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Wireless Systems Development for Distributed Machinery Monitoring and Control

Abstract

Over the past decade efforts have been underway to utilize wireless technology to enable higher functioning monitoring and control of machinery systems. The technologies associated with wireless communication have undergone a revolutionary evolution since the early 1990’s. This paper highlights the programs demonstrating the use of wireless technology for monitoring and control of shipboard machinery during the past 10 to 15 years at NAVSEA Philadelphia. This work includes the demonstration and testing of wireless systems hardware and software, and also the development of suitable architectures to fold such technologies into an overall ship machinery control and human interface that is highly functional and affordable.

Introduction

In the past twenty years the development of wireless technology has changed paradigms for communication systems. Since the early stages of the development of this commercial technology the US Navy has explored the possibilities of addressing shipboard requirements in machinery control and monitoring as well as survivability for the suitability of wireless communications.

Wireless communications offer several advantages over their wired counterparts in flexibility of communications points, reduced wiring, reduced installation costs, and other factors. Technical concerns include security and the general environment of the Navy ship and machinery spaces which can act as faraday cages that block wireless transmissions. While never viewed as a replacement for all Navy wired communications and sensors systems, certain applications present themselves as very favorable for the use of wireless communications.

To this end, presented below is a top down view of work done to better define an overall system architecture, and descriptions of wireless efforts accomplished to date that have proven the concept as well as provided the requirements for the use of wireless systems.

SHIPBOARD AUTOMATION ARCHITECTURE

Next generation Naval Ship automation systems will require a new paradigm in systems design. A much greater degree of systems engineering in the approach to requirements, design and integration is required. The required architecture segments common components of all automation systems, that are connected through defined interfaces, and integrated in such a way to provide real-time modeling and analysis capability. Total ship modeling will provide real time shipwide situational awareness, systems capability assessment and mission readiness – in an optimally manned environment.

HORIZONTALLY LAYERED ARCHITECTURE

The “Integrated Autonomic Ship” (IAS) concept was developed from a 1994 NAVSEA, Carderock Innovation Center Project. It addressed leveraging advanced computer technology to achieve total systems integration, automation and manning reduction in future ships. The concept integrated a distributed architecture with information technologies and modular systems. The modular systems utilized four integrated automated principles; 1) fault tolerant systems, 2) software objects, 3) ubiquitous computing and 4) task and functional analysis. Low-level control and monitoring is embedded in subsystems, freeing the operator from routine actions, and providing high-level information to assist the decision maker.

The Autonomic Ship further defined its horizontally layered architecture into four distinct layers: Operator, Software, Processing Resources, and Sensor/Effectors. This enables a whole new
systems integration approach – automation will not be structured by the task to be automated, but by the four main elements of ALL automation systems.

**Figure 1 – Autonomic Ship Concept**

**Technology Demonstrations**

What follows is a discussion of technology demonstration conducted by NAVSEA Philadelphia in the area of wireless sensing for machinery systems. Included are details of technology development and demonstration, and the considerable logistical and compliance issues required when working with or field testing such technologies. In the early stages of development, investments were not made in novel sensor development, but rather, innovative wireless sensor communication schemes, and work towards the interfaces required between wireless communications hardware and standard sensors. As advances from the commercial sector continue to come to fruition in both wireless communication and scavenged power, work has begun in developing sensors for lower power operation and lower cost.

**REDUCED SHIPS CREW-BY VIRTUAL PRESENCE (RSVP) FY99 ADVANCED TECHNOLOGY DEMONSTRATION (ATD)**

RSVP was a three year, $15M, proof-of-concept technology demonstrator for the DD-21 (now DDG-1000) program. The program was executed by NAVSEA Philadelphia, and was sponsored by the Office of Naval Research (ONR) Ship Hull, Mechanical, & Electrical Systems Science and Technology Division. RSVP demonstrated an intra-compartment, wireless shipboard sensor network as a prototype for the Sensor and Actuator layer.

RSVP evolved out of the ‘Smart Compartment’ concept in response to directives for reduced manning for DD-21. The goal was to remove the watchstanding required for monitoring machinery spaces. The RSVP program team chose to monitor four functional areas; environment, machinery, structural and personnel. It was anticipated that the directive for reduced manning aboard DD-21 would result in a requirement that would increase the number of shipboard sensors by an order of magnitude from the DDG 51 Class design. A wireless architecture would save installation costs and well as lifecycle costs in maintenance and reduced manning.

**Figure 2 – RSVP ATD**

RSVP built breadboard components using 1999 technologies – there were no common, affordable commercial-off-the-shelf (COTS) solutions at that time. The intent was to provide proof-of-concept.

Key attributes of the RSVP demonstration was the use of the commercial 2.4 GHz ISM band, low power electronics, low power transmission techniques, MEMS sensors, and power harvesting. The architecture pushed as much processing as possible down to the lowest level of the architecture. The RSVP architecture supported an autonomous system - self calibration, self diagnostics, self healing, graceful degradation, remote updates and minimal maintenance. Survivability and reliability were enhanced
through the dynamic reconfigurability provided by the wireless architecture.

**ADVANCES IN COTS WIRELESS TECHNOLOGY**

When the RSVP ATD hardware design was finalized and demonstration hardware manufacturing was begun, COTS wireless network equipment was not readily available. COTS wireless technology was so immature at this point that IEEE 802.11.b was not yet an approved standard. However, by the time the RSVP demonstration aboard USS MONTEREY (CG 51) occurred in 2001, wireless networking technology became available in consumer electronics and computer hardware stores. These COTS technologies emerged through the home computer industry, primarily aimed at short range peripheral components (Bluetooth – 802.15.11), and medium range LAN and WLAN access (WiFi – 802.11). Since then wireless network standards and hardware have continued to improve with higher bandwidth standards such as 802.11.g and improved security features such as Wireless Encryption Protocol (WEP). Another advance made available commercially in this timeframe were Zigbee devices, wireless transceivers designed for low power operation, and organization into ad-hoc mesh networks. Ad-hoc mesh networks allow sensors and communication devices to communicate using multiple paths making them very survivable to interference or failure of one of the devices.

While these advances in wireless networking standards and speed were an interesting development for the RSVP architecture, none were engineered for low power applications. Fortunately, the development of the IEEE 802.15.4 standard appeared to be the technology enabler for the RSVP architecture. The low bandwidth, low power, wireless sensor oriented design of 802.15.4 seemed to be a perfect fit for another required leap in technology for the RSVP architecture to become a reality – power harvesting.

**POWER HARVESTING**

During the requirements development for the RSVP ATD, it became fairly apparent that a ship with a reduced crew would not have the available manpower to perform maintenance on the thousands of wireless sensors that were installed to act as a force multiplier and crew reduction tool. This led to the RSVP requirement that the wireless sensor suite would be designed so that the life span of the sensor would typically be seven years or more, enough time to last between major overhauls of the ship. During a major overhaul the entire sensor suite would be replaced with a technology refresh of improved wireless sensor technology. It was also envisioned that wireless sensor technology would continue to rapidly advance and create obsolescence issues with the existing architecture and at the same time become inexpensive enough to warrant this type of comprehensive upgrade during an overall.

It was also noted that there would not be enough crewmembers on an RSVP enabled ship to perform battery maintenance on thousands of wireless sensors. The power supplies of RSVP wireless sensors would have to last the seven or more year lifespan of the sensor. Battery technologies have still not advanced far enough to meet the power requirements of the current generation of wireless sensors over the required life span. Additionally, power sources that required wiring would greatly impact the installation cost and would in effect make the sensor a wired sensor. If power cable installation was required, installation of a data cable at the same time could also be easily accomplished and the wireless requirement is no longer cost effective.

During the development of RSVP, initial research was conducted to determine if existing technology could be leveraged to eliminate all battery maintenance requirements over a seven-year lifetime. Power harvesting, sometimes referred to as power scavenging, involves converting readily available ambient energy sources to electrical power. The sources investigated during RSVP included electrical generation from waste heat with thermal electrics, ship structure and machinery vibration to electric power with
piezocrystals and induction, and photovoltaic technology. Photovoltaic sources were eliminated from consideration when an RSVP study of ambient light levels in the engineering spaces of a U.S. Navy ship revealed that the ambient light levels were not high enough to support the technology. During the RSVP ATD, MJR Scientific Corp. developed a vibration power harvester and Hi-Z, Inc. developed a thermal electric power harvester. These proof of concept demonstrators were both too large in size and too low in efficiency to be applicable to a small and cheap wireless sensor concept. However, both technologies showed that vibration and waste heat could generate electric power, and that more research was required to fully integrate this technology with a wireless sensor.

In 2002, NAVSEA Philadelphia acted as the TPOC for a Small Business Innovation Research (SBIR) topic N02-124, Power Harvesting for Wireless CBM Sensors. During the period of performance of this SBIR, COTS wireless technology had advanced far enough so that commercially available 802.15.4 radio sets were readily available. At the conclusion of Phase II, Microstrain, Inc. was able to demonstrate a prototype 802.15.4 wireless temperature and humidity sensor node that only utilized the machinery vibration as its source of power. The demonstration took place at the Virginia Advanced Shipbuilding and Carriers Integration Center (VASCIC) in Newport News, VA.

During the same time frame as topic N02-124, Program Executive Office (PEO) Ships, and the Office of Naval Research (ONR) sponsored the SBIR topic N02-064, Advanced Energy Scavenging. This topic led to the successful demonstration of an IEEE 802.15.4 accelerometer and temperature sensor integrated with a vibration based power harvester developed by RLW, Inc. The demonstration was done on the STAR Low Pressure Air Compressor (LPAC) at the DDG 51 Class Land Based Engineering Site (LBES) at NAVSEA, Philadelphia in 2005.

The efforts described above matured power harvesting technology for Navy machinery systems – bringing forward a critical piece of the RSVP architecture.

EMBER WIRELESS MESH NETWORK PROJECT

The Ember wireless mesh network project was an evolutionary step towards demonstrating mesh wireless networks, sensor/wireless node interfacing, and also providing a compliance/approval process for the demonstration and fielding of wireless technology systems on Navy ships. In the process of executing such a demonstration, work was also done in thinking ahead to how such a sensor network would fit into the larger machinery control and monitoring systems.

VENTURE CAPITALISTS AT SEA

In 2002, the ONR Commercial Technology Transition Office (CTTO) decided to work with a series of technology based venture capital firms as a pilot project to fast track technologies to Navy platforms. CTTO believed that venture capitalists and the entrepreneurial business community could provide valuable and accurate information as to advanced technology availability in the near and far term. CTTO also believed that this information needed to be clearly provided to shipbuilders and the Navy community, so they in turn could design their system with these enabling technologies in mind. To this end, in collaboration with PEO Carriers, CTTO sponsored the Venture Capitalists (VC@Sea) Program. A group of VCs rode aboard USS Coronado (AGF 11) in San Diego so they could observe first-hand how the ship operated and determine technology insertion opportunities.

By 2004, a series of technologies were selected by the VCs, and recommended to the PEO Carriers Venture Capital. A down selection to two technologies was performed – Voice Over IP and EmberNet. CTTO then brokered a ‘deal’ to put both technologies on a Carrier, with Northrop Grumman Newport News (NGNN) serving as the technology integrator.
EMBERNET

EmberNet is a Zigbee-ready network platform from Ember Corporation of Boston, Massachusetts. EmberNet allows products to communicate wirelessly in self-organizing, self-healing mesh-style networks. Ember manufactures wireless networking components, their products are not end products, but act as subcomponents to devices that are designed to communicate with each other. Developers buy an Ember ‘kit’ and build custom applications using the Ember wireless nodes. CTTO and PEO Carriers were investigating what type of application to build with the Ember nodes.

CTTO contacted NAVSEA Philadelphia after learning about the RSVP program. NAVSEA Philadelphia saw Ember as an ideal radio component of an all new shipboard wireless sensor network based on the RSVP architecture. NAVSEA Philadelphia proposed to PEO Carriers to remake the RSVP sensor cluster based on Ember, with the four original monitoring areas. Due to budgetary constraints, and the desire to conduct the test with as little intrusiveness as possible, it was mutually decided to build a sensor cluster for ‘heat stress’ monitoring only for proof of concept demonstration.

HEAT STRESS

Many shipboard spaces contain environments of high heat and humidity. Sustained high temperatures leading to heat stress conditions can lower work performance, impair mental alertness, increasing the risk of workplace accidents, and ultimately compromising the readiness of the ship. Heat stress is defined as any combination of work, airflow, humidity, air temperature, thermal radiation, or internal body condition that strains the body as it tries to regulate its temperature. The Navy mandates work-rest regimens, based on work activity, ambient temperature, humidity, and radiant energy to protect personnel who work in hot environments. These limits are published in OPNAVINST 5100.19 series, Chapter B2, Heat Stress Program. Heat stress conditions that are high enough to require work-rest rotations will impact manpower aboard ship, which is typically a key performance parameter on new ships.

Navy personnel exposed to high heat and/or highly humid environments are placed in a heat stress prevention program, which identifies safe Physiological Heat Exposure Limits (PHELS). In order to determine PHEL stay times for personnel who work in these hot environments, a Heat Stress Survey must be conducted. Conducting a Heat Stress Survey at each workstation within each "high heat" workspace currently requires using a portable, hand-held heat stress meter. A complete Heat Stress Survey, which measures the Wet Bulb Globe Temperature (WBGT) and determines the appropriate PHEL stay times in all required shipboard work spaces might take three to five hours depending on the size of the ship. The number of man-hours spent performing Heat Stress Surveys per year has been conservatively estimated at 3,300 for a destroyer and 5,800 for a carrier.

AUTOMATED HEAT STRESS MONITORING SYSTEM

An existing wired Navy Automated Heat Stress System (AHSS) has been developed and installed on some platforms. Automated Heat Stress Monitoring can save hundreds of hours spent on manually conducting HSS aboard ships. The AHSS measures dry bulb (DB) temperature, globe temperature, and relative humidity (RH) and calculates wet bulb temperatures from the known DB and RH. The software program derives a WBGT value, displays the appropriate PHEL stay times, stores the data in a spreadsheet file, and
prints the required information on a heat stress form.

PEO Carriers decided to leverage the VC@SEA feedback to utilize EmberNet to develop a wireless version of the AHSS. This would also demonstrate the general backbone technologies extensible to a total ship wireless sensor network, in essence a next generation RSVP. NAVSEA Philadelphia and Northrop Grumman Newport News (NGNN) decided to contract out node design to a commercial firm due to limited resources.

In 2002 PEO Ships sponsored a SBIR program to develop power harvesting for wireless sensor nodes (N02-124). One of the companies selected for Phase II was Microstrain, Inc of Burlington, VT. Microstrain had excellent commercial experience with wireless sensor technology, including the development and fielding of wireless strain sensors to monitor for further propagation of the Liberty Bell’s crack during the 2003 movement of the bell to it’s current location in Liberty Bell Center. In 2005 Microstrain successfully demonstrated that a wireless temperature and humidity sensor node could be powered by a vibration based power harvester during a Phase II demonstration at VASCIC. This experience would help Microstrain develop a battery powered wireless heat stress sensor for the PEO Carriers demonstration and would also lead to integration of the wireless heat stress sensor with power harvesting during the Phase II Option of SBIR N02-124.

**NAVY WIRELESS MORATORIUM**

A new obstacle was in place for the Ember program that did not exist when RSVP ended in 2001. In July 2004, the Naval Network Warfare Command (NETWARCOM) Network Security Division (NNWC-NSD) imposed a "wireless moratorium" for Navy platforms both afloat and ashore. This moratorium included but was not limited to "commercial wireless technologies and their derivatives, as standardized in IEEE standards 802.11, 802.15 and 802.16 commercial wireless devices, services and technologies and voice and data capabilities that operate either as part of the Navy enterprise network or stand-alone systems."

However, NETWARCOM also introduced a process for obtaining a waiver for wireless technologies that could be deployed under an Interim Authority to Operate (IATO). The DoD Information Technology Security Certification and Accreditation Process (DITSCAP) is a formal process that documents both risks and risk mitigation strategies for a wireless system. A System Security Authorization Agreement (SSAA) is created documenting a system’s architecture, risks and risk mitigation and reviewed to determine whether the system met the requirements of DoD Directive 8100.2, Use of Commercial Wireless Devices, Services, and Technologies in the DoD Global Information Grid (GIG).

**FEDERAL INFORMATION PROCESSING STANDARDS (FIPS)**

Key to DoDD 8100.2 is the mandated use of a security implementation for data encryption on all wireless networks on Navy platforms. As stated in 8100.2, "Encryption of unclassified data for transmission to and from wireless devices is required.... At a minimum, data encryption must be implemented end-to-end over an assured channel and shall be validated under the Cryptographic Module Validation Program (CMVP) as meeting requirements per Federal Information Processing Standards (FIPS) Publication (PUB) 140-2." The National Institute of Standards and Technology (NIST) published FIPS 140-2, Security Requirements for Cryptographic Modules, May 25, 2001. This standard describes the requirements that hardware and software products should meet for sensitive but unclassified (SBU) use. FIPS 140-2 compliance is mandatory for federal agencies and has become the de facto standard for industry.
FIPS 140-2 COMPLIANCE PROBLEM

The DITSCAP regulations were put into place to stop the proliferation of COTS wireless products that were being installed aboard ship by contractors and crews. The Navy knew it had a situation emerging where the risks of this new technology were not quantified.

The intent of the compliance process is to ensure that any wireless technology brought aboard a Navy platform has certain security mechanisms implemented, and is properly documented and supported. However, NETWARCOM had no guidance for a wireless Test and Evaluation (T&E) system aboard an active platform. To incorporate FIPS 140-2 into the Ember nodes was neither practical nor possible at that time. It would not have been prudent to build in a security layer to the Ember nodes until it was verified that the basic Ember Zigbee technology could actually communicate within and between ship compartments. There also was no commercial engineering solution for FIPS 140-2 integration, so one would have had to be developed from the ground up, and effort well beyond the time and resources of the program. The technology available in 2005 with FIPS 140-2 certification would drive the power requirements well beyond what was being considered low power for wireless – which was the intent of the architecture.

The program decided to proceed on parallel tracks. Microstrain would engineer and manufacture a 10 node wireless heat stress sensor set, working with NAVSEA Philadelphia heat stress domain experts and NGNN for design and evaluation. On the program side, NAVSEA Philadelphia and NGNN would draft an SSAA and submit it to NETWARCOM for approval to do a temporary test aboard an active aircraft carrier. It would be the first wireless system to ask for an IATO that did not have FIPS 140-2 certification. Doubt existed regarding the approach - if the IATO was not granted, no shipboard test would occur.

EMBER HEAT STRESS NODE DESIGN

MicroStrain utilized three sensors to perform heat stress measurements - a Relative Humidity (RH) sensor, a Dry Bulb (DB) sensor, and a Black Body Globe (BBG) sensor.

Microstrain developed a Heat Stress Monitoring (HSM) node that worked as a low power autonomous device. PHEL curves were calculated directly in the nodes, requiring only transmitted heat stress vectors, conserving bandwidth as well. The EmberNet radio provided wireless adhoc Mesh networking.

Figure 4 – Ember Node Design

By late 2005, MicroStrain had delivered 10 HSM nodes, in their final configuration and packaging, to NGNN to be tested at VASCIC. The nodes were installed in several mock carrier spaces, where humidity and temperature levels were varied. The spaces did consist of steel bulkheads, simulating a shipboard RF environment. Several machinery monitoring nodes were also added to the Zigbee network. Ember development software was run on an RSVP watchstation computer, and heat stress data as well as signal strength information were recorded.

EMBER LABORATORY TESTING

The VACIC lab wasn’t a complete substitute for a real shipboard environment. The spaces were not completely sealed to both RF and the environment. A complete test of the technology necessitated a demonstration in a ship space to see if they could communicate in challenging RF conditions and could collect real heat stress data. The initial laboratory results were very positive. Within the limited heat and humidity that could be
generated, the results were accurately measured and communicated. The viability of the RF communications was also surprisingly excellent. It was expected that putting low power wireless nodes in steel boxes would have major degradation due to possible EMI interference or blockage. This was not the case. It was then eagerly anticipated to install the HSMs in a real ship space to see the impact on connectivity.

**DITSCAP CERTIFICATION AND IATO**

During the testing described above, a team consisting of members from PEO Carriers, NGNN and NAVSEA Philadelphia was in negotiation with Program Management Warfare (PMW) Office 160 to obtain a recommendation to install the HSMs and run a temporary test aboard the USS GEORGE WASHINGTON (CVN –73). The DITSCAP certification required NETWARCOM to approve an SSAA, which would then lead to an IATO, with the final component the issuance of a wireless waiver message. The Ember installation also had to be approved through the Navy’s new SHIPMAIN program. SHIPMAIN is the Navy-wide surface ship maintenance and modernization program. A SHIPMAIN Ship Change Document (SCD) was required to be approved by PEO Carriers to permit the installation. The SCD process had recently replaced the TEMPALT/SHIPALT process.

Initial discussions with PMW 160 indicated that they would not recommend a non-FIPS certified system aboard an active platform. The Ember team presented the case that the Ember network was a standalone system – it did not, nor could not interface with any other information system. The system was acquiring only unclassified environmental information, and it would be a temporary, short term installation. It would be operated only by test personnel. In order to intercept, spoof, or interfere with the system one would have to be in close proximity to the nodes. This reality would indicate there would be much greater security implications due to an intruder in a ship compartment.

However, due to the lack of specific language in the DITSCAP instructions for the special conditions of a T&E program, approval was steadfastly refused. Compounding the programmatic was the fact that the SCD approvals were suffering from large backlogs due to the immaturity of the process and evolving procedures. A ‘catch-22’ finally occurred where the Ember SCD would not be approved by PEO Carriers without a signed SSAA, and the Ember team was informed by NETWARCOM that the SSAA would not be approved without ship installation approval. And the IATO would not be granted without a signed SSAA.

The Ember team considered going aboard a test ship, which would most likely get a waiver. However, no real heat stress data would be generated, rendering that option without value for PEO Carriers. The SSAA continued to be written, with a clear emphasis on the security mitigation features inherent in the system. It was finally decided to submit the SSAA to NETWARCOM anyway, and when the anticipated disapproval came, obtain the reasons for refusal. The team would then use the feedback to petition for the creation of official guidance for T&E of wireless systems. Finally the Ember MESH program SSAA was submitted to and vetted by PMW 160. Unexpectedly, it was approved by August 2006 - the whole process taking 10 months. The SCD, the IATO and wireless waiver message were then issued. The IATO was granted for one year, to accommodate unexpected changes in the ships schedule. In September 2006, the wireless moratorium was unexpectedly lifted. Systems would still require DITSCAP certification, however the requirement for a wireless waiver message was dropped.
SHIPBOARD INSTALLATION AND TEST

It was decided to install the HSMs aboard CVN-73 in four, non-critical, high heat/humidity spaces:

- Laundry (3-235-0-Q)
- Laundry (Dry Area) (4-235-0-Q)
- Steam Heat AC & R and Outside Repair Work space (4-238-2-Q)
- Self Service Laundry Room (4-235-1-Q).

The HSM mounts were attached with industrial strength adhesive to bulkheads to minimize impact to the ship and to facilitate removal. The HSMs wirelessly communicated to Wireless Access Points (WAPs) which then were wired to a central workstation.

RESULTS

The main purpose of the Ember MESH Program was to validate that a Zigbee MESH type sensor network would be operable aboard ship. It was a complete success in this objective. Full RF connectivity was realized to all HSMs, even between spaces and between decks, which was an interesting and unexpected result. The prevailing expectation that steel bulkheads would inhibit RF from transiting ship spaces was proven inaccurate. Unfortunately the ship only had minimal laundry operation due to the ships operational schedule while the system was aboard, so a wide range of heat stress data was not available. The system under went degradation tests, where nodes were deliberately removed from the network, or RF access was blocked, and the data was rerouted effectively. The system was removed in December 2006.

LESSONS LEARNED

The certification and compliance process was unexpectedly difficult. However, wireless systems guidance and processes are evolving. The rescinding of the wireless moratorium formalized DITSCAP as the guidance for IA certification and accreditation of DoD information systems. The finalized guidance is evolving into the DoD Information Assurance Certification and Accreditation Process (DIACAP).

The approval of the Ember SSAA is a precedent for continued R&D for wireless systems for Navy platforms. There have been many Navy-funded wireless sensor projects that are declaring laboratory testing as successful completion, however they have not transitioned to shipboard testing due to the rigors required in the SHIPMAIN process. Without a shipboard test these projects transition to new construction is difficult.

Technologically, the demonstrations described above showed how commercial wireless technologies are now beginning to provide enabling technologies to ship builders and designers. Technical requirements that became very apparent included powering of sensors, survivable networking, security of wireless sensor
signals, and sensor-wireless communication interfaces.

**Future Efforts**

There are other aspects of this technology that have to be further developed to realize the RSVP concept of a sensor network. Regarding the Ember demonstration the Wireless Access Points required AC power, and the nodes were powered by replaceable batteries. As a result of the HSMS low power design, the nodes operated continuously for about 30 days. Further development of power harvesting technologies will be required to remove the requirement for battery replacement. In addition to development of power harvesting technologies, emphasis now has to be placed on the wireless transceivers and the sensors they are coupled with to provide for low power operation.

**RSVP II**

RSVPII is a current effort continuing the development described above. Aepco, Inc. of Gaithersburg, MD, is engaged in a project with NAVSEA Philadelphia to demonstrate the next step in enabling technologies for the RSVP vision. RSVP II is the result of an additional congressional appropriation to ONR, to further continue the work of the ATD.

RSVP II proposes to fabricate and demonstrate an ad-hoc wireless mesh sensor network that is reconfigurable, is fully FIPS 140-2 compliant, and shows a generic sensor interface so the system can be used with any COTS sensor. By using the latest COTS equipment, the project is designed to provide affordable enabling wireless sensor & network technology to the Navy.

**Transition To The Fleet**

As wireless technologies become bona fide enablers for shipboard machinery systems, shipbuilders and OEMs will be free to address shipboard requirements with them. A number of requirements for shipboard use have been under investigation to this end.

One pressing issue is that of cabling and power. Wireless sensors eliminate the need for signal cabling, but cables are still required to supply power to the sensor. Tetherless (completely wireless) sensing, where no cabling at all is required, maximizes the wireless sensor’s location flexibility but raises issues (both technical and logistical) in powering. To power wireless devices with no power cable, either batteries or a power scavenging system must be used. Batteries can provide sufficient operational life if the sensor and communications do not draw too much power. Since sensor power demand varies widely, this needs to be analyzed on a case by case basis. Also, with the number of sensors projected for ships such as the DDG-1000 there are concerns as to the cost and logistics to carry sufficient numbers of batteries to supply the wireless sensors and access points.

ONR and NAVSEA Philadelphia have been working with PEO Ships and PEO Subs to advance power harvesting technology. N02-124 was a PEO SHIPS sponsored SBIR to develop vibration and thermal power harvesting for a wireless sensor. As previously discussed, Microstrain was able to demonstrate that peizocrystals could be used to power a temperature and humidity sensor. Future plans include testing of additional Microstrain WHSMs with power harvesting at the US Navy’s DDG 51 Class Land Based Engineering Site (LBES) at NAVSEA Philadelphia.

ONR, PEO Subs 450 and NAVSEA Philadelphia are currently administering STTR N064-020, *Power Harvesting for Encrypted Wireless Sensor Clusters*. This STTR entered Phase I in August 2006 after five Phase I contracts were offered after review of 28 Phase I proposals. It is expected that one company will be selected for Phase II in early 2007. The goal of this topic is to develop technology that can utilize ambient energy found aboard ship (vibration, thermal, light) to eliminate battery maintenance requirements for a wireless node with two or more sensors, an expected life cycle of at least seven years and a wireless communications link that is FIPS 140-2 certified. This is a very challenging concept that if successful will be a large enabler for an RSVP architecture.
Conclusion

A shipboard wireless sensor network only provides value in the context of the architecture in which it is incorporated. It is not a standalone system in itself; it is just one possible aspect of a next generation machinery monitoring and control system. Naval ship design as mandated by NAVSEA is no longer the process for building ships. Performance specifications are given to the Program Executive Offices and industry shipbuilders, whose goal it is to meet those metrics with an architecture of their choosing.

Machinery monitoring and control is accomplished with sensors and instrumentation. As shipboard machinery systems evolve (e.g., electric ship concepts, reduced manning, lower cost operation, extension of operating time, greater automation) so too do shipboard sensor and communication systems. The work highlighted above, to that end, attempts to push commercial technologies towards Navy shipboard machinery requirements, while at the same time addressing higher level ship wide information system architectures. As these sensor & communication systems become operationally proven, they become a valid option for the ship designer or original equipment manufacturer to attain their specific technical goals.

References

2) Navy wireless networks—FIPS 140-2 or bust!, CHIPS, July-Sept, 2005 by John MacMichael

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