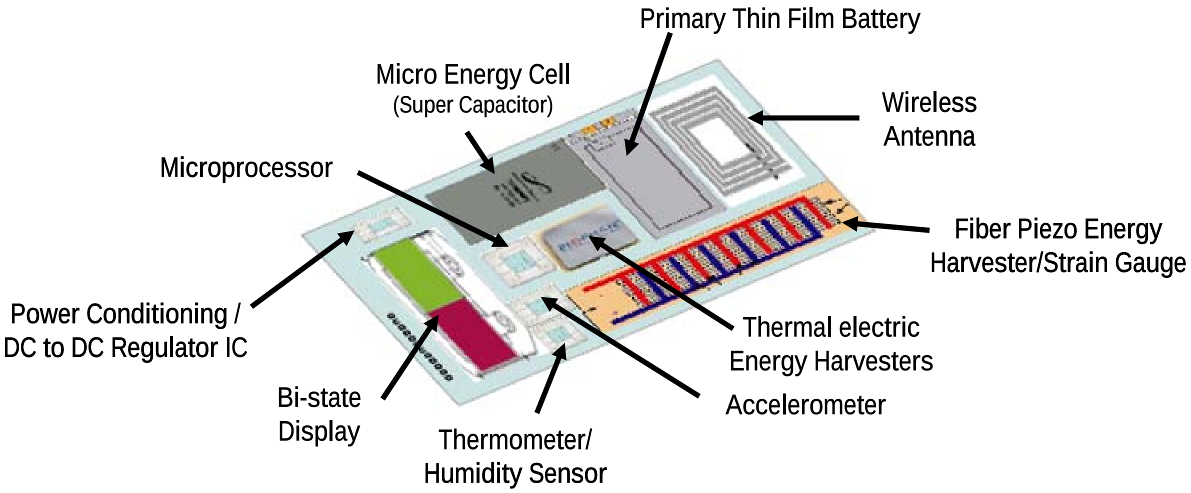
DANS^4 - Distributed Autonomous Network of Ship Structural Strain Sensors

a Small Business Innovative Research proposal



submitted to:

The Office of Naval Research
Dr. Ignacio Perez
Materials Division, Code 332
875 North Randolph Street
Arlington, VA 22203-1995

submitted by:

Mark Krawczewicz
Tocreo Labs
410.562.9846
mark.kraz@tocreo.com

Eric Greene
Eric Greene Associates
410.263.1348
EGAssoc@aol.com

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Background

The U.S. Navy and other ship operators would benefit greatly if they had a better understanding of vessel structural health. Recent operational trends have moved toward faster vessels built with reduced scantlings, which has been made possible by our ability to better analyze ship structure with finite element analysis. We are also trying to extend the service life of these ships. A reliable structural health monitoring (SHM) system that is inexpensive enough to be ubiquitous throughout the ship will provide ship owners and operators historical and real time information on the stress state throughout the vessel, thus greatly improving ship safety and increasing her operational envelop.

To date, "hard-wire" mechanical strain gauges have been used to measure strain in complex engineering structures, such as ships, submarines and other weapon systems. The cabling installation and support costs plus the need to supply power to these sensors has limited their use to dedicated surveys. An autonomous SHM system that utilizes energy harvested from the structure itself is now possible as the power requirements of micro-electronic mechanical systems (MEMS) have declined drastically.

Abstract

Our Distributed Autonomous Network of Ship Structural Strain Sensors (DANS^4) will be a very powerful yet low-cost SHM system. Sensor suites will be manufactured on thin-film substrates designed to be mounted directly on ship structure. The sensors will communicate wirelessly to a central hub located in each compartment. These hubs will then be connected using the ship's standard communications network. This distributed network system will have the ability to perform complex data algorithms at the nodes, hubs and central processor, which will greatly reduce data transmission requirements.

The DANS^4 will serve as a long-term SHM to trend data and also have the ability for detailed damage detection using impedance-based analysis. Piezoelectric strain gauges will form the backbone of the sensor suite in order to provide strain data without the need to run cabling to each gauge for supply current. The sensor nodes will also incorporate accelerometers, temperature and humidity gauges to help diagnose the cause of structural failures and to support damage control assessment.

A unique feature of our sensors will be the ability to harvest energy from the host structure. This will be accomplished through a combination of piezoelectric and thermoelectric devices. A thin-film battery in parallel with a micro-energy cell will charge via the energy harvesters. Data acquisition and transmission will be designed to minimize power requirements.

The sensor suite will be manufactured using aerosol jet technology to minimize connections on the printed circuit board at reasonable cost for the number of units envisioned. The entire electronics package will be encapsulated in polyurethane to produce an extremely durable sensor designed to operate unattended for a minimum of ten years.

Anticipated Benefits

DANS^4 will revolutionize SHM for ships and infrastructure applications. The ability to produce powerful sensor suites very inexpensively using domestic technology will permit up to 64 sensors in each node. For ships, structure that is subject to high stress but is inaccessible for inspection can now be monitored. This will allow ship captains to increase a vessel's operational envelop and reduce the amount of required structural repairs.

Beyond military applications such as ships, submarines, land vehicles and weapon systems, affordable SHM will be valuable for bridges, industrial equipment and transportation platforms. What excites us the most is that DANS^4 technology will be developed and manufactured in the U.S. to help improve safety and preserve our nation's assets.

Keywords

structural health monitoring (SHM), strain gauges, sensor networks, piezoelectric, impedance-based SHM, energy harvesting, micro-electronic mechanical systems (MEMS), aerosol jet deposition

Identification and Significance of the Problem or Opportunity

In the 23 years since the publication of Ship Structure Committee report SSC-344, "Development of an Onboard Strain Recorder" [ref 1] the need for ship structural health data has increased dramatically along with the ability to produce low-cost data acquisition sensors. Current and future surface combatants make use of lightweight structures and are designed to operate at higher speeds under conditions that deviate from our experience base [ref 2]. We envision a distributed network of sensors with a very low installed cost that will provide both real-time operational information and the ability to conduct sophisticated damage detection. Our sensors will be integrated micro-electro-mechanical systems (MEMS) fabricated using aerosol-jet technology. Energy-harvesting piezo strain gauges will form the backbone of the sensor suite, which will also include accelerometers, temperature and humidity gauges. The sensors will have onboard data processing capability and support wireless data transmission. Our experience building prototype smartcards gives us confidence that these devices can be produced at very low cost.

Drastically Reduce Installed Sensor Cost

Our experience conducting structural response surveys on U.S. Navy ships has highlighted the difficulty with installing and maintaining instrumentation cabling. Aside from the cost of the shielded (or fiber optic) cable itself, the process is very labor-intensive and interferes with other ship systems. So although fiber optic Bragg-grating technology has been very effective for ship surveys [refs 3, 4, 5, & 6] as shown in Figure 1, we believe that a data acquisition system that doesn't require cabling to the sensor is the only option for a permanent installation.

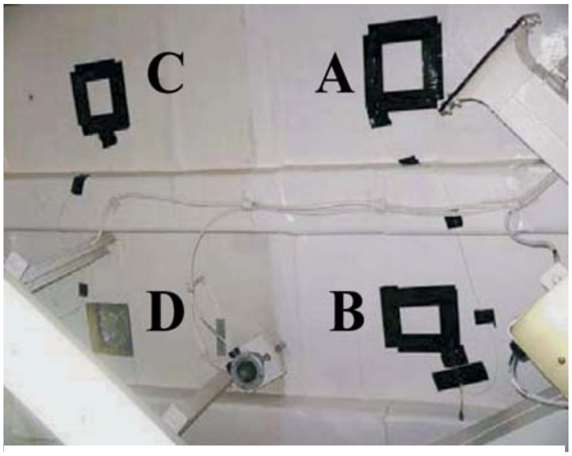


Figure 1. Fiber Optic Strain Gauges are used to Survey Aluminum Deck Cracking Problem on U.S. Navy Cruisers [ref 5]

We plan on producing integrated sensor suites using aerosol jet manufacturing technology, which is very well suited to the "card" form factor we envision and the quantities of devices needed, as shown in Figure 2. Printed circuits on flexible plastic substrates are very durable and inexpensive. The large surface area to weight ratio will simplify installation and minimize the impact on other ship systems.

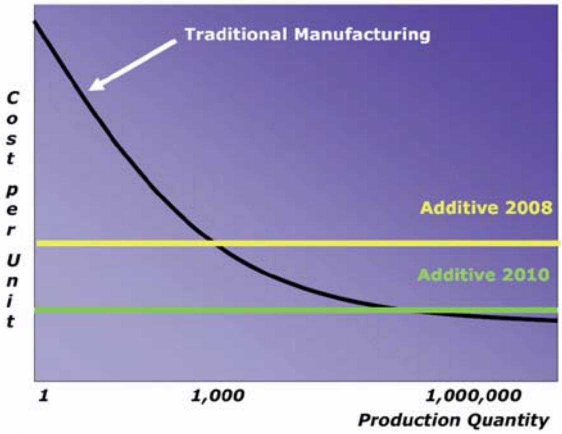


Figure 2. Aerosol Jet Circuit Board Manufacturing Cost [ref 7]

Structural Damage Detection

Our structural health monitoring (SHM) system will be designed to: (1) detect the existence of damage; (2) locate damage; (3) quantify the extent of the damage; and (4) estimate remaining service life. It has been demonstrated that the type of damage shown in Figure 3 can be detected with surface-bonded piezoelectric transducers [ref 8]. Park [ref 9] has shown that "when a crack or damage causes the mechanical dynamic response to change (a frequency phase shift or magnitude change in the mechanical dynamic response), it is manifested in the electrical response of the PZT wafer." Thus we have the basis for a damage detection system with self-powered piezoelectric strain gauges acting in passive mode and a powerful damage location capability by employing impedance-based SHM techniques.

Fatigue Damage

We would like to have the ability to predict the onset of fatigue damage before it manifests itself as shown in Figure 3. To facilitate this diagnostic feature, our sensor suite will have on-board data processing capability to reference historical data trends.

Figure 3. Fatigue Crack Initiated at Bilge Web Detected by Piezo Gauges [ref 8]

Extreme Event Damage
Ship structural damage is often caused by an extreme event, such as impact from a large wave or triggering of a structural resonance, as shown with the strain gauge data in Figure 4. The timescales for the data are 8 seconds (left) and 20 seconds (right), illustrating the need for high sampling rate to capture transient data. Note the high-frequency strain data superimposed over the low-frequency hull girder (hogging/sagging) measurements.
Our SHM system will record transient data and save that information at the sensor suite only when triggered by an extreme event. Otherwise, data will be recorded at frequencies necessary for long-term trending. Examining raw data from slamming and whipping events gives us a good understanding of the strain sensor dynamic range required.

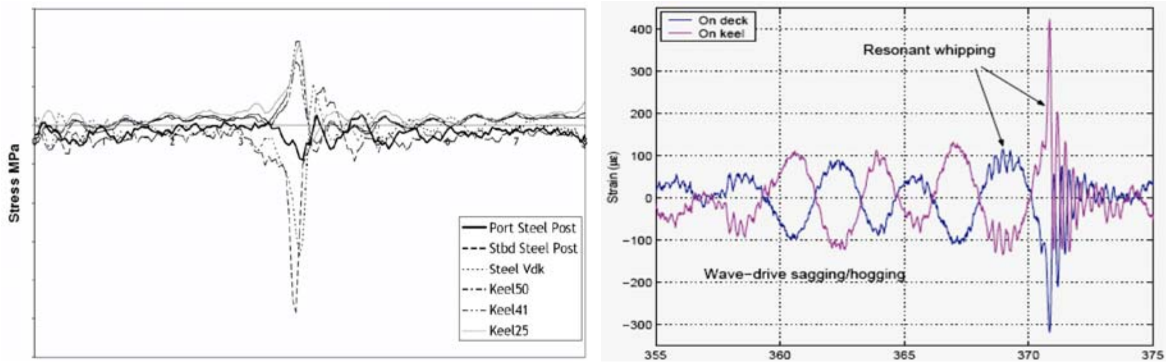


Figure 4. Strain Data from Catamaran Wet Deck [ref 10] and Composite Skjold Class SES [ref 6]

Locate Damage and Determine Cause
Our SHM network will have the ability to passively record strain data continuously using energy harvested from peizo-electric strain sensors. We will also have the ability to conduct a detailed damage location survey using impedance-based technology. Figure 5 shows an example of damage detection using electrical impedance measurement [ref 11]. The ability to cost-effectively deploy a large number of strain sensors will enhance our ability to locate structural damage that may not be visually apparent due to insulation and other ship outfitting. An a-priori assessment of local structure established through baseline measurements will help us establish damage detection algorithms. As all recorded data will be accurately time-stamped, damage detection events can be correlated to the ship's operational parameters, which will facilitate diagnosing the cause of the failure.

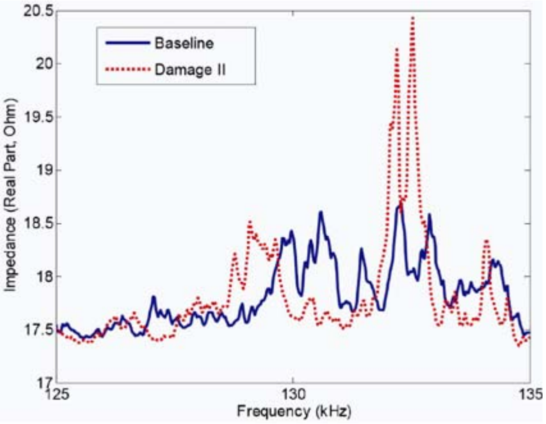


Figure 5. Structural Damage Detection using Electrical Impedance Measurement [ref 11]

Operational Envelop Feedback
We know from experience and finite element analysis (FEA) that each ship will have its own set of structural "hot spots" where stresses are higher than the surrounding structure. Wave slam areas and midship structure are two such areas that we will target for real-time data monitoring with increased frequency. This data will form the basis for an "alert system" that will allow the ship's master to assess safety margins while he or she is making operational decisions.

Hull Girder Response
Our large network of sensors with integrated accelerometers will make it possible to characterize a ship's overall hull girder response. This information is traditionally acquired during sea trials and post-overhaul surveys by dedicated technicians. A permanent system will have the advantage that it can also be monitored after a vessel has sustained combat or operational damage.

Wave Slam
Novel high-speed surface combatants, such as catamarans and surface effect ships, may encounter local damage in wave slap areas that can limit a vessel's allowable operational envelop. This is also a concern with smaller, fast patrol boats. The wave slam phenomenon is a transient event that results in a time-varying pressure field on the impacted hull structure, as shown in Figure 6. Correlating the structural response of the edge of the panel to the middle of the panel is essential for damage prediction, especially with sandwich composite construction [ref 13].

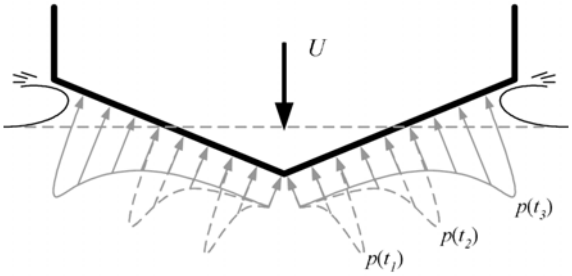


Figure 6. Pressure Distribution during Hull-Wave Impact [ref 12]

Assess Fire and Flooding Conditions during Damage Control Scenarios
Although the primary objective of our SHM sensor suite will be to measure structural response, temperature and humidity sensors add little cost or energy requirement. Indeed, correlating measured strain to a temperature will help us determine if stresses are cause be variations in temperatures throughout the structure, such as the so-called diurnal effect of moored ships. However, the temperature and humidity sensors can also serve to alert damage control personnel as to the condition of a space without entering it. This feature is particularly attractive as we strive to reduce manning levels on future combatants.

Phase I Technical Objectives

The primary objectives of our Phase I research will be to design a SHM sensor suite and wireless network that will operate a minimum of ten years on a naval surface combatant and to build a working prototype to demonstrate operability. We have identified the following project goals required to satisfy program requirements:

1. Develop ship SHM methodology that can identify damage and make failure predictions.
2. Characterize the sensor suite and network requirements to achieve a sensitivity of 1 $\mu\varepsilon$ over a dynamic range of $\pm$ 5000 $\mu\varepsilon$ at frequencies from DC to 200 Hz.
3. Design an integrated sensor suite that incorporates piezo-type strain gauges and can be manufactured on a thin plastic substrate using aerosol jet technology.
4. Develop piezo-electric and thermal energy harvesting capability for sensor suite.
5. Establish distributed network sensor protocol that utilizes wireless transmission within a space and the ship's electronic communications backbone to interconnect spaces.
6. Develop network algorithms to optimize data utilization.
7. Optimize sensor suite and hub data storage and transmission architecture to minimize energy requirements.
8. Develop "bi-state" (only uses power to change display) entry placard that will indicate the damage control condition of a space.
9. Build a prototype piezo strain sensor and demonstrate durability by collecting data for 10^6 cycles.
10. Build a distributed network of 50 sensors and demonstrate operability by mounting them to a cantilever beam with a 10 Hz natural frequency.

Phase I Work Plan

Task 1. Characterize Data to be Measured

Our main objective is to measure strain but the recent drastic reduction in MEMS sensor costs makes it feasible to consider an integrated sensor suite. Figure 7 [ref 1] provides an overview of the relative occurrence of long-term stress phenomena as a function of shipboard event. The x-axis shows the frequency content of the data. Project guidelines stipulate that strain be measured at a sensitivity of 1 με over a dynamic range of ± 5000 με.

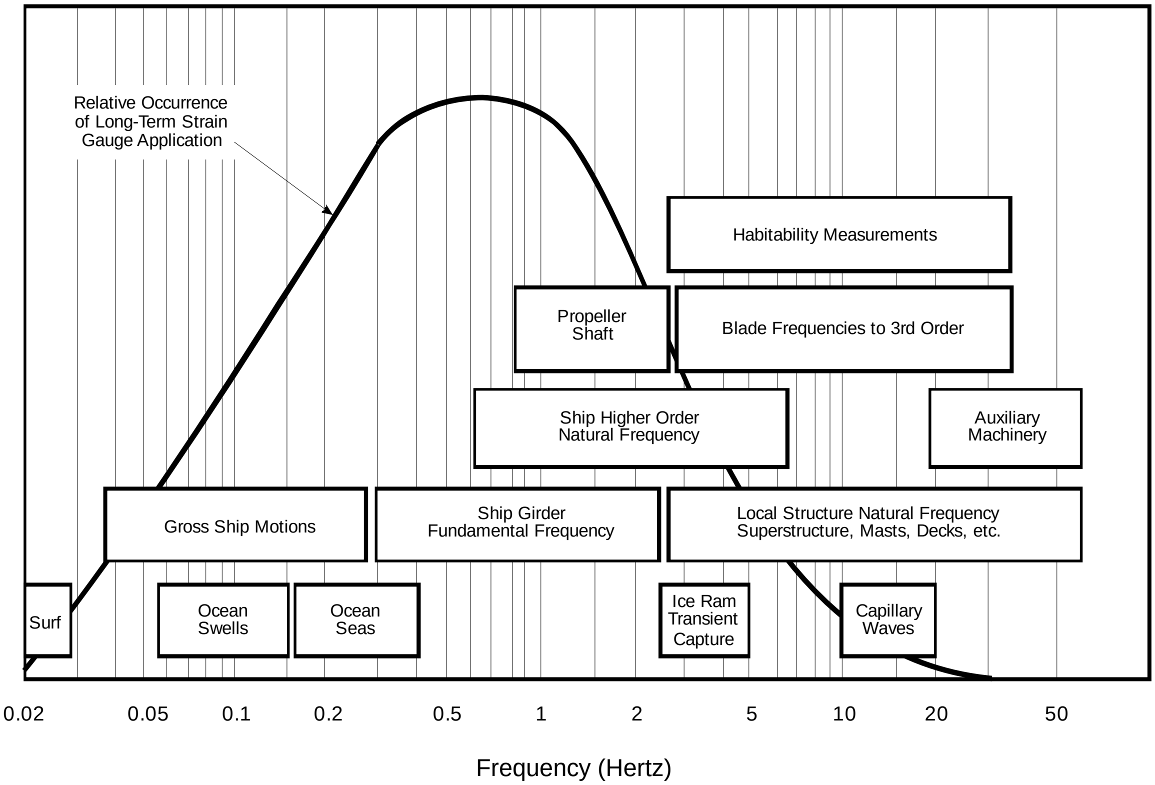


Figure 7. Shipboard Strain Gauge Application versus Phenomenon Frequency [ref 1]

To increase the value of a ship SHM, Jensen [ref 14] has proposed that a shipboard monitoring system should be able to measure and report on: wave height and direction; ship speed, trim and displacement; global load components to be compared with the design loads; local stress; accelerations; fatigue life calculations; slamming events; data to be used for statistical prediction of events; decision support with respect to speed and course; real time warnings and information on bridge; and black-box function in case of accidents.

Beyond data collection and reporting, we intend to build upon Hess' vision of Model-Based SHM to incorporate failure modes and limit states to form structural resistance models. This methodology will support desired prognostic capability, such as service life prediction, platform availability and damage repair recommendations [ref 2]. We hope to be able to integrate strength prediction models for hull girders of ship structures that are suitable for Load and Resistance Factor Design (LRFD) formats [ref 15]. LRFD supports the concept of "strength limit states" and "serviceability limit states," which we would like DANS^4 to be able to predict.

Our primary goal is to develop a SHM system that can characterize damage to predict structural failures. Research will focus on strain and acceleration data acquisition but we expect to integrate other ship performance parameters at the central processing unit. Damage control features will be designed to operate with no power being supplied to the system.

Task 2. Design Sensor Suite

This task builds upon the sensor suite performance specifications developed in Task 1. Our novel design approach is to manufacture the entire system on a flexible thin film printed circuit board that conforms to any hull shape, girder, cylindrical pipe, or other structural component. The total thickness of this planer design will be approximately 18 mils or about half the thickness of a standard credit card. Other attributes of utilizing a thin film design configuration include better thermal and piezo energy efficiency and lower manufacturing cost. Integrating the strain, accelerometer, temperature and humidity sensors with energy harvesters and a wireless interface results in a "mount and forget" sensor. A local microprocessor will provide memory management by monitoring and buffering data. In addition, we've incorporated an electro luminous bi-state (only uses power when switching) display that visually changes from green to red indicating a sensor event change or stress event to the structure. We expect to develop a "repeater" display for installations where the sensor suite is located under insulation and to also relay damage control data to a location just outside of a compartment. Figure 8 shows the arrangement of our proposed sensor suite.

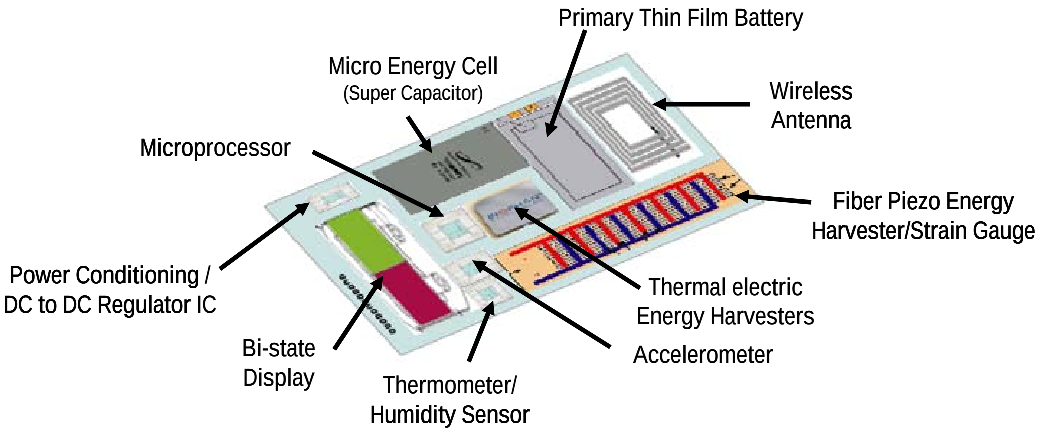


Figure 8. Proposed Arrangement for Sensor Suite

The thin film substrate will form the integrated "backbone" of the sensor suite. This film will incorporate ruggedized laminated piezo strain gauges into the thin film for maximum protection and gauge sensitivity. Although the sensor suite will have a "footprint" about the size of a credit card to maximize energy harvesting, the sensors themselves will be approximately 1 cm^2.

Newly developed microcontrollers and MEMS sensors operate on electrical currents so small they're measured in millionths of an amp. "Texas Instrument's MSP430 microcontroller, for example, consumes just 160 µA/MHz (microamps per megahertz) in an active state and 1.5 µA/MHz in standby. Similarly, ADI has created an ultra-low-power MEMS sensor, the ADXL345, which can pull as little as 120 µA in full dynamic range and 25 µA in sleep mode." [ref 16]

Integrated circuit technology for providing a secure, duplex communication channel optimized for low-power consumption from the sensor pod to the network node has not progressed as much as sensors and microcontroller management. Peak power requirements for wireless applications are attributed to transmission distance, data rate, duty cycle, and collision avoidance algorithms.

Over the past few years, university and industry integrated circuit designers have significantly reduced power by a factor of 100. Figure 9 illustrates this trend for wireless transmitter devices. To wit, the ANS1601 radio transmitter chip developed by AnSem consumes only 3mW in active mode and 15µW in sleep mode [ref 17]. The transmitter operates in the unlicensed 433MHz band using frequency-shift keying modulation. The over-air data rate is 115kbit/s, with burst-mode transmissions enabling further reduced power consumption. The target power goals for our energy harvesters will be between 3-4mW for continuous operation but will be vary depending on transmission rate and local vibration and thermoelectric characteristics.

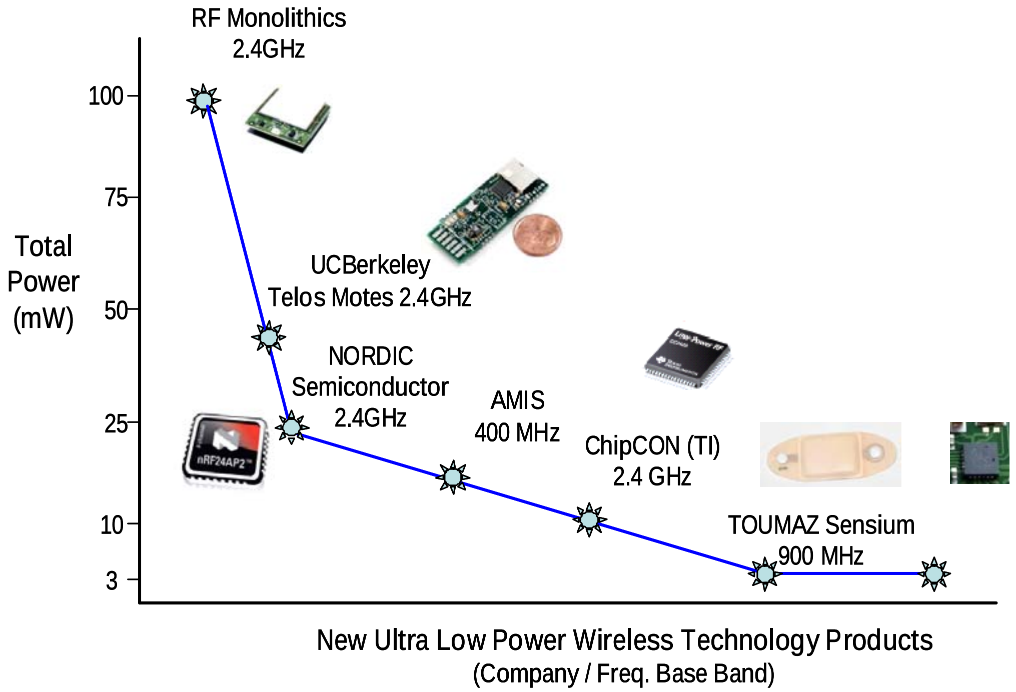


Figure 9. Commercial Wireless Power Trend, Approximately 100-foot Range

Task 3. Develop Energy Utilization/Harvesting Strategy
We are conveniently approaching a nexus where the amount of energy that can be harvested from the environment (kinetic and thermal) coincides with the miniaturization of MEMS devices that require decreasing amounts of energy. Our multi-disciplinary project team will develop power management strategies designed to minimize system energy requirements. Our sensor suite will be designed to have a relatively large surface area for its very small mass, consistent with keeping the overall footprint of the sensor small.

Piezoelectric Energy Harvesting
We propose integrating two types of piezoelectric devices for this effort: a bulk or monolithic piezoelectric (PZT) and a Macro Fiber Composite (MFC). PZT is a more mature energy harvesting technology and the crystal structure within the PZT tends to deliver maximum power when stimulated at a certain harmonic. The power harvesting potential of the two types of piezo devices is shown in Figure 10. The output of both piezo devices will also serve as our strain measurement signal.

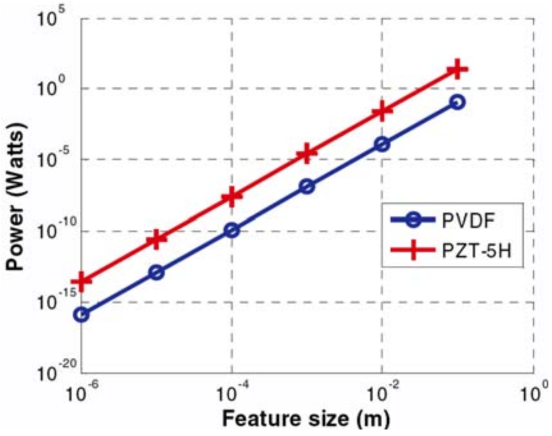


Figure 10. Maximum Power Delivered to Piezoelectric Sensors when Subjected to Mechanical Loading of 100με at 1Hz. [ref 18]

A PZT energy harvester consists of a piezoceramic layer laminated between two electrodes and insulating polymers (shown in Figure 11) and easily integrated to our thin film design. The electrical insulator layer must be mechanical preloaded to maximize mechanical to electrical conversion efficiency.
When mechanically excited, piezoelectric devices act like a high voltage, low current power source to harvest energy. The open circuit voltage can be expressed as:

$$V_{OC} = -\frac{dt}{k}T$$

where d is the piezoelectric strain coefficient, t is the thickness of the piezoelectric material, T is the mechanical stress, and k is the dielectric constant of the piezoelectric material. This voltage output is most commonly AC in nature and is intrinsically dependent on the mechanical stress and the crystal makeup of the dielectric constant. Since ship structures have multiple and localized vibration harmonics with various magnitudes, we have chosen two types of piezoelectric harvesters operating in parallel to optimize total power generation over a wide frequency range.

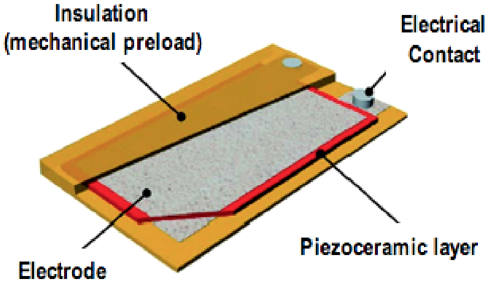


Figure 11. Cross Sectional view of a Monolithic PZT Energy Harvester [ref 19]

The MFC is the second type of piezoelectric device we will integrate into the sensor suite. These devices have the potential to harvest more energy than PZTs, but are efficient only at high vibration frequencies [ref 9]. The MFC has two uniform inter-digitized electrodes comprising the top and bottom surface areas that produce energy harvesting at broader stimulus frequencies. MFC combine the advantages of the large piezoelectric constants of ceramics with the mechanical flexibility of polymers. This type of device is illustrated in Figure 12, which shows a composite sensor made with PZT fibers inside a polymer matrix.

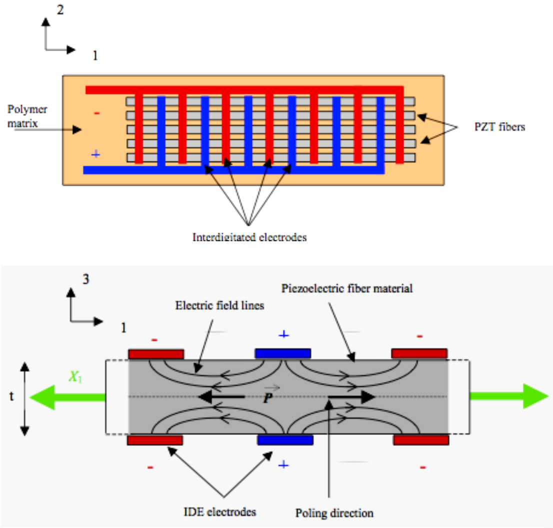


Figure 12. Top and side view of Macro Fiber Composite (MFC) Piezoelectric Energy Harvester [ref 9]

Thermal Energy Harvesting

There exist sufficient temperature gradients between the outside hull plates and inside air volume that can be exploited using thermoelectric energy harvesting devices. Similar temperature gradients exists between pipes, ductwork and inside air volumes of ships.
Existing thermoelectric devices use couples of *n*-type and *p*-type thermoelectric semiconductors, which are connected electrically in series and thermally in parallel to make a thermoelectric generator. The ceramic heat absorption and heat rejection plates generate high electron transport with larger temperature gradients and more *p-n* "islands". The Seiko Thermic wristwatch uses 10 thermoelectric modules (104 *p-n* elements) to generate sufficient power to run its mechanical clock movement from the small thermal gradient provided by body heat over ambient temperature. Under normal operation, the bulk thermoelectric device produces 22 µW of electrical power, with only a 5ºC temperature gradient. [ref 20]

We are proposing an alternative thin film thermoelectric design manufactured using the direct write aerosol jet process onto the thin film substrate to create the *p-n* thermoelectric elements, as shown in Figure 13. The thermoelectric elements consist of *n*- and *p*-type thermoelectric Bi_2Te_3 materials, which are deposited on separate thin film substrate, then laminated together with interdigitized elements spaced at an optimal distance. As with our piezo devices, large surface area will allow much greater energy harvesting efficiencies.

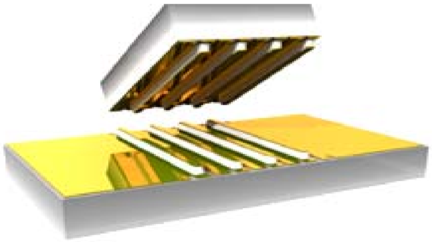


Figure 13. Proposed Thin Film Thermoelectric Design

The PZT, MFC piezoelectric and thermoelectric energy harvesting devices will be placed in parallel to power the sensor suite. Under our Phase I effort we will quantify the ambient vibration and temperature values for various surface combatant spaces to develop the required size of each of the three energy harvesters. Previous research shown in Table 1 provides power density values obtained experimentally during laboratory testing for similar energy harvesting devices.

Table 1. Size Metrics of Various Energy Harvesters [ref 21]

Harvesting Method	Current Output Range	Voltage Output Range	Power Output Range
Piezoelectric Active area = 17.46 cm^2	10 – 100 µA	1 – 10 V	3 – 7 $\mu W/cm^2$
Thermoelectric (ΔT = 30ºC) Active area = 36cm^2	10 – 25 mA	0.1 – 1.0 V	86 – 225 $\mu W/cm^2$

Three types of energy harvesters will supply enough energy to sense, process, store, and transmit structural health data at each sensor node. The output of our proposed energy harvesters vary and are AC in nature, so efficient energy capture and storage is a critical component of our design. The block level architecture of our energy harvesting and management system is shown in Figure 14.

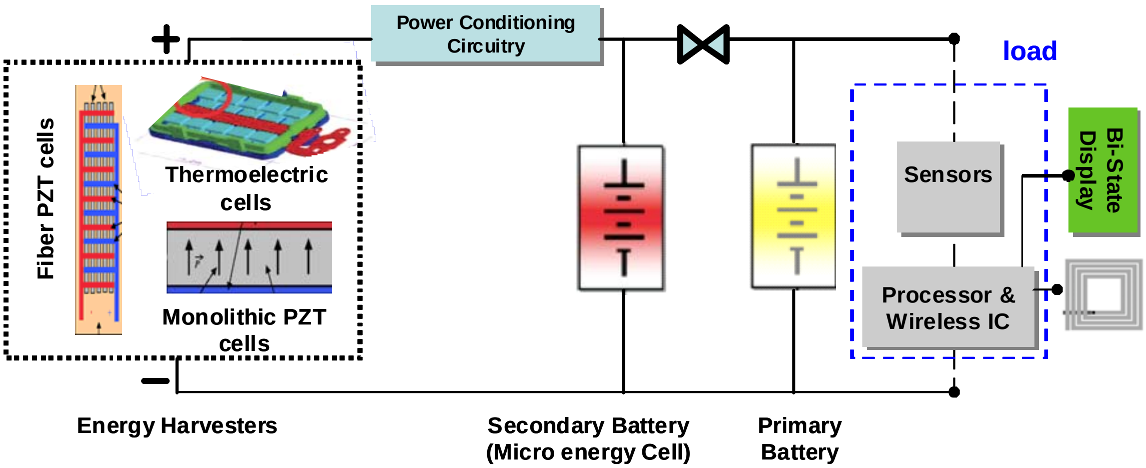


Figure 14. Block Level Diagram of Sensor System

Figure 15. Solicore's Thin 25m A-H Battery (top) and Infinite Power Solutions Micro-Energy Cell (bottom)

Primary Battery – Ultra thin (18 mil) batteries developed by Solicore shown in Figure 15 generate the highest specific energy of any commercially available battery. These batteries could easily power the processor and one sensor for up to ten years. However, this time exponentially decreases with the addition of the wireless chip and accelerometer. The objective of this effort is to never replace the primary battery and/or power the system entirely using the energy harvesters. Even in ideal conditions, our energy harvesters will not produce enough current to re-charge the primary batteries. However, micro-energy cell charging chemistry is ideally suited for capturing and storing small packets of charge from the harvesters.

Secondary Battery – Sometimes called super capacitors, ultra capacitors, micro-energy cells, or electrochemical double layer capacitors, the chemistry of these devices is different from conventional batteries and electrostatic and electrolytic capacitors because they contain an electrolyte that enables the electrostatic charge to also be stored in the form of ions.

Figure 15 also shows a micro-energy cell manufactured by Infinite Power Solutions, which employs chemistry that has both super capacitor and rechargeable battery characteristics. The 4.0V, 0.7 mAh thin film micro-energy cell measures 1 x 1 x 0.0043 inches and performs similar to a super capacitor without the leakage current and with superior energy density. This unique device represents a new class of electronic component that bridges the performance gap between batteries and super capacitor.

Placing the primary battery and micro-energy cell in parallel will optimize the charging efficiency and load sharing, thus extending the life of our system. The micro-energy cell is very attractive in that it can trickle charge energy generated from the piezoelectric harvesters many times more efficiently then the primary battery. However, existing rechargeable technology is not capable of delivering as much energy in a single use as the incumbent primary battery technology, which will force us to optimize system power management. We will also investigate inductive charging technology to augment energy harvesting output.

Power Conditioning Circuitry – Additional circuitry is required to efficiently capture the charge from the energy harvesters. Outputs from the PZT and MFC piezoelectric devices are connected to a full bridge rectifier, which consists of four standard diodes connected in such a way that the voltage reaching the load is always positive. These diodes are chosen specifically for their very small forward voltage drop of around 0.2V. This allows for the largest possible DC voltage to develop across the capacitance or load. Thermoelectric generators typically do not require such rectification, since their output is fairly DC, is always positive, and varies only due to temperature gradients. In order to provide a relatively stable voltage for electronics, a capacitor is added to the output terminals of the bridge rectifier. If it is small enough, the capacitor is charged up to the first peak of the voltage input. Once the input voltage drops below the voltage stored in the capacitor, the capacitor slowly discharges until the next peak of the input.

Microprocessor – In the past, processors and auxiliary hardware would lower power by simply lowering clock oscillators (typically 32kHz). We will integrate a microprocessor with not only overall low active and sleep power states but operate it without the use of an external oscillator to save energy. Ultra low powered Microchip and TI processors have embedded internal watchdog timers. As the radio control network passes below a certain threshold, it triggers the processor to wake-up into the active mode. Alternatively, a sensor event from the strain gauge, accelerometers or a signal from the wireless cluster node could switch the processor from sleep mode to active mode. For the majority of operation the node is in a low power sleep mode, as shown in Figure 16.

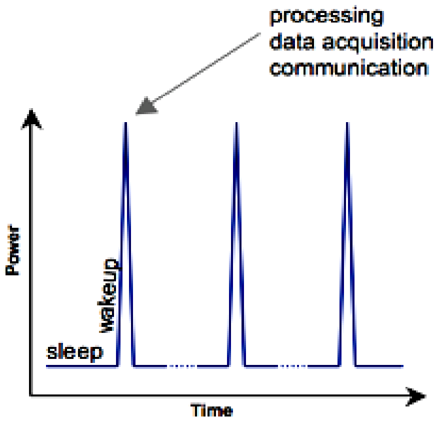


Figure 16. Processor Power use during Sleep and Active Modes

Task 4. Establish Distributed Sensor Wireless Communications Protocol

Our proposed low-cost wireless sensor nodes will ubiquitously connect to a cluster head or hub for each sensor group within a ship's compartment. Sensor nodes are designed for low power so are limited to around 100 foot transmission range, depending on obstructions. Our sensor node architecture will resemble the example illustrated in Figure 17, although we envision using the ship's data bus to connect nodes between compartments. Alternatively, if the ship's data bus is not available, we can configure an independent data bus that could be wired or wireless. Our design strategy will be to use a commercial available wireless chipset for each sensor node to communicate with cluster heads. Cluster heads and super node hardware will utilize commercial off-the-shelve (COTS) hardware like Motes or any of their varieties (MicaDOT [ref 22], Micaz [ref 23], iMotes [ref 24], tMotes [ref 25], uParts [ref 25, 26], ECOs [ref 27], BTnodes [ref 26], and Millennial nodes [ref 28]), which will all be investigated. Our selection criteria will include:

Ease of Installation – We shall choose a cluster node that will permit wireless connection of up to sixty four (64) sensor nodes at each cluster head. The wireless communications protocol shall have error correction if sensor data is corrupted during transmission. The number of sensor nodes will be dynamic depending on various location and internal space boundaries within the interior of the ship. More than one cluster node can be fitted in a compartment, effectively permitting an unlimited number of transducers per compartment.

Ease of Use – Our network will use a generic easy-to-customize operating system as well as network and Media Access Control (MAC) protocols that allow sensor mode configuration by navy personnel who are not experts in networked sensors. Each of the cluster network topologies will be self-configuring if sensor nodes are deleted, added or replaced.

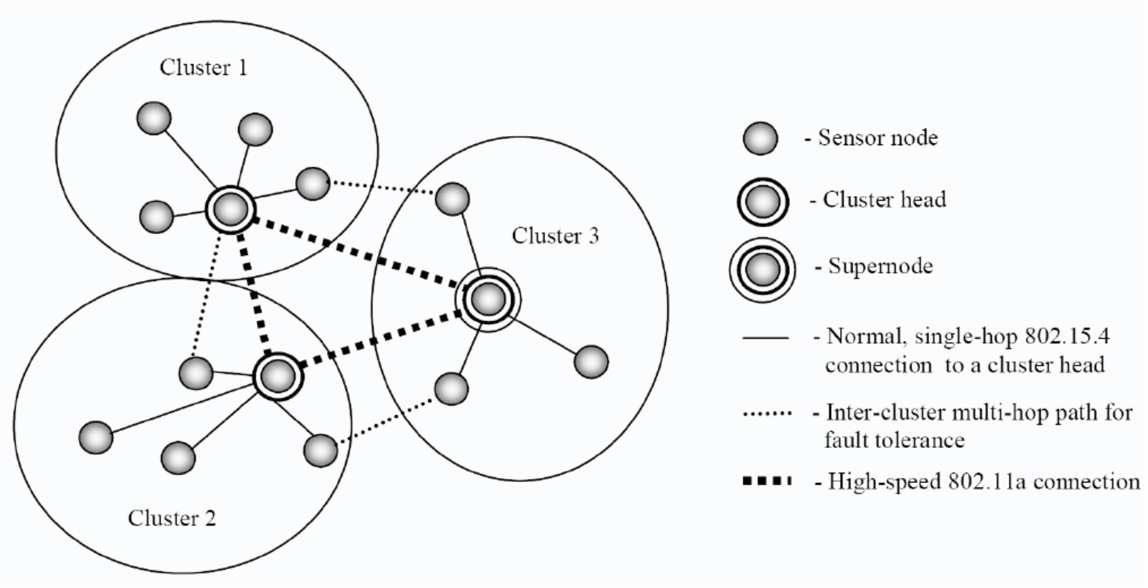


Figure 17. Two-Level Cluster–Tree Architecture of WISAN [ref 29]

Adequate Performance in Ship Compartment – Due to the uniqueness with each interior ship space, the cluster nodes are unique as a fingerprint. Performance parameters such as transmit/receive ranges, energy use, and effects of environmental noise will be challenging to simulate and characterize. Our approach will attempt to achieve a balanced solution that can operate within parameters of all ship spaces.

Our hybrid SHM system requires the ability to sample from an event trigger, switching from a relatively low sampling rate (e.g. Motes, uParts [ref 25], and BTNodes [ref 26]) to a higher sampling rate mode for certain sensors within a cluster designed in some commercial ubiquitous networks (e.g., ECOs [ref 27], MIThril [ref 30], iMotes [ref 31]). This will provide the capability for on-demand advanced damage diagnostics.

Task 5. Build Prototype Wireless Strain Sensor

Our experience developing smartcards (see Figure 18) that must be low cost yet very durable will give us guidance to design a sensor suite that can survive in a shipboard environment. Current flexible backplanes use screen-printing techniques on polyethylene terephthalate (PET) with a minimum resolution of 150µm and require multiple screening operations.

Our proposed approach is to use novel nano-silver materials with aerosol-jet direct deposition printing equipment. Nano-materials support low temperature processing for pattern features below 10µm, including conductor, insulator and adhesive formulations.

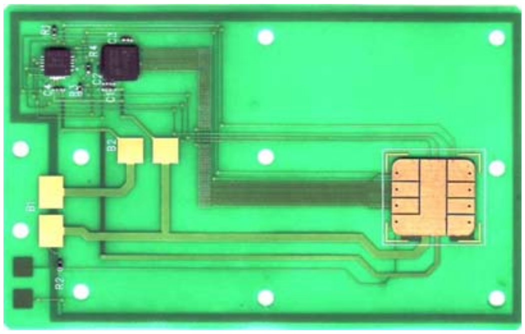


Figure 18. Prototype Circuitry on a Flexible Substrate Built by Project Team

We will also use a flexible urethane encapsulation technology to surround the sensor suite. This new assembly process is both low-temperature and low pressure to avoid damaging the sensors or circuitry. The encapsulation becomes structurally integral with the electrical components and makes it feasible to build a complex sensor suite into a robust, flexible card that can easily be mounted to ship structure. One of the most innovative manufacturing concepts of this proposal is the blending of direct write aerosol jet deposition process with a printed circuit board (PCB) encapsulation process.

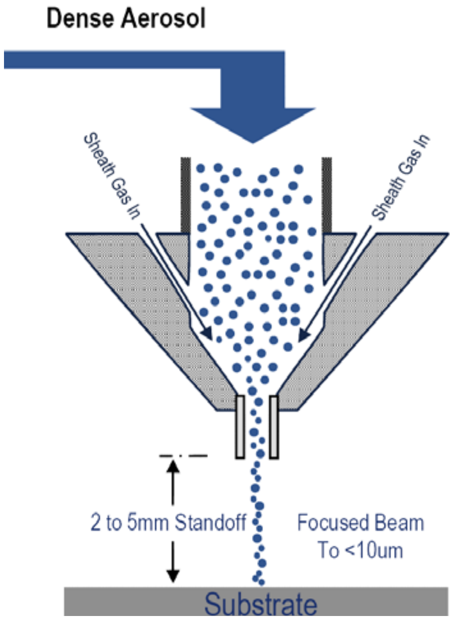


Figure 19. Aerosol Jet PCB Manufacturing Technology from Optomec [ref 32]

The aerosol jet deposition process shown in Figure 19 has the capability to deposit a variety of conductors and insulator materials from 5 microns to 5 mm on a PCB. Our project applies a new additive type assembly technique needed to manufacture a low cost sensor node. The key manufacturing technologies that vary significantly from standard PCB assembly are:

Integrated Circuits – The proposed packaging technology has the contact pads on the die modified for PCB metallization, then thinned to ~50 microns and placed in a thin package. Figure 20 shows a comparison to present thin packaging methods. Electrostatic, conductive adhesive, or reflow bonding can be used to attach the package to the polymer substrate. The intent of "planorizing" of the components is to reduce the mechanical stress on the interconnect, while allowing full testing of a prepackaged component prior to integration of the entire thin film board.

Thin Film Substrate – We shall use either Teslin™ or liquid crystal polymer (LCP) for the flexible PCB material. Both Teslin™ and LCP have the ability to accept a wide variety of nano-metals to make the insulators, dielectrics, conductive layers and interconnects of the PCB. A characteristic of both these core materials is their ability to insulate from the high exothermic bonding process during encapsulation. Once the encapsulation materials cure, it provides a robust barrier from chemical, water, and other containments that can adversely affect the internal components.

Additive Assembly Process – No photo resist or etching is used to create the circuit traces. All layers will use an additive direct write aerosol jet process to form interconnect layers. We will use the 300P and 300CE gas based aerosol jet machine by Optomec Corporation [ref 32]. The aerosol jet deposition process has the capability to create complex geometries over nonconforming surfaces with a diversity of nano materials. The proposed flexible sensor node will be limited to two layers of conductive nano-silver conductive trace layers. The resulting systems with their components and connections locked in epoxy will be designed to be extremely durable, even under high stress.

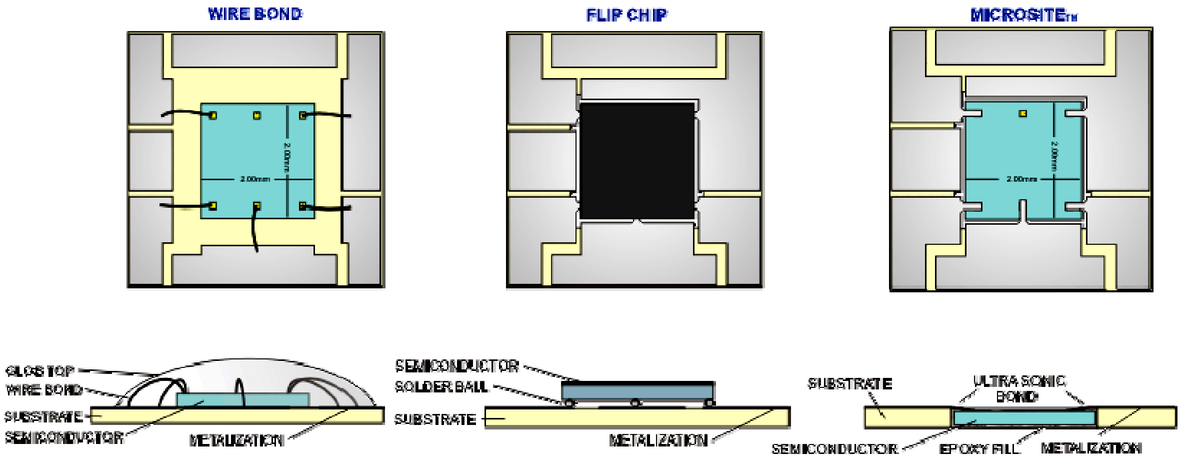


Figure 20. Microsite Packaging Technology Compared to Other More Costly Die Attachment Solutions

Phase I Option Work Plan

A prototype strain sensor will be built and tested during the Phase I base period. The Phase I Option Period will be dedicated toward building a network of fifty (50) sensors that will be demonstrated with a cantilever beam.

Task 6. Manufacture a Minimum of 50 Prototype Sensors

During the Phase I Option at least fifty (50) strain sensors will be manufactured for distributed network evaluation. The sensor design will incorporate lessons learned from Phase I, Task 5. Development of a sensor node integrating the strain gauge, a MEMS accelerometer, temperature and humidity sensor, microcontroller, storage, and wireless transmitter in a 1cm^3 volume has been demonstrated in a University of CA at Irvine prototype called the Eco, shown in Figure 21 [ref 33].

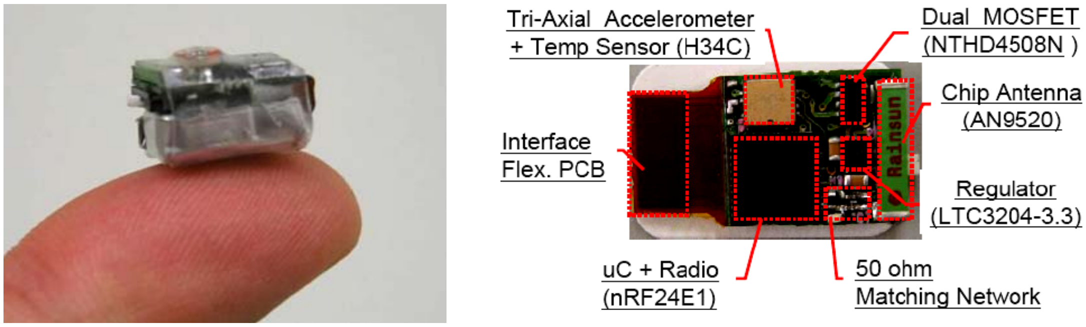


Figure 21. Eco Sensor and Battery (left) and Components (right) [ref 33]

Given the aggressive schedule of this task, our approach for Phase I development of 50 sensor prototypes will be to use the Eco as a sensor baseline. The Phase I schedule would not support the development of a completely new PCB. Among other challenges, prior research has shown that the efficiency of the miniature antennas is extremely sensitive to their distance to other components and ground.

To mitigate the design and layout risks and reduce unnecessary redundant design effort, we will integrate the Eco sensor node using the flex connector to our custom card sized flex circuit, which embeds the piezoelectric and thermoelectric energy harvesters. The target power harvesting goals will be to generate approximately 30mA to operate the sensor with a data transmit duty cycle between 5 to 50%, depending on the sample mode selected. This task will include detailed power analysis of the energy harvesting and storage efficiencies on the cantilever beam testing apparatus described in Task 7. The test results will feedback into the size optimization of our three energy harvesting devices for the Phase II fully integrated thin film design.

Task 7. Test Sensors using Cantilever Beam

We will demonstrate the ability of our SHM system to monitor strains in a loaded steel or aluminum panel by mounting fifty strain sensors on a cantilever beam with a concentrated mass at its tip to produce a natural frequency of 10 Hz.

The natural frequency, ω_n of a cantilever beam can be expressed as:

$$\omega_n = 3.5156\sqrt{\frac{EIg}{wL^4}}$$

where: E = material modulus of elasticity
I = beam moment of inertia
g = gravitational constant
w = weight of the beam
L = beam length

For a cantilever beam with a concentrated mass W at the end and neglecting the mass of the beam, ω_n can be expressed as:

$$\omega_n = \sqrt{\frac{3EIg}{WL^3}}$$

Using the above equations, a 10 Hz steel cantilever beam would measure 0.5 inches thick by 6.0 inches wide and 17.58 inches long with an added tip weight of 5.0 lbs. The aluminum beam will measure 0.5 inches thick by 6.0 inches wide and 16.94 inches long with an added tip weight of 2.0 lbs.

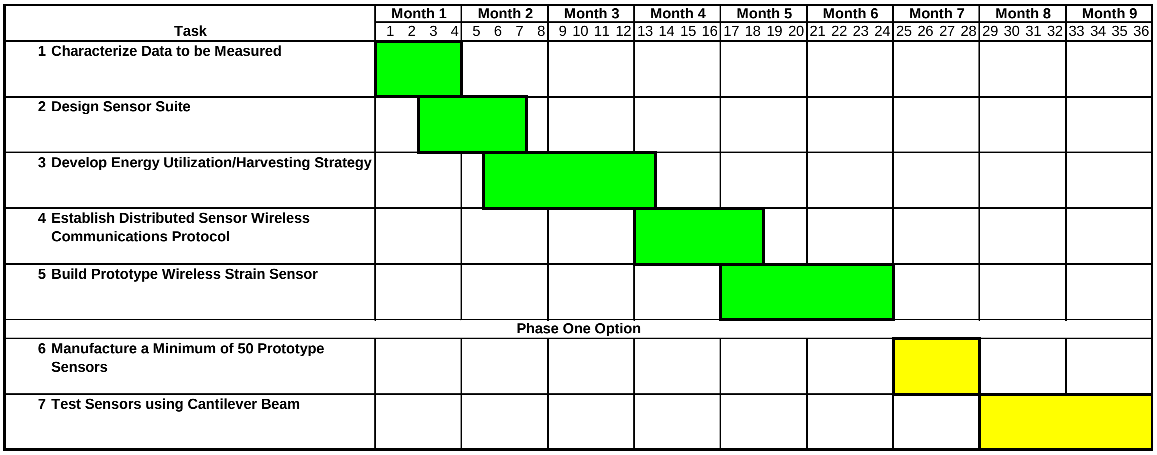
Strain sensors will be attached to the top and bottom of the test beam and data will be recorded over a broad range of excitation frequencies (DC to 200Hz).

Schedule

We are able to propose an aggressive Phase I schedule because we plan on using two investigators who will focus on unique aspects of the design problem. This allows for scheduling "overlap" of tasking. Mr. Greene will focus on the requirements of a ship SHM system. Mr. Krawczewicz will concentrate on circuit design and leading edge manufacturing.

Dr. Colin Ratcliffe will provide technical oversight of both the SHM and circuit design portions of the project based on his experience developing NDE methodologies and test equipment for naval structures.

We also plan to partner with Optomec, with whom we've already had collaborative discussions, for the development of aerosol-jet manufacturing technology they developed with funding from DARPA. We have found that by leveraging state-of-the-art research done by other researchers, ideas germinate faster and technology insertion can be accomplished in a shorter time frame. Figure 22 is the proposed schedule for Phase I and Phase I Option work.



	Month 1				Month 2				Month 3				Month 4				Month 5				Month 6				Month 7				Month 8				Month 9			
Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1 Characterize Data to be Measured	🟩	🟩	🟩	🟩																																
2 Design Sensor Suite			🟩	🟩	🟩	🟩	🟩																													
3 Develop Energy Utilization/Harvesting Strategy						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																							
4 Establish Distributed Sensor Wireless Communications Protocol													🟩	🟩	🟩	🟩	🟩	🟩																		
5 Build Prototype Wireless Strain Sensor																	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
Phase One Option																																				
6 Manufacture a Minimum of 50 Prototype Sensors																									🟨	🟨	🟨	🟨								
7 Test Sensors using Cantilever Beam																													🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure 22. Proposed Work Plan Schedule

Our entire project team is located in Annapolis, Maryland so we anticipate frequent meetings for coordinated collaboration. We also expect to meet often with Navy TPOCs to leverage their considerable knowledge in the field of warship SHM. ONR, NRL and NSWCCD are all with in easy driving distance of the project team to facilitate this.

Related Work

Project Team Related Research

In the early 1980s, Mr. Greene worked on U.S. Navy surface combatants measuring machinery vibration signatures, hull girder response using force-balance transducers and conducting shaft alignments using strain gauges. He also has experience surveying naval and commercial ships with structural vibration problems.

In 1985 Mr. Greene authored the Ship Structure Committee (SSC) report "Development of an Onboard Strain Recorder," and in 1987 edited SSC 350, "Ship Vibration Design Guide," written by Edward Noonan.

More recently, Mr. Greene was Program Manager for the Composite Twisted Rudder project and was responsible for designing full-scale static and shock tests and coordinating with NRL to acquire dynamic strain data using fiber optic technology they developed. Figure 23 shows a portion of the conventional and fiber optic strain gauge package.

Figure 23. Strain Gauge Cabling for DDG 51 Rudder Shock Tests

Mr. Greene is a member of the U.S. delegation to the International Electrotechnical Commission (IEC) TC 114 committee on Marine Energy Devices and works to develop Design and Safety standards for Wave Energy Converters.

Mr. Krawczewicz spent 22 years at the National Security Agency as an integrated circuit designer, senior cryptographic research engineer, and manager. During his design career, Mr. Krawczewicz developed new technologies, including a 10Gbit high speed encryptor, the first CMOS monolithic randomizer, a low powered CMOS fingerprint sensor array, a patented integrated zeroizable RAM with active tamper sensors, a novel smartcard with cryptographic co-processor, and the first secure key processor IC for type 1 mobile devices. Mr. Krawczewicz was chairman of DoD's Secure Mobility Forum charted to collaborate national research efforts between academia, industry and Government Labs for secure mobile devices.

Mr. Krawczewicz successful patented, developed and piloted an ID badge for airline and airport employees using an integrated novel thin film flexible windowing display. Upon authentication into the secure part of the airport, the employee's badge switches from an obfuscated state to transparent state visually displaying their photo, name, and other biographical data.

Dr. Colin Ratcliffe is a co-inventor of ONR's (Office of Naval Research) Vice Admiral Harold G. Bowen Award award-winning NDE technique known as SIDER (Structural Irregularity and Damage Evaluation Routine). SIDER involves exciting a structure with a modally tuned impact "hammer" and recording the vibration response using accelerometers. This information is input into a frequency analyzer, where the frequency response function (FRF) is determined. Conventional NDE vibration methods use either mode shape or frequency shifts to determine whether damage exists. These methods can detect damage only when it is extensive.

With SIDER, the FRF is used to obtain the operational deflection shape from which the operational curvature shape can be determined, which is much more sensitive to minimal levels of damage. For example, SIDER was capable of identifying the area on a 4-inch x 36-inch 0.0125-inch thick steel beam where a 0.002-inch groove was machined across the width of the beam.

Related Research of Other Investigators

Skjold-Class Surface Effect Ship (SES)

In 1997 the Norwegian Defence Research Establishment and the U.S. Naval Research Laboratory installed an extensive hull monitoring system on a Skjold-Class SES [ref 6] with collected data analyzed by Los Alomos Laboratory using their statistical pattern recognition techniques developed for SHM [ref 34]. The installed system consisted of 56 fiber Bragg grating strain gauges, a radar altimeter to characterize oncoming waves and accelerometers to measure ship motions (the ship's inertial navigation system and

GPS were also used to assess ship motions). The location of the installed gauges was determined to measure both global hull loads and local stress at locations critical to the ship design. The results of the data acquisition exercise and subsequent analysis highlighted the importance of understanding the relations between the hull loads, sea state and ship state.

Composite T-Joint Damage Detection

A real-time SHM technique that is capable of detecting the presence of damage, predicting its location, and the severity of damage was investigated in 2007 at RMIT University in Melbourne, Australia [ref 35]. Their SHM system used artificial neural networks in tandem with a pre-processing program to localize damage based on the examination of the strain signature of the structure under operational load. Figure 24 shows a schematic of their test arrangement and network architecture. The researchers concluded that “the ability of the neural network to learn after it has been trained is one of the reasons for the accuracy of the system.” Twelve sensors were used to analyze a 700mm long T-joint, emphasizing the need to produce low-cost sensors for an affordable ship-wide SHM system.

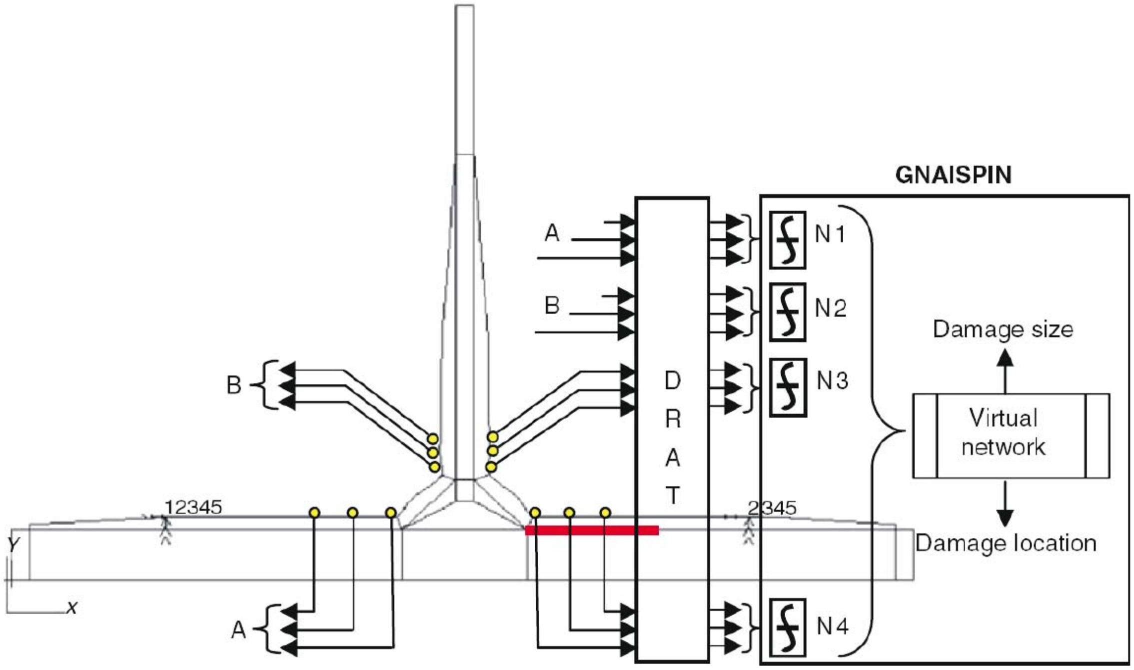


Figure 24. Schematic of the Algorithm to Virtually Combine the Sub-Networks into a Global Network for SHM of a Composite Bulkhead Attachment [ref 35]

LPD-17 Ship Sensor Network

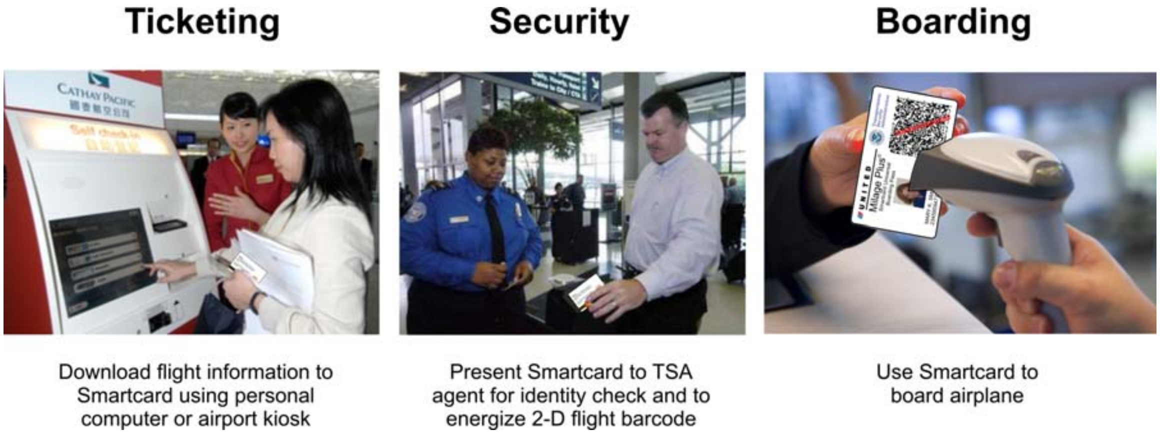
In 1999 the Office of Naval Research (ONR) funded a project to consider using Bragg gratings and a prototype multiplexing system for a proposed ship-wide health monitoring network system [ref 36]. The investigators developed a system that allowed 120 gratings to be sampled at a rate of 2000 samples per second. The system was tested on a LPD-17 propeller, with conventional strain gauges installed in parallel for data validation. The results of this investigation were not that encouraging, with variation form conventional strain gauges up to 68%, which the project team attributed to low optical signal intensity, imager misalignment and processing priority errors. It should be noted that since that time researchers at NRL have developed robust Bragg grating fiber optic strain sensor systems that exhibit strain sensitivities from 1 to 10^7 $\mu\varepsilon$ and frequency response from DC to 1 MHz [ref 37]. NRL has used their system for strain monitoring on a navy cruiser [ref 5] and the Principal Investigator has worked with NRL using their system to monitor a DDG 51 rudder during an underwater shock test.

Relationship with Future Research or Research and Development

The project team is actively involved in the development of sophisticated electronic devices built on thin film substrates for applications distinct from DANS^4. However, much of the manufacturing technology and energy harvesting schemes envisioned for DANS^4 can be assisted by future R&D on related technology.

Smartcard Boarding Pass

We are proposing a reusable Smartcard Boarding Pass for airline passengers to eliminate wasted paper while improving convenience and security. As shown in Figure 25, flight information will be downloaded by passengers via personal computers or airport kiosk to a Smartcard. The card's active pixel display will show a 2-D barcode (see Figure 26) only when energized at the airport terminal. The Smartcard Boarding Pass will use a 7816 contact interface to communicate back and forth with airport terminals. This two-way electrical interface is required to activate the barcode display using advanced encryption algorithms. The same encryption technology will ensure that any biometric data stored on the card can't be compromised. Development of the card's bi-state display will support the remote display envisioned for DANS^4.


Ticketing

Security

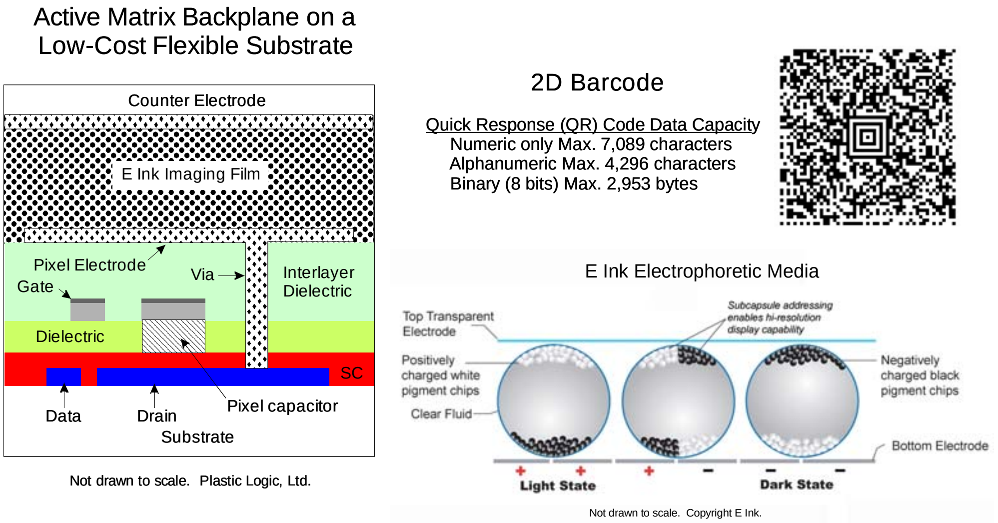
Boarding

Download flight information to Smartcard using personal computer or airport kiosk

Present Smartcard to TSA agent for identity check and to energize 2-D flight barcode

Use Smartcard to board airplane

Figure 25. Smartcard Boarding Pass Concept of Operation



Quick Response (QR) Code Data Capacity
Numeric only Max. 7,089 characters
Alphanumeric Max. 4,296 characters
Binary (8 bits) Max. 2,953 bytes

Not drawn to scale. Plastic Logic, Ltd.

Not drawn to scale. Copyright E Ink.

Figure 26. Elements of a Bi-State 2- Barcode Display

Pilot Alertness Monitor (PAM)

According to federal data cited by Sen. Byron L. Dorgan (D-N.D.), chairman of the Senate aviation subcommittee, sleepy and overworked pilots have been linked to 20 air carrier accidents from 1989 to 2008, resulting in 273 fatalities. We are proposing an unobtrusive health monitoring sensor suite that will alert pilots of fatigue onset. The Pilot Alertness Monitor (PAM) will continuously measure physiological data and update a graphic display only when information changes according to programmable thresholds. PAM will issue an audible warning signal when a state of drowsiness is detected.

The integrated sensor suite will be manufactured on a flexible substrate using aerosol jet direct write technology. Thermo and piezoelectric energy harvesting techniques will be combined with very low power sensors to create a lightweight device that does not require an external battery. PAM will have applications beyond the aviation industry. Truckers and motorists on long trips can avoid accidents if they are alerted to the onset of drowsiness. A self-powered health monitor will also be useful for individuals involved in dangerous activities, such as warfighters, first responders and extreme sports enthusiasts.

Nano-Power Card Technology

A family of smartcards powered by harvested energy is proposed. The nano-power cards will leverage the emerging field of wearable electronic devices that harvest energy from human activity. However, we intend to build these sophisticated electronics packages on plastic cards for the following reasons:

1. High surface area to weight makes card ideal format for energy harvesting (heat, solar & wind).
2. Mass-produced gift cards are very inexpensive showing that manufacturing costs can be kept low.
3. Flexible plastic cards are durable.
4. Aerosol printing on flat cards eliminates connectors.
5. Cards are thin enough to fit in a wallet.

Figure 27. Pilot Alertness Monitor

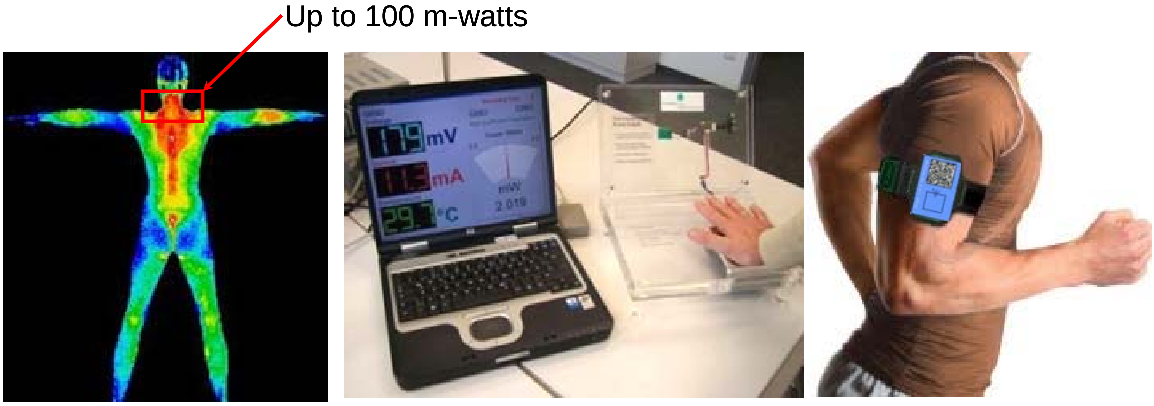


Figure 28. Thermal Energy Harvesting from Human Activity

Commercialization Strategy

A distributed network of wireless sensors that are powered by energy harvested from the environment is truly the Holy Grail of SHM. Our hybrid system that operates at very low energy levels in "monitoring" mode combined with powerful damage detection capability in "analysis" mode can make such an autonomous system a reality. The applications for such a SHM system go beyond surface ships. For the military, submarines, aircraft, land vehicles and weapon systems could benefit from a low-cost, durable SHM system. On the commercial side, ships, oil industry equipment, bridges and buildings are but a few of the applications in the multi-billion dollar SHM industry.

Our initial method of technology transfer will be via relevant symposia presentations and articles published in peer-reviewed journals, which the project team has much experience doing. Within the Navy, targeted presentations will be made to appropriate program offices. A web site will also be developed to provide a clear overview of our system's capabilities.

Key Personnel

Eric Greene, Naval Architect/Marine Engineer

EDUCATION

S.B. in Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, 1979

EXPERIENCE

Eric Greene Associates, Inc., President, 1987-Present

Mr. Greene founded Eric Greene Associates, Inc. to advance our understanding of composite materials for marine structures. Engineering advanced materials for marine structures, understanding the performance of composites in fires, composites education, instrumentation of marine equipment and ocean renewable energy are the primary areas of corporate expertise. Some recent projects include:

- Technology transfer assistance for major Norwegian shipbuilder supporting the U.S. Office of Naval Research (ONR)
- Lecture series in the Netherlands on marine composite construction for the megayacht industry
- Cost modeling of next generation Navy hovercraft for ONR ManTech program
- Development of a “stowable” megayacht helicopter landing platform
- Riser load calculations for a Floating Transit Offloading & Storage platform
- Revision of NAVSEA Technical Publication T9074-AX-GIB-010/100, “Material Selection Requirements,” to include updated guidelines for composites
- Fire workshops for the National Association of Marine Surveyors and NASA

Structural Composites, Inc., Naval Projects Program Manager, 1990-Present

Mr. Greene served as the Program Manager for the Composite Twisted Rudder project. In this capacity, Mr. Greene was responsible for securing $7 million in funding from various Government resources and managing all technical and programmatic aspects of the project.

Giannotti and Associates, Inc., Naval Architect, 1985-1987

Mr. Greene's responsibilities with this firm started at the level of Project Engineer and graduated to Program Manager.

Severn Companies, Inc., Manager, Marine Systems, 1984-1985

Mr. Greene was responsible for marketing and product development of a microprocessor-based fuel management system for diesel propulsion plants.

DLI Engineering Corporation, Marine Engineer, 1981-1982

Mr. Greene was involved in test plan preparation, data acquisition and analysis of machinery condition monitoring and hull structural response. Conducted strain gauge shaft alignments and DDG 963 sea trails.

MEMBERSHIP

Society of Naval Architects and Marine Engineers, member since 1979.

International Electrotechnical Commission (IEC) TC 114, Marine Energy Devices, U.S. delegation

SELECT REPORTS, PRESENTATIONS and PUBLICATIONS

1. “Composites for Renewable Energy, 2008, http://change.gov/open_government/entry/composites_for_renewable_energy/
2. “Labor-Saving Passive Fire Protection Systems for Aluminum and Composite Construction,” Ship Structure Committee Report Number SSC-442, NTIS#: PB2005-108998, Publish date: 09/15/2005.
3. “Composite Twisted Rudder,” presented at ShipTech 2005, March, 2005 at the Beau Rivage Resort, Biloxi, MS.
4. MARINE COMPOSITES Overview Course presented at the 6th Annual Multi-Agency Craft Conference at the Naval Amphibious Base, Little Creek, Norfolk, Virginia 18 June 2003
5. “Thermo-Mechanical Testing of Marine Laminates” invited presentation at the Office of Naval Research, July, 2002.
6. “Closed Molded Integral Shock Mitigation for Special Operations Craft,” presented at the 5th Annual Multi-Agency Craft Conference at the Naval Amphibious Base, Little Creek, Norfolk, Virginia 18 June 2002.
7. “Consideration of Composite Materials for Moderate-Sized Warships,” with Loc Nguyen, U.S. Navy NSWCCD, presented at the 8th International Conference on Marine Applications of Composite Materials, Melbourne, FL, March 16, 2000.
8. *MARINE COMPOSITES*, Second Edition, 377 pages, 1998, Annapolis MD.
9. “The Development of a Standard Shipboard Strain Recorder,” 1987. SSC-344, Final Report for the SSC.

Mark S. Krawczewicz, Electrical Engineer

EDUCATION

B.S. Electrical Engineering, University of Maryland, College of Engineering, 1984
Graduate Program, Johns Hopkins University, Applied Physics Lab
Graduate Studies, George Mason University, Computer Engineering
Part time Adjunct Professor, Loyola College, College of Engineering, 2000- present

SECURITY CLEARANCE

TSSI Security Clearance

EXPERIENCE

<u>Tocreo Labs, Chief Executive Officer, July 2009 - present</u>
Tocreo Labs is developing several products including, thin film power harvesting, medical, security, authentication, and security smart cards integrating displays, sensors, and actuators.

<u>Priva Technologies Inc., Executive VP of Travel Division & Product Development, April 2007 – July 2009</u>
Patented novel authentication technology (Patent pending no. 61025088). Successfully launched a smart card integrating a plastic display from concept to prototypes for live pilot for secure airport authentication of employees and flyers. Patented display obfuscates user's photo & biographic data until authentication, and then switches display states inside secured area. These prototypes were then designed into high volume / cost efficient products. Other duties included hiring, strategic planning & forecasting, sales & marketing, management, program review and partner agreements & program development.

<u>National Security Agency, Cryptographic Product Development Technical Director, Feb 1984 – April 2007</u>
Crypto Modules Product Group INFOSEC
Mr. Krawczewicz designed & developed the Secure Key Storage IC, novel active tamper for crypto modules. He was part of a senior technical team working with leading US security companies to evaluate & enhance their security products.

NSA – Chairman, The Secure Mobility Forum
Mr. Krawczewicz started and ran this National Conference to bring Government Labs, Academia, and small innovative companies together to solve the problem of securing mobile devices. He also led an internal NSA integrated process team to tackle the same challenge.

As a Senior Electrical Engineer at NSA for INFOSEC, Mr. Krawczewicz managed security for Bluetooth, Land Warrior, Risk Adaptable Security Policy, LPI / LPD/ AJ, and software defined radio. As a Research & Engineering Hiring Executive, he was responsible for hiring R2, M1, and R5 personnel.

With responsibility as Secure Token Technology Team Leader, Mr. Krawczewicz initiated and led the smartcard research effort for NSA. As a Biometric Analog Sensor IC Designer, he designed numerous CMOS imaging sensors. He started his career at NSA as a High Speed Key Generator Designer working with integrating circuits, including Key Generators, Analog Sensors, Randomizers, biometric sensors, and secured memory.

<u>Kraz Publishing, Chief Executive Officer, Aug. 1987 – June 2001</u>
Mr. Krawczewicz managed production and sales operations for a monthly periodical that supported the Real Estate industry. Kraz Publishing was named one of the top 10 of 400 franchises in US for 8 years.

Dr. Colin Ratcliffe, Mechanical Engineer

EDUCATION

PhD (1985) The Institute of Sound and Vibration Research, University of Southampton, England.
BA and MA (1977, 81) Cambridge University (Sidney Sussex College), England. Mechanical Engineering.

EXPERIENCE

Dr. Ratcliffe is a Professor at the United States Naval Academy, where he teaches courses in the Mechanical Engineering Department. He is a Professional Engineer, registered in London, England, and is an engineering consultant to industry and the U.S. Government.

Dr. Ratcliffe's academic and research interests predominantly lie in the field of mechanical structural analysis. This includes experimental and theoretical work in such topic areas as vibration methods for damage detection, the characterization of vibroacoustic materials, and finite element modeling of linear and non-linear systems. He is internationally known for his work in modal analysis, the characterization of composite materials, and the nondestructive evaluation of large-scale composite structures. He has over 100 published papers and reports in national and international journals.

Dr. Ratcliffe has been a consultant to several engineering companies. His work has included designing a new marine engine anti-vibration mount system for the United States Navy, investigating the impact of paint coatings on vibration mounts, experimental and analytical vibration analysis of a wide variety of structures from a few inches up to more than 100 feet, teaching Professional Engineer's review courses, and supervising shock testing of marine components. He also conducts short courses in experimental modal analysis, statistics, measurement uncertainty, and shock testing of structures, as requested by academia and industry. Dr. Ratcliffe holds the patent to a vibration-based nondestructive structural examination procedure, SIDER (Structural Irregularity on Damage Evaluation Routine).

MEMBERSHIP

Member Society for Experimental Mechanics
Member Institute of Marine Engineering, Science and Technology.

SELECTED PUBLICATIONS

1. "Local Damage Detection with the Global Fitting Method Using Mode Shape Data in Notched Beams," Myung-Keun Yoon, Dirk Heider, John W. Gillespie Jr., Colin P. Ratcliffe and Roger M. Crane, Journal of Nondestructive Evaluation, Volume 28, Number 2, June, 2009, pp 63-74.
2. "Investigation into the use of Low Cost MEMS Accelerometers for Vibration-Based Damage Detection," Colin P. Ratcliffe, Dirk Heider, Roger M. Crane, Carl Krauthauser, Myung Keun Yoon, John W. Gillespie, Jr., Composite Structures 82(1) 61-70, 2008.
3. Permanent Digital Object Identifier (DOI) link: http://dx.doi.org/10.1016/j.compstruct.2006.11.012
4. "Local Damage Detection using the Two-Dimensional Gapped Smoothing Method," Myung Keun Yoon, Dirk Heider, John W. Gillespie, Jr., Colin P. Ratcliffe, Roger M. Crane, Journal of Sound and Vibration, V279, pp119-139, accepted October 2003, published January 2005.
5. "Underwater SIDER Testing: A Proof of Concept Demonstration," Colin Ratcliffe, William Marr, Roger Crane and Maureen Foley, NSWCCD-65-TR-2007/49, August 2007, 13p.
6. "Preliminary Report on the SIDER Testing of Sandwich Panels for the Composite High-Speed Vessel (CHSV) Program," Ratcliffe, Colin P., and Crane, Roger M., NSWCCD-65-TR-2005/04, March 2005.
7. "Structural Irregularity and Damage Evaluation Routine (SIDER) for Testing of the ½-Scale Corvette Hull Section Subjected to UNDEX Testing," Colin P. Ratcliffe and Roger M. Crane, NSWCCD-65-TR-2005/24, October 2005.
8. "A report on the SIDER Testing of Panels for the Composite High Speed Vehicle Program," Colin P. Ratcliffe and Roger M. Crane, NSWCCD-65-TR, 2004.
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Facilities/Equipment

Eric Greene Associates, Inc. developed a fatigue testing apparatus to evaluate passive fire protection coatings applied to aluminum and composite panels for a Ship Structure Committee project [ref 38]. Panels were subjected to L/25 deflections for 10^6 cycles at 1 Hz. The test apparatus is shown in Figure 29. This device will be used to evaluate prototype sensors built in Task 5.

Figure 29. Panel Coating Fatigue Test Apparatus Developed for SSC-442 [ref 38]

The vibrations laboratory available to our consultant includes a test frame that can accommodate structures up to about 6 ft x 15 ft. It also incorporates a wide variety of vibration test methods and equipment, including:

- One portable (field capable) 8-channel Oros signal analyzer.
- One 16-channel Oros signal analyzer
- Several 2- and 4- channel analyzers
- Schlumberger step-sine analyzer
- Impact (hammer) and electrodynamic shakers (grounded and inertial)

The laboratory is stocked with a good variety of other standard testing equipment (memory scopes, transducers, strobes, etc.)

For routine impact testing (including modal analysis and damage detection testing), the equipment is portable, and has been used worldwide. In this case, the size of the structure is limited by the facilities offered by the parent organization.

Subcontractors/Consultants

Dr. Colin P. Ratcliffe is the co-inventor of the Structural Irregularity and Damage Evaluation Routine (SIDER), which is a SHM routine that identifies locations where there are variability in structural stiffness. He will act as a consulting subcontractor on this project to assist with the development of damage assessment protocols.

Prior, Current, or Pending Support of Similar Proposals or Awards

Eric Greene Associates, Inc. has no prior current or pending support of similar proposals.

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