-junction carbon nanotubes have been studied as a nanoscale molecular electronic switch. These junctions may serve the building blocks of self-sensing materials. The major set back is the random nature of

Y-junction occurrence (L. Chico 1996; Andriotis et al. 2001b; a; Srivastava et al. 2001a; Andriotis et al. 2002; Srivastava and Atluri 2002). In order to accelerate the development of self-sensing materials, future research should concentrate on naturally occurring dendritic nano-structures.

While there are no studies directed towards a search for materials that combine neural network capability with structural functionality, researchers at the University of Cincinnati proposed to enhance structural health monitoring systems by developing an artificial neural system using piezoceramic and nanotube materials (Schulz et al. 2002). An artificial neural system is a highly distributed and massively parallel signal processing system. A successful proof-of-concept was conducted with piezoceramic nerves and electronic components. Carbon and boron nanotubes have been identified as ideal candidates for building the artificial neural system because of their remarkable electrical, mechanical, and piezoelectric properties (Schulz et al. 2002). The University of Cincinnati team is now concentrating on building a material neural system with carbon nanotubes. Their research includes development of the neural system architecture and growth of carbon nanotube networks. In the near future, the team will develop, first, a prototype system with two neurons connected to micron sized carbon nanotube film or fiber dendrite sensors. Then they will demonstrate a neural system that has nano-scale carbon nanotube dendrite sensors. Finally, a neural system with multiple neurons connected to carbon nanotube dendrite sensors will be demonstrated (Pammi et al. 2003).

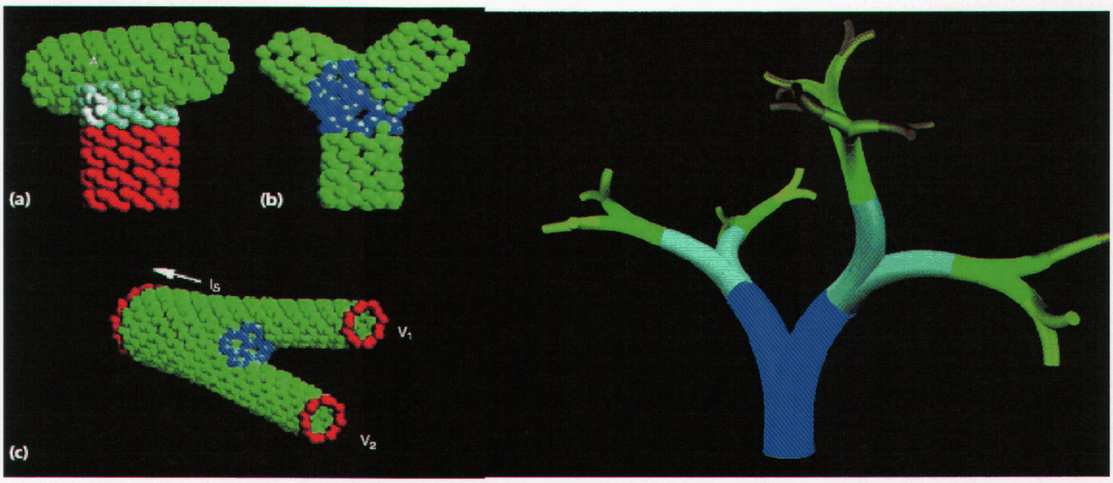

Figure 3 Y-junctions and Dendritic tree made of Y-junctions (Srivastava et al. 2001b).

MEMS sensor networks as a prototype of self-sensing materials

Micro-electro-mechanical systems (MEMS) have developed rapidly alongside of integrated circuit fabrication processes. Accelerometers, optical switches /micro-mirrors, and inkjet printer heads are the most prominent commercially available MEMS devices. Combination of MEMS, integrated circuits, and active materials (e.g., piezoelectric, magnetostrictive, and shape memory alloys) has resulted in the development of smart wireless systems suitable for health monitoring functions (Malas et al. 2003). For example, a microcomb-type transducer was used to generate ultrasonic waves for monitoring cracks from rivet holes (Varadan and Varadan 2000). Another example is selectively coated microcantilevers with integrated wireless telemetry circuits for sensing biological and chemical agents developed at Oak Ridge National Laboratory (Britton et al. 1999). The principle of capacitance changes on which the ORNL's devices are based, can be used in displacement, pressure, and force sensors. Combined with wireless telemetry, these MEMS sensors are envisioned to address health monitoring system issues and are receiving considerable attention from NASA (NASA 2000), DARPA (DARPA 2002), and other government agencies.

While self-sensing materials with subgrain size sensors (scale of micrometers) remain in the realm of basic research, meso-scale (millimeters to centimeters) sensors and their networks are part of mature research and have begun to find their way into commercial applications (Hill et al. 2000). Macro-scale (centimeters to decimeters) sensors and networks are commercially available from various sources(Wilcoxon; Crossbow 2004; MicroStrain 2004). The research of large-scale networks of wireless sensors (MEMS and conventional) have attained significant progress in recent years. Federal (DARPA, ONR, NSF) and state (CITRIS Center at Berkley established by the State of California) agencies are actively involved in research pursuing sensor network related research. While the majority of applications that employ sensor networks are driven by the needs of the Department of Defense, these sensor networks are becoming increasingly available for not only military but commercial, environmental, health, civil, and other applications:

Military applications (Navas 2001; Buckner et al. 2002):

- Monitoring friendly forces, equipment, and ammunition
- Battlefield surveillance and awareness
- Reconnaissance of enemy forces
- Targeting and guidance
- Multi-target tracking
- Battle damage assessment
- Nuclear, biological, and chemical attack detection

Commercial applications (Calvaneso 1999; Teresko 2003; Culler et al. 2004):

- Managing inventory
- Monitoring product quality
- Factory instrumentation, process control, and automation
- Smart office spaces (i.e., environmental control in office buildings)
- Self-identification
- History tracking

Environmental applications (Estrin 2001; Haowen and Perrig 2003; Ullah Khan 2003):

- Tracking the movement of animals
- Monitoring environmental conditions that affect crops and livestock
- Environmental monitoring of soil, marine, and atmospheric contexts
- Meteorological and geophysical research
- Forest fire detection
- Flood detection
- Pollution study

Health applications (Calvaneso 1999; Forcinio 2003):

- Interfaces for the disabled
- Patient monitoring
- Diagnostics
- Drug administration

Home applications (Calvaneso 1999; Culler et al. 2004):

- Home automation
- Smart environment (human-centered and technology centered)

Other (Lynch 2002; Yuan et al. 2002; Malas et al. 2003; Nelson 2003; Culler et al. 2004):

- Monitoring material fatigue
- Smart structures with sensors embedded inside
- Monitoring disaster area
- Machine diagnosis
- Vehicle tracking and detection
- Virtual keyboards
- Interactive toys
- Interactive museums

Widespread adaptation of sensor networks has been limited by, on one hand, the sensor's high cost of design, development, and deployment, then on the other hand, a lack of reliable long-term power sources. Solutions to both of these drawbacks require significant investments driven by real-life applications. The potential application of sensor networks at Sandia National Laboratories is in dense data collection techniques for validation of numerical methods and material parameter identification. For example, an array of distributed wireless sensors can record the response of soils and reinforced concrete during explosive loading. Another example is an array of surface mounted microsensors that can record modal response of nuclear weapon components (e.g., electronics enclosure). The collected data is then used to validate existing numerical codes and help to identify new physical mechanisms necessary to improve Sandia's computational models. Smart Dust sensor networks that were developed at UC Berkley are one of the most prominent candidates to address Sandia's applications.

The Smart Dust project at the UC Berkley is on the forefront of wireless sensor research (SmartDust 2001). The project's fundamental goal is to explore the limitations of micro-fabrication to design a cubic millimeter sensing, computing, and communication mote (a small particle or speck) to form the basis of integrated, massively distributed sensor networks (Warneke et al. 2001b). In 2001, a 138 mm^3 autonomous unidirectional sensing/communication mote was demonstrated (Warneke et al. 2001a). In 2002, a 16 mm^3 autonomous solar-powered sensor node with bidirectional optical communication for distributed sensor networks was developed (Warneke et al. 2002).

General requirements for Smart Dust include low power consumption (under 10 microwatts), operation at high volumetric densities, low production cost /disposable, autonomy, and adaptability to environmental change (Kahn et al. 1999). Estimates for Smart Dust energy requirements are (Doherty et al. 2001) 1pJ/instruction for computation; 100nJ/bit for communication via RF; and 4nJ/sample for sensing. These goals can be met through power-conscious designs such as a zero power theme and self-powered nodes by energy harvesting or scavenging (Abidi et al. 2000; Rabaey et al. 2000; Karakehayov 2002). The cost per unit sensor is expected to decrease since microsensors are now following manufacturing curves that are at least related to Moore's Law (Pister 2003).

Recommendations for future research

The current state of nanotechnology, MEMS systems, communication, sensor networks, and data processing technologies indicate that it will take ten to fifteen years for the technologies to mature enough to make self-sensing materials a reality. To accelerate the development of self-sensing materials, future research should concentrate in the following four areas. The first and the most significant area of research should be investigation of naturally occurring dendritic nano-structures. The second area of future research should concentrate on efforts to solve the problem of interconnectivity between nano- and macro-scale systems, possibly with an innovative use of MEMS technology. The third area of research should focus on improving current multi-scale and multi-physics computational methods to fully describe integrated nano-systems. The fourth area of research should be aimed at sensor networks not only because the sensor networks will play an important role in designing and simulating new self-sensing materials but also because the sensor networks may provide solutions to data collection, model validation, and material parameter identification. Collaboration with researchers at universities and other research institutions is of paramount importance for success of a multi-disciplinary and challenging tack for designing self-sensing materials.

Investigation into synthesis of materials with dendritic structures that may have sensing capabilities must be the first priority in order to create self-sensing materials. Various materials (metals, ceramics, carbon structures, etc.), properties (conducting, semi-conducting, piezoelectric, and insulating), structures (nano-particles, nano-rods, nanotubes, etc), and manufacturing methods (chemical vapor deposition, electrochemical, template growth, dispersion, arc discharge, etc) should be cross-referenced and analyzed. The most promising materials should be selected to begin synthesis experiments.

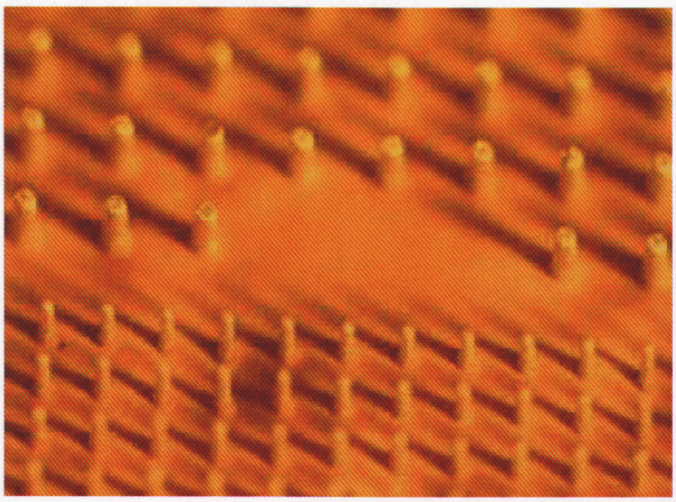

Figure 4 An array of electrodes electroplated through an insulating frame.

Since one of the biggest issues associated with using nano-structured materials is their interconnectivity to macroscale systems, micromachined electrodes to connect to nano-scale dendrites must be developed. Sandia's micro-fabrication facilities at the Compound Semiconductor Research Laboratory (CSRL) have unique capabilities to develop interconnecting electrodes. For example, electrode arrays that are electroplated through an insulating photo-definable glass frame are demonstrated in Figure 4. The micromachined interconnects can be used in the nanomaterial's testing and integration studies in the following manner. The nano-structured materials can be dispersed into a solution and spin-coated onto the interconnecting electrodes. The solution containing the nano-structured aggregate will solidify and encapsulate the aggregate. Inevitably, some of the nano-structured material will contact the electrodes and will bridge electrical contacts between the electrodes as illustrated in Figure 5. A series of baseline studies will follow to identify inherent transfer functions. Incorporation of nano-dendrites into films or coatings should be investigated as a first step toward structural component functionality.

Numerical models must be developed to predict structural behavior of the synthesized nanomaterials and integrated micro-structures (Wachutka 1999). Modeling and simulation faces major challenges include: a) capturing discontinuities in geometric and material properties; b) multiple and interacting failure modes; c) scaling material and structural behavior from the micro- and meso-levels to the macro-level for full-scale system simulation; d) multi-physics scale dependent phenomena (Garg et al. 2002). These challenges can be addressed by utilizing Sandia's computational resources including cluster and supper computers and parallel multi-physics numerical tools.

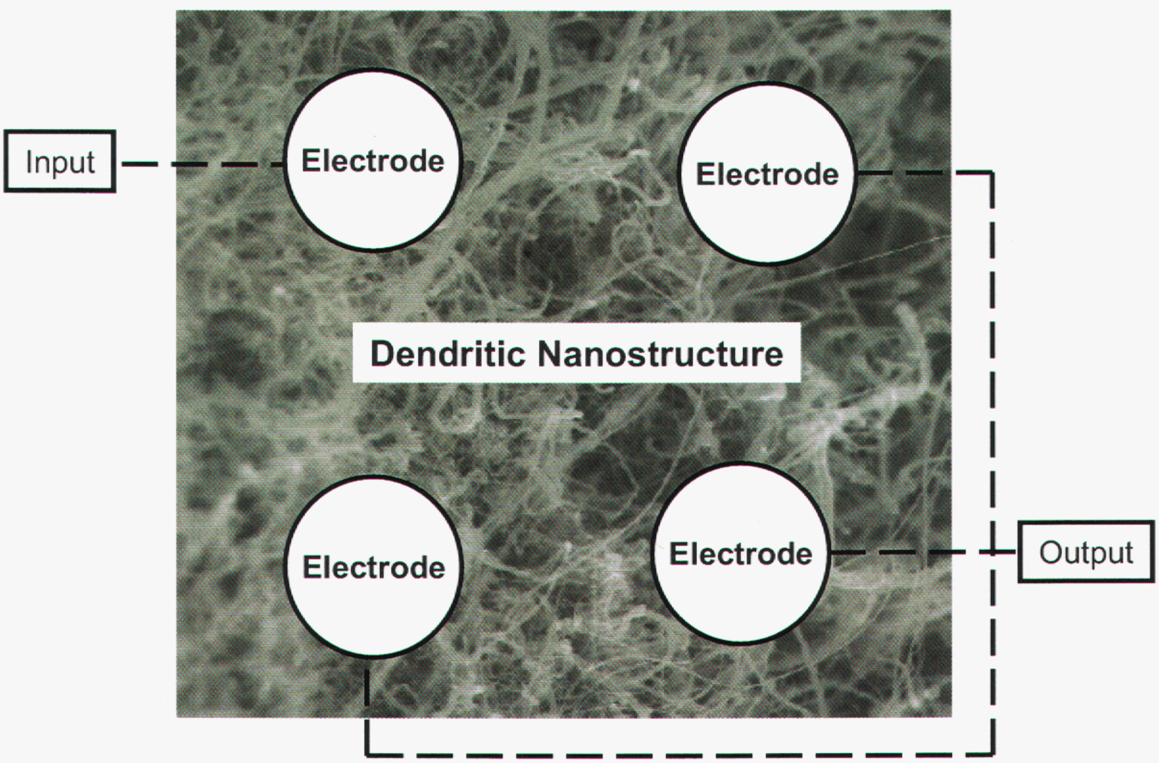

Figure 5 Dendritic structure with self-sensing capability

The concept of a decentralized sensor network will play an important role in designing new self-sensing materials. The electronics-compatible processing in the Microelectronics Development Lab (MDL) and non-standard bulk and surface micromachining processing at the CSRL can be used to develop a MEMS neural cell prototype based on interconnected p-doped polysilicon piezoresistors on suspended silicon nitride films. For example, a Wheatstone bridge configuration of micromachined piezoresistor based pressure sensors can be fabricated in SiC on Silicon-on-Insulator wafers. Such a sensor array will produce a continuous sheet of elements capable of structural-event detection. Interconnections between individual "pixels" will need to be explored to determine the feasibility and resolution of such layout. Integration of the sensor array with on-chip NMOS electronics as well as optimizing the density of sensor pixels will be investigated. Methods for addressing node sensing network algorithms for deconvolution of node data will be developed based on MEMS neural cell prototypes and will be applied to dendritic nanomaterial networks.

Conclusions

The goal of this study was to evaluate the feasibility of a new smart self-sensing material that incorporates subgrain nanosize sensors to provide structural health monitoring functions. Based on a review of the current efforts in the fields of heath-monitoring, nanotechnology, micro-electro-mechanical systems, and wireless sensor networks, it was found that the envisioned self-sensing materials will not be technologically feasible in the next ten to fifteen years. Manipulation and manufacturing of nanomaterials was identified as a major limitation of the modern nano-science. Research into naturally occurring dendritic nano-structures was identified as a new approach to accelerate development of these self-sensing materials. Wireless networks of MEMS sensors have been identified as possible prototypes of self-sensing materials. Sensor networks were also recognized as enabling technologies for dense data collection techniques that can aid in the validation of numerical methods and material parameter identification. The sensor network research for dense data collection techniques will provide an immediate impact and a short term return on investment while expanding expertise to develop self-sensing materials, a product with significantly greater pay-off with a potential to impact every industry where structural integrity is important.

A road toward self-sensing materials must include of the following three research directions. The first direction is an investigation into properties and design of dendritic nanomaterials. This type of basic research will leverage existing nano-technology capabilities, will expand Sandia's expertise in new materials and processes, and will result in unexpected discoveries en-route toward self-sensing materials. The second direction is leveraging MEMS technology to a) fabricate interconnects between nano and macro scale for testing and integration, and b) develop sensor network prototypes that will expand expertise in hardware neural network implementation. The sensor network prototype may provide the most immediate benefits of the project in an area of dense data collection techniques for validation of numerical methods and material parameter identification. The third direction is development of analytical and computational models to provide insights into physical mechanisms of the nano-fabricated materials. Numerical models must capture multi-physics and scale-dependent phenomena with multiple interacting failure modes.

Success of the project will require interdisciplinary collaborations between material scientist, structural engineers, control systems, communications experts, physicists, chemist, and mathematicians. The search for self-sensing materials will promote basic science and technology leading to discovery of materials with fundamentally new functionality. The needs of the proposed work will open new research directions into nano-mechanics modeling and simulation over multiple length scales. The highly innovative area of the proposed research is likely to lead to a number of significant scientific findings. A tremendous payoff impacting any industry where structural integrity is important is expected. Self-sensing materials will enhance national civil and military infrastructure providing Sandia with competitive and strategic advantage. The self-sensing materials are going to find applications in structural monitoring and diagnostic, data collection for experimental validation, and weapons surety through anti-tempering mechanisms.

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