SSC Project Recommendation for FY 2020

Digital twin methodologies for the integration of hull monitoring systems with physics-based models to support ship operations and service life extensions

1.0 OBJECTIVE.

1.1 The objective of this project is to investigate methodologies for coupling physics-based models with structural health monitoring (SHM) data in order to (1) support fatigue life assessments and corresponding condition-based maintenance and service life extension decisions, (2) provide operator feedback to minimize the risk of global or local failures due overload.

1.2 An additional objective of this project is to provide a discussion on the process of establishing low sensor density hull monitoring systems (HMS) for a platform.

2.0 BACKGROUND.

2.1 The broad concept of digital twin has been introduced as a framework for integrating available structural health monitoring data with multi-scale, multi-physics, probabilistic models that can be used to help track the status of assets and aid in decision support [8.1, 8.2]. The challenge in the digital twin framework is the depth and breadth of the scope of the topic. Data can range from hand-written notes on the corrosion wastage of plating to 3-D point cloud data developed from scanning the surface of a plate with deformities and out-of-planeness to strain gauge data to motions data and more. The concepts should be applicable to a broad range of platforms for small craft to 500-1000ft vessels. Furthermore, physics-based models for evaluating hull performance can be static finite element (FE) models, computational fluid dynamics models, fluid-structure interaction models, crack growth models, etc. While the scope can be overwhelming, it is important to focus on what can be gained through developing the digital twin framework. This project will focus on two main concepts: (1) how digital twin can aid in the fatigue assessment of vessels and (2) how digital twin can assist in the operational use of ships by providing warnings for overload events.

2.2 In the design of ships, fatigue damage assessments are based on assumed operational environments and stress developed with FE models [8.3]. The actual ship operations, observed conditions, and structural response will be different from design estimates and will vary from ship to ship within a class [8.4]. This uncertainty in what has actually been observed is one of the major limitations in provided engineering-based support for maintenance deferrals and service life extension decisions. Thus, a SHM system is essential for quantifying the lifetime observed responses. However, there are many fatigue critical details on a ship and instrumenting all would be infeasible. The available measurements must therefore be coupled with a FE model in the digital twin framework in order to estimate the response of fatigue critical locations and inform inspections and service life extensions.

2.3 The structural integrity of the vessel is also governed by the ability of the structure to withstand extreme loads. A seasoned operator may be able to identify when conditions have a high potential for structural or subsystem damage, but others may not. SHM systems and the digital twin framework can be utilized to assess the current loading condition on the ship and evaluate the potential for local and global failures due to overload. Providing a capability to assess this risk on the platform and provide decision aids to the crew that may help the crew alter their operations to minimize risk, prevent the costly repairs associated with failures, and enable the continued operation of the ship.

2.4 Current efforts have focused on the use of GPS data coupled with regional wave data to inform environmental estimates for a ship to better characterize the operational use of the ship [8.5].

Furthermore, algorithms have been developed to use shipboard motions data to estimate the environment in a ship-as-a-wave-buoy approach [8.6]. While these methods represent a major improvement on the knowledge of the use of the ship, they focus primarily on data regarding environment. This project focuses on the use of response data, i.e. strain gauge measurements, and the digital twin approach for supporting management and use decisions.

2.5 As the DoD is actively undertaking the Industry 4.0 paradigm shift towards the use of large data sets to provide previously unobtainable, real-time insights into numerous systems, processes, or assets, the 2018 Digital Engineering Strategy (DES) serves to "guide the planning, development, and implementation of the digital engineering transformation across the DoD." [8.7] Furthermore, the recent shift towards weight-optimized hulls and the introduction of novel hull forms into naval vessels has led to less inherent conservatism in structural capacity and an uncertainty in loads on the structure in littoral or open ocean operations. A large component of the digital transformation and safe operations and maintenance of these ships is the development and employment of digital twins.

2.6 This project proposes a digital twin framework for integrating SHM data with an FE model that accounts for the uncertainties inherent in the process and can be used to support fatigue and overload assessments and decisions. This project will utilize existing full scale trials data as a platform to verify and validate the approach and demonstrate associated capabilities.

3.0 REQUIREMENTS.

3.1 Scope.

3.1.1 The Contractor shall perform a literature review on the methods for incorporation of strain gauge data with global FE models to support condition based maintenance, service life extension, and operations. An emphasis shall be placed on the methodologies for estimating global loads and developing basis vectors for estimating unobserved responses.

3.1.2 The Contractor shall identify and develop methodologies for utilizing SHM data with FE analysis to support fatigue damage accumulation estimates in the digital twin framework. This methodology shall be developed around the expectation that it be used to inform service life extensions and be performed in a near-real time environment. The methodology shall account for the uncertainties inherent in the process.

3.1.3 The Contractor shall also identify a methodology for estimating the likelihood of exceeding structural damage thresholds in-near real time based on SHM data. This methodology shall be developed around the expectation that it be used to inform operational guidance and be performed in a near-real time environment. The methodology shall account for the uncertainties inherent in the process.

3.1.4 The contractor shall utilize available rough water trials data to demonstrate the approach. The Contractor shall provide a methodology for identifying a low sensor density HMS system.

3.2 Tasks.

3.2.1 The Contractor shall perform a literature review of relevant technical documents.

3.2.2 The Contractor shall refine and evaluate an existing finite element model for the particular vessel, load the model with respect to the relevant global loads, develop calibration factors to be used to estimate global loads, and establish the basis vectors for estimating unobserved responses (i.e. stresses at critical locations). The establishment of dynamic response characteristics (i.e. mode shapes) shall be investigated as an alternative to a global loads basis.

3.2.3 The Contractor shall develop the methodology to estimate global loads acting on a ship and the stresses at unmonitored locations. The developed methodology shall be integrated with fatigue damage models and assessments for individual platforms based on the actual operational use and response of the ship. Attention shall be given to the uncertainties associated with the digital twin framework.

3.2.4 The Contractor shall develop and demonstrate the applicability of an algorithm for utilizing near-real time SHM data to assess the probability of exceeding structural thresholds for damage within a future period of time.

3.2.5 The Contractor shall review the full-scale data available for the ship from the rough water trials. A quality check on the data shall be performed to identify and remove any quality issues including drift, interference, and spurious points. The data shall then be divided into two data sets. The first will include the data collected for the measurement of global loads. The second will include the data collected at stress concentrations. By separating the data set in such a way, the first data set can be coupled with the digital twin framework in order to estimate the response at stress concentrations. The results can then be compared with the second data set in order to validate the approach.

3.2.6 The Contractor shall compare the response estimated through the integration of the digital twin framework and the first data set with the second data set. The Contractor shall investigate the sensitivity of the methodology to the available data set and establish a methodology for the selection of a set of sensors a long-term HMS based on the objectives for the system, the uncertainties and accuracies introduced in the digital twin approach, and the cost of the system.

3.3 Project Timeline.

	Month																	
Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3.2.1																		
3.2.2																		
3.2.3																		
3.2.4																		
3.2.5																		
3.2.6																		
Reporting																		

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: 18 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: 18 months.

7.2 Total Estimate: $100,000

7.3 The Independent Government Cost Estimate is attached as enclosure (*1*).

8.0 REFERENCES.

8.1 Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA*. p. 1818.

8.2 Tuegel, E.J., Ingraffea, A.R., Eason, T.G. and Spottswood, S.M. (2011). Reengineering aircraft structural life prediction using a digital twin. *International Journal of Aerospace Engineering*, 2011.

8.3 Sieve, M.W., Kihl, D.P., & Ayyub, B.M. (2000). Fatigue Design Guidance for Surface Ships. *NSWCCD-65-TR–2000/25*, Naval Surface Warfare Center Carderock Division, West Bethesda, MD, USA.

8.4 Stambaugh, K., Drummen, I., Cleary, C., Sheinberg, R., & Kaminski, M. L. (2014). Structural fatigue life assessment and sustainment implications for a new class of US coast guard cutters. *Ship Structure Committee*.

8.5 Thompson, I.M., (2018). Virtual Hull Monitoring: Continuous fatigue assessment with additional instrumentation. *International Journal of Maritime Engineering*, 160, pp.A293-A297.

8.6 Nielsen, U.D. (2017). A concise account of techniques available for shipboard sea state estimation. *Ocean Engineering*, 129, pp.352-362.

8.7 US Department of Defense (2018) *Department of Defense Digital Engineering Strategy.* Office of the Deputy Assistant Secretary of Defense for Systems Engineering, Washington D.C.