SSC Project Recommendation for FY 2018

Exploring the Suitability of COTS Structural Health Monitoring Hardware and Software for Naval Use

1.0 OBJECTIVE.

1.1 This effort proposes to investigate the long-term practical use of the commercial off-the-shelf (COTS) structural health monitoring (SHM) sensors and data acquisition hardware. In particular, a recently licensed guided wave SHM system will be investigated, along with the corresponding data analysis, sensor placement optimization, and data acquisition algorithms and software.

2.0 BACKGROUND.

2.1 The process of implementing a damage detection and characterization strategy for engineered structures is referred to as structural health monitoring (SHM) [8.1]. Current ship inspection procedures rely on visual inspection and other traditional nondestructive evaluation (NDE) techniques such as liquid penetrant inspection, magnetic inspection, eddy-current inspection, radiography, or ultrasonic inspection to detect damage [8.2]. In particular, visual damage inspections are tedious, can easily bypass or mischaracterize damage, and can be very intrusive to the ship. In areas prone to damage or difficult to access with respect to NDE techniques, SHM may provide a complimentary solution to traditional inspection methodologies. SHM has the potential for reducing the cost of inspections, identifying changes in material state, and developing repair plans for surface ships.

2.2 SHM sensor development has been an active area of research for many years, but ruggedized, COTS SHM systems which have been proven effective and validated in relevant maritime operational environment are generally limited to systems with only basic measurements of ship strain or acceleration. These systems are typically not capable of detecting damage before it grows to a potentially problematic magnitude. Previous SHM research for shipboard applications revealed the ability of active SHM techniques to detect damage in relevant ship construction materials and structures [8.3, 8.4, 8.5]. However, the conducted research and design processed revealed the perceived benefits of utilizing COTS products as opposed to the often tedious administrative burden of developing technology solutions in-house. Also, sensors and data collection hardware comprise just one part of a total health monitoring system necessary to provide a coherent representation of ship structural status. Optimal sensor placement locations, data collection and retrieval, data processing and damage detection algorithms, and reporting of relevant results all need to be considered.

The testing proposed here looks to build upon previous maritime SHM studies to determine if COTS hardware is suitable for inclusion in larger shipboard health management systems. Recently, a guided wave-based SHM system was licensed for commercial sales and support [8.6]. Lab testing will use surrogate 'representative' structural components, that include typical ship structural details, in a controlled test environment designed to focus on the holistic performance of the SHM 'system' from the sensor through the analytics and visualization or graphic interface. Long duration lab testing will provide data to validate updated configurations and/or further improve hardware and firmware designs. The product proposed for evaluation is a complete commercial damage detection and localization SHM system based on a piezoelectric phased array sensor package which employs Lamb-wave propagation that actively excites the structure, much in the same manner as a traditional sonar system, but in solid material. At a TRL level of 6+, the SHM hardware and arrayed sensors are particularly well suited for sensing changes in plate structure with a relatively low sensor density as compared to other sensor approaches. The proposed testing efforts will re-evaluate the system-level maturity and stability of the new commercially available technology while conducting controlled testing on structure of relevant complexity. This serves to improve familiarity and confidence with the analytics and visualization of the data sets before attempting shipboard measurements. The goal of this proposed work is to fully enable use of the entire SHM package (hardware and software) for shipboard usage while reducing reliance on costly external support.

3.0 **REQUIREMENTS.**

3.1 The proposed test effort will leverage fabricated structural components, and, as much as possible, experimental testing already scheduled to take place during the period of performance. The test plan aims to build confidence in the COTS hardware by increasing structural complexity over the course of the program. The first test structure will consist of a welded joint undergoing either quasi-static ultimate failure or fatigue loading. The specimens will be representative of a normal Navy structural detail or component. Work on similarly-sized structures demonstrated the feasibility of guided wave detection in welded aluminum structures [8.4]. Articles will include several typical structural details and also challenge the sensors and analysis algorithms to interrogate across weldments and transverse structure typified in a shipboard installation. Before testing, a baseline measurement will be taken before applying the first loads. The COTS tools will be used to independently detect the existence and location of any cracks or defects in the specimen. The SHM equipment will also be used to determine the degree to which damage growth can be detected and quantified. Once confidence is gained with the SHM system on the intermediately-sized structures, the system will be installed on a much larger ship grillage. The grillages to be tested will be cut out of a decommissioned ship. After failing under compressive loading, it is expected the grillage will be further exercised in both tension and compression to generate additional structural defects. Instrumenting grillages with COTS SHM hardware will provide an accurate representation of actual ship structure for validation of the complete SHM system.

Testing will focus on the performance of the holistic SHM system, not just the performance of the sensors, to assess viability for shipboard use of all system components as follows:

3.1.1 The Contractor shall conduct an assessment of the SHM firmware and software to examine system reliability and robustness. The system will be setup in a manner to interrogate all of the instrumented test articles throughout the serial completion of the test matrix. The data acquisition system (DAQ) must remain running for a period of several weeks, allowing effective evaluation of the firmware reliability. Efforts will be taken to challenge the stability of the system in manners likely to be experienced on the vessel to include dropping/impacting acquisition nodes, disrupting power to the system UPS and/or varying source power quality, temperature variations, and moving/stressing electrical connections. The corresponding software has a number of features which will be explored in addition to the damage visualization tools.

3.1.2 The Contractor shall perform SHM data management and analytics. Prior testing has demonstrated the effectiveness of the sensors to collect useful data, but those efforts required extensive post-processing of the data by the vendor over the course of weeks. The acquisition of large data sets has little value without the post processing required to extract features sensitive to damage from the raw data. This test series will evaluate the capacity of the COTS software tools to collect and manage data, but more importantly, the ability of the software to quickly analyze the data onsite when operated by ship maintainers. Additionally, this assessment will determine the degree to which this data can be assessed near-real-time as would be desirable in order to minimize costs and maximize feedback to ship crews from a long-term deployed system. Data management and the usefulness of the gained knowledge is the largest technical hurdle to long-term shipboard deployment and practical usability for SHM use on naval or commercial vessels. Capabilities and gaps noted from this portion of the assessment will be critical in either guiding further design efforts by the vendor, or informing the end users where investment would be required to develop in-house tools or capabilities to close the gap.

3.1.3 The Contractor shall establish a working data collection architecture. One of the unique features of the COTS SHM system architecture is the ability to modularize the sensor system into 'zones' that are highly scalable and can locally collect and digitize signals from multiple sensor signal types (such as strain, temperature, and acceleration) in addition to guided waves. This functionality has great potential to streamline shipboard data acquisition efforts and provide the capability to grow or scale the architecture in a highly-dynamic and flexible manner. However, this capability has not been assessed for shipboard usage. This effort will look to make strain and temperature measurements on each test specimen in addition to the guided wave measurements. Strain measurements will be made continuously throughout the test, but the temperature measurements will only be taken during guided wave measurement intervals. These measurements will also be made at different sample rates between sensor types as might be expected during shipboard measurements.

3.1.4 The Contractor will further investigate the SHM sensing capabilities. There will be particular emphasis is attempting to determine how accurately the nucleation of a crack can be detected by these sensors both as a function of time (when the crack appears) and location (the geometric location of the crack tip). Both of these factors are critical to assess the value of data from this type of system on decision making. Once the cracks appear and are detected, the testing will continue to determine how effective the sensors and COTS software suite can be at quantifying the growth of a known defect. This could be particularly useful by providing remote data to support assessment of critical crack length without the need for periodic manual inspections.

3.2 Tasks.

3.2.1 The Contractor shall investigate the viability of COTS SHM software for maritime use. Numerical models of the testing structures will be generated and imported into the SHM hardware. The sensor placement optimization portion of the software will be assessed, as well as the tools for optimal data acquisition parameters (frequencies of interest, number of averages, etc.).

3.2.2 The Contractor will instrument welded test articles in at least two sensor node configurations.

3.2.3 The Contractor will conduct SHM measurements before and during testing. Prior to each test, several baseline measurements will be acquired. The SHM system will not be deactivated or powered down until the completion of each test in order to evaluate the stability impacts of improvements to the firmware and software. An additional test article will be used to determine the impact of operational loading on the SHM process by collecting guided wave data during any extended fatigue testing.

3.2.4 The Contractor shall analyze the collected data, report the results, and modify testing parameters as necessary. Initial setup of the damage detection software is critical in assessing if COTS SHM software will be useful for maritime applications.

3.3 This effort will be performed in one calendar year from the date of contract award. A spreadsheet containing the cost and time estimates can be seen in Enclosure (A).

3.3.1 SHM Software Investigations and Planning: 2 months
3.3.2 Instrumentation of Test Specimens: 3 months
3.3.3 Testing Support: 4 months
3.3.4 Data Analysis and Reporting: 5 months

4.0 GOVERNMENT FURNISHED INFORMATION.

4.1 Standards for the Preparation and Publication of SSC Technical Reports.

5.0 **DELIVERY REQUIREMENTS.**

5.1 The Contractor shall provide quarterly progress reports to the Project Technical Committee, the Ship Structure Committee Executive Director, and the Contract Specialist.

5.2 The Contractor shall provide a print ready master final report and an electronic copy, including the above deliverables, formatted as per the SSC Report Style Manual.

6.0 PERIOD OF PERFORMANCE.

6.1 Project Initiation Date: date of award.

6.2 Project Completion Date: 12 months from the date of award.

7.0 GOVERNMENT ESTIMATE. These contractor direct costs are based on previous project participation expenses.

7.1 Project Duration: 12 months.

7.2 Total Estimate: $100,000

7.3 Table of Cost and Time Estimate can be found in Enclosure (A).

8.0 REFERENCES.

8.1 Farrar, C. R., and Worden, K. 2007. "An introduction to structural health monitoring," *Philosophical Transactions of the Royal Society A*, Vol. 365, pp. 303–315.

8.2 Doherty, J. E., 1987. "Nondestructive Evaluation," Chapter 12 in: Kobayashi, A. S. (Edt.), *Handbook on Experimental Mechanics*, Prentice-Hall, Inc., Englewood Cliffs, NJ.

8.3 Grisso, B. L., Salvino, L. W., Singh, G., Singh, G, Tansel, I. N., 2011a. "A comparison of impedance and Lamb wave SHM techniques for monitoring structural integrity of and through welded joints," Proceedings of SPIE Volume 7984.

8.4 Grisso, B. L., Park, G., Salvino, L. W., and Farrar, C. R., 2011b. "Structural Damage Identification in Stiffened Plate Fatigue Specimens Using Piezoelectric Active Sensing," Proceedings of the 8th International Workshop on Structural Health Monitoring, September 13-15, Stanford, CA, pp. 1683-1690.

8.5 Grisso, B. L., 2013. "Development of a Structural Health Monitoring Prototype for Ship Structures," Ship Structure Committee, SSC-468.

8.6 "UTC Aerospace Systems Acquires License for Structural Health Monitoring System." Accessed January 10, 2017. http://www.utc.com/News/UTAS/Pages/UTC-Aerospace-Systems-acquires-license-for-structural-health-monitoring-system-te.aspx.

9.0 SUGGESTED CONTRACTING STRATEGY.

9.1 Contracting strategy.