Undersea Weapon Design and Optimization

James Griffin and William A. Kusmik
Naval Undersea Warfare Center
1176 Howell Street
Newport, RI 02841

Abstract

Undersea weapon development initiatives must not only enhance the military utility of the design-of-record weapon system, but must also serve to reduce ownership cost and increase system reliability. This paper will describe an Undersea Weapon Design and Optimization (UWDO) environment that has reached a sufficient state of maturity to enable the value-based assessment of new capabilities to be introduced within the framework of incremental upgrades to existing United States (US) Heavyweight torpedoes. UWDO is designed to support the concurrent development of systems that can be readily integrated into current US heavyweight torpedoes and the continuous assessment of emerging technologies to allow for potential early transition of high payoff technologies to the Fleet while sustaining the development of technology areas critical for next generation weapons systems, those which will address the challenges of warfighting in the 21st century. This paper will also highlight the potential value of the UWDO knowledge base for new acquisition strategies including the Advanced Processor Build (APB) and Hardware Technology Refresh and Insertion (HTRI) Process.

Introduction

Meeting the threat posed by ever more sophisticated submarines, torpedoes and countermeasures requires the development of a next generation torpedo with significantly increased effectiveness. At the same time, performance trade-offs will be required to provide the requisite functionality within budget constraints and technology limitations. In an environment of declining defense budgets, significant reductions in turn-around and lifecycle costs (LCCs) are also needed to maintain Fleet proficiency. The introduction of new systems into the torpedo inventory must provide the advantages of significantly reduced ownership cost and increased weapon reliability. In the current cost-constrained environment this will require an assessment of "optimal value," a metric that combines cost and technical performance.

Simulation Based Design (SBD) couples modeling and simulation information with enhanced information management and analysis capability to provide a validated, high fidelity design synthesis and optimization resource that is not reliant on the fabrication and testing of physical hardware. The resulting virtual prototyping capability dramatically increases the responsiveness of the advanced technology development and acquisition process to emerging military threats and streamlines technology transition to the Fleet. SBD enables the timely, engineering-based identification of high payoff technologies to support an agile, performance-driven detailed design process that ensures the rapid convergence on the optimal design solution.

To achieve these objectives for Undersea Weapons and Unmanned Undersea Vehicles (UUVs), the Office of Naval Research (ONR) has created a program focused on the development of an UWDO environment. The UWDO environment currently under development has reached the state of maturity required for the value-based capability assessment within the framework of incremental upgrades to existing US Heavyweight torpedoes. UWDO is designed to support the development of systems that are compatible with current US heavyweight torpedoes to drive the timely transition of emerging technologies to the Fleet and the integration of additional technology areas to enable the development of a comprehensive new weapon system, one that will address the challenges of warfighting in the 21st century.

UWDO Environment

The UWDO environment must ultimately provide a set of tools for exploring design options and their impact across the entire product lifecycle rather than being limited to the hardware development process itself (Figure 1). While analysis tools have long existed to address specific issues that emerge during the hardware design process, the effective utilization of UWDO requires that these tools be restructured to support exploration of a design space rather than simply the assessment of a heuristically-derived point design. The UWDO environment is structured into four major components; Warfare Simulation, Design Space Exploration, Lifecycle Analysis and Multi-Disciplinary Optimization.

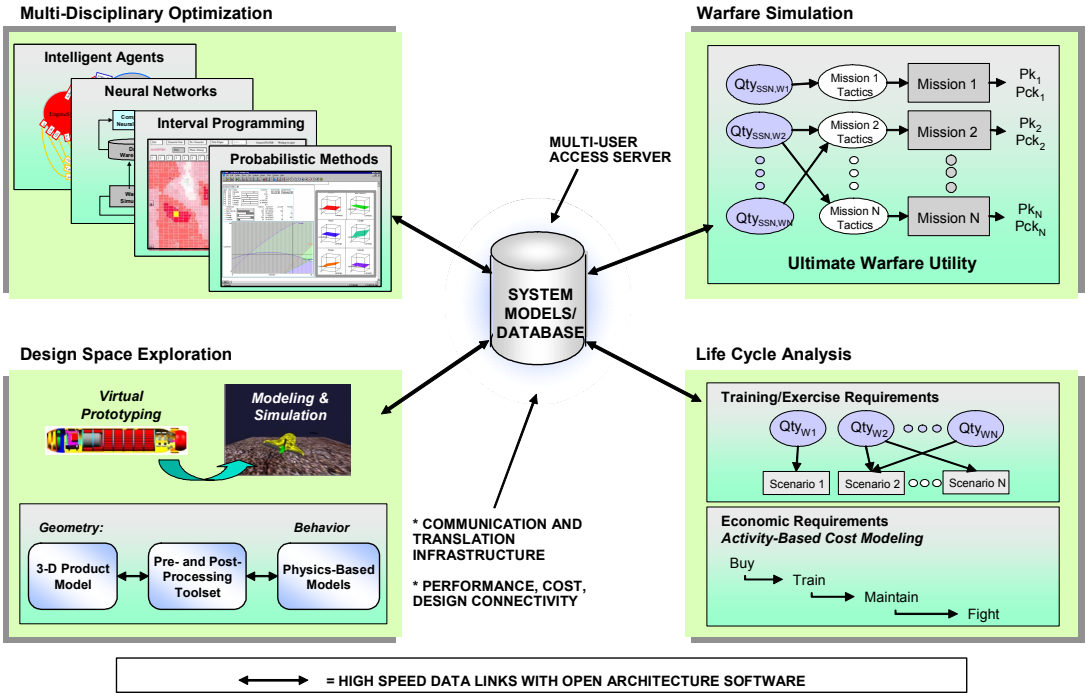

Figure 1. UWDO Environment

Warfare Simulation

Warfare simulation and analysis provides the domain expert with the capability to explore the value of system technical requirements in terms of battlefield performance. Historically this linkage has been sustained by postulating a specific capability and then performing an extensive set of simulations to judge its impact on mission performance. The UWDO implementation restructures the software tools to allow the flexible exploration of the design/effectiveness trade space. In the UWDO environment, the domain expert is able to explore the marginal change in warfare capability that accompanies modifications to the technical requirements required to reduce development risk and/or cost of ownership. Configuring the warfare analysis software in this manner also enables the automated exploration of the performance space and the utilization of numerical optimization techniques.

The Advanced Collaborative Engagement Model (ACEM) simulation is a research-oriented tactical vehicle simulation that relates torpedo design parameters to operational effectiveness in a manner that closely parallels the functionality of accepted analysis models including SIMII and Torpedo Requirements Model (TRM), ACEM (1). However, it is uniquely structured to support integration with the UWDO architecture and is used to generate complex nonlinear datasets to support Multi-Disciplinary Optimization (MDO) methodology development. Specifically, it is configured to support the continuous optimization of both the engineering and tactical vehicle characteristics in response to changing military threats.

Design Space Exploration

Design Space Exploration encompasses the solids-based design environment coupled with the Physics Based Modeling (PBM) capability that supports the conceptual and detailed design process. In the UWDO environment, models are seamlessly integrated to provide a comprehensive virtual prototyping capability. The process has been structured to support the automated or semi-automated discretization of continuum models for rapid identification and assessment of high payoff system alternatives. Critical system attributes that span multiple disciplines, including kinematics, vibration and stress analysis, thermal analysis, acoustics, electromagnetics and hydrodynamics are concurrently addressed from a system-level perspective. As noted for the warfare analysis capability, these tools have been restructured from their conventional form to support exploration of the design space versus assessment of a point design.

Lifecycle Analysis

The most critical and complex aspect of UWDO is the process for assessing lifecycle impacts of design decisions. While cost of manufacture is well understood, the complexities of lifecycle logistics can defeat well-intentioned attempts to mathematically quantify the "cost of ownership" associated with deployment and sustainment. For example, a simple cost of ownership modeling tool might ignore the costs associated with deploying multiple variants of a particular system or subsystem or miss the impact that periodic maintenance requirements might have on bunkered weapons. These challenges are, to some degree, addressed by new acquisition strategies including the APB and HTRI in which spiral development is achieved through pre-planning for incremental upgrades to allow deployed systems to keep pace with technology development with minimal impact on upgrade and deployment costs. The APB and HTRI process provide a framework in which lifecycle analysis can be bounded to perform design optimization iterations from a value perspective, NUWC (2).

The high fidelity prediction of the Total Ownership Cost (TOC) for next generation undersea weapon systems requires an integrated set of cost models that enables the concurrent assessment of the impact of both the design attributes of the field systems themselves and the associated operational and support processes. Particular emphasis must be placed on the identification of key cost drivers prior to design commitment, providing real-time visibility into the cost, benefit and risk of potential engineering changes, and the development of automated and expert-in-the-loop decision aids to support timely, information-based decision making.

Multi-Disciplinary Optimization

The MDO component of the UWDO environment is focused on the development of methodologies and tools that enable the timely development of highly effective, inherently affordable undersea weapon systems. MDO from the undersea weapon design perspective refers to both the rapid convergence on optimal next-generation solutions and the continuous improvement of fielded systems. The UWDO environment includes a suite of complementary optimization tools that leverage an extensive optimization environment originally developed by Georgia Tech for aircraft design, Frits, et al (3). Additional tools for design space exploration and optimization have been developed for UWDO by transitioning algorithms originally designed for automated tactical decision making and agent-based constructs developed in support of distributed autonomous undersea vehicles. The UWDO environment currently incorporates a design agent architecture that enables the creation of intelligent agents that can mediate between subsystem design requirements to support the optimization of complete systems and a neural network tool that supports system-level optimization.

Cooperative Agent MDO: Cooperative Agent MDO leverages research funded by the Office of Naval Research (ONR) under the Very Shallow Water/Surf Zone Mine Countermeasure (VSW/SZ MCM) Autonomous Operations program. This research is focused on the group control of multiple autonomous vehicles that cooperate to perform a reconnaissance mission. Under this effort, NUWC with university partners has been developing behavior-based group control.

NUWC teaming with the Robotics Group at University of Southern California has taken the commercially available Ayllu behavior-based group control tool, which can be linked with any C program, and produced a NUWC version called ChaCha. In NUWC's implementation of ChaCha, extensions and enhancements were made beyond Ayllu for real-time behavior processing and additional port operations. A ChaCha shell allows independently written controllers/models to use ChaCha port arbitration features to communicate between agents. It is this capability that we are using as the initial framework for the cooperative agents effort (Figure 2). Much like the cooperative behavior of multiple vehicles, we would apply this framework to the cooperative behavior of multiple software agents with extensions to support the MDO process.

Currently, the cooperative agent framework is being applied to the development of hybrid torpedo propulsion systems, Duarte, et al (4). This construct was selected because it enables the flexible integration of both discrete and parametrically described propulsion system components to drive the emergence of optimal system-level solutions from the perspective of engineering performance and cost. The current implementation utilizes the ChaCha development tool to test and validate the proposed agent design process and the effectiveness of the framework for engineering design applications.

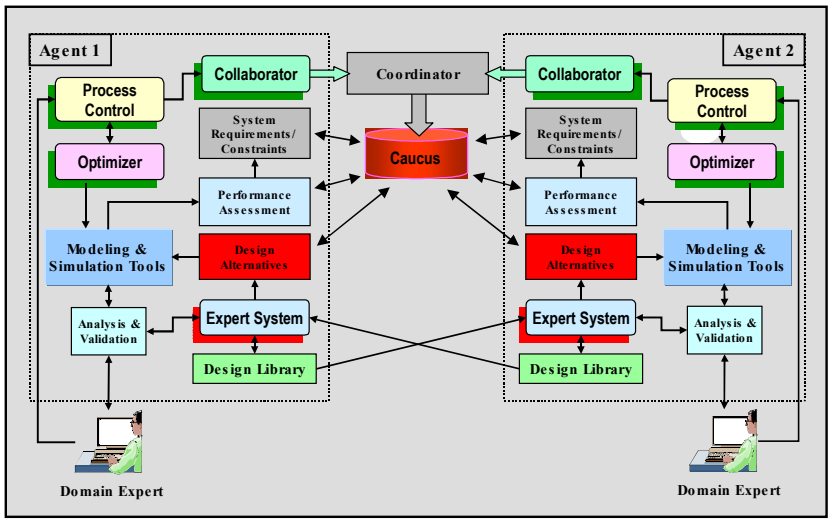

Figure 2: Cooperative Agent Framework

Neural Network MDO: The UWDO Neural Network MDO tool applies Commercial-Off-The-Shelf (COTS) business intelligence tools to support undersea weapon design and optimization initiatives, Kusmik, et al (5). This MDO methodology, depicted in Figure 3, utilizes a data-driven paradigm that enables the concurrent development of engineering design and warfare tactics that produce highly effective military systems. Specifically, adaptive pattern recognition algorithms are utilized to find associations among the variables based on the values of those variables within large datasets of modeling and simulation information. One of the unique characteristics of this approach is that it directly generates complete system concepts that can be readily grouped in terms of their ultimate military utility. The potential to concurrently evaluate both the engineering and tactical characteristics also provides the design team with the additional insights required to effectively respond to emerging military threats.

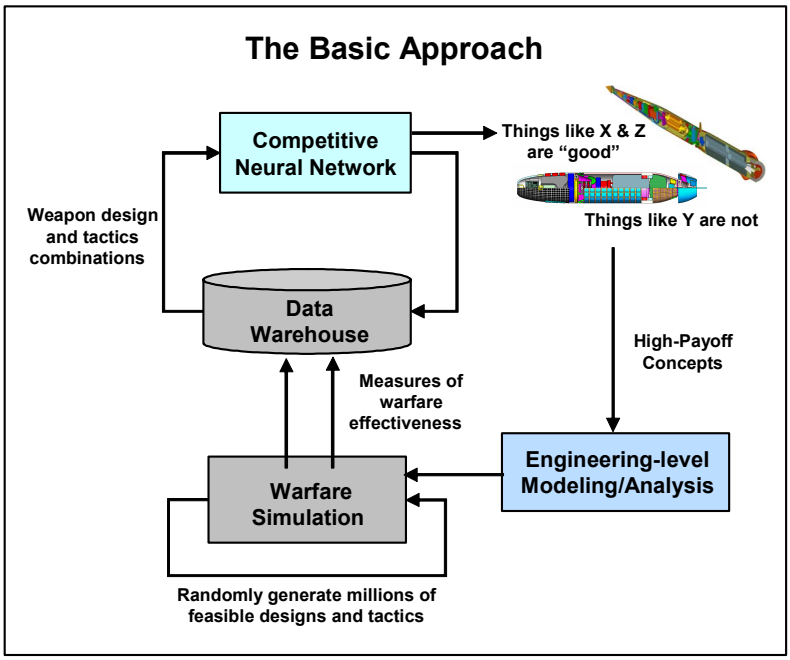

Figure 3: Neural Network Design Methodology

Enabling Technologies

A critical enabler for the UWDO environment is a knowledge management system that provides for the capture of the design process and a persistent database that supports the product throughout its lifecycle. The second key enabler is a three-dimensional visualization environment to overcome the limitations of current two-dimensional work environments that prohibit full realization of system interactions by the domain expert.

Knowledge Management System

The UWDO environment incorporates a data warehouse component that utilizes enterprise-quality information storage solutions to support the caching, archiving, and retrieval of massive amounts of design information. This information resource serves as both a repository for corporate design information and a design tool that is pre-populated with modeling and simulation runs for regions of interest to enable the interactive real-time exploration of solution alternatives. The current data warehouse implementation combines the Oracle 9i relational database, Computer Associates portal environment and the Virginia Tech Diverse Toolkit to provide the requisite capability.

Immersive Visualization Environment

The UWDO environment employs immersive visualization technology to provide high-end user interfaces that enable seamless and intuitive interaction with information-intensive SBD environments. The UWDO effort leverages emerging technologies in the fields of visual simulation and scientific visualization to enable the cradle-to-grave support of undersea weapon systems by distributed stakeholders using portable software applications that run on diverse computing platforms ranging from desktop environments to fully immersive facilities. The ultimate goal is to provide a highly intuitive, real-time interface for the design and testing of virtual undersea weapons that incorporates high-end stereographic viewing, real-time immersive interaction, and embedded design optimization capabilities.

UWDO System Demonstration: SwampWorks Torpedo

The SwampWorks next-generation heavyweight torpedo is small in size to reduce its required storage space, contains advanced arrays to increase its warfare capabilities, and is powered by a propulsion system designed to operate over a wide mission envelope while maintaining vehicle stealth and overall system reliability. The UWDO process for the SwampWorks torpedo was initiated with a warfare analysis to establish requirements for tomorrow's weapons facing tomorrow's threats. SIMII and TRM simulations were utilized along with the warfare analysis of torpedo exercise data to rapidly develop an initial set of performance requirements to drive the design space exploration process that is at the core of the UWDO environment. The simulations postulate anticipated system capabilities for the technology alternatives under consideration to ensure that the performance excursions align with realistic estimates of technological capabilities. The high-level requirements for the system include required depth and range of operation, payload, target detection range, and vehicle acoustic and electromagnetic radiation signature goals. These requirements in conjunction with physical constraint information based on platform handling and loadout requirements are posted to the design environment to initiate the preliminary design process. For this system, the initial assessment determined that a new sonar capability was required to improve littoral weapon performance and that the reduced length vehicle required a significant percentage of the speed and endurance of the existing heavyweight torpedo.

Using design space exploration tools, a preliminary assessment of design alternatives is performed. The use of parametrically defined design tools enables the rapid iteration of propulsion and sonar system alternatives to arrive at a feasible initial design concept. A sonar design tool is applied to develop a baseline array selection based on sonar characteristics which include source level, homing frequency band or bands and sensitivity as well as mechanical parameters that include size constraints, material strength and shock toughness. Utilizing a cyclic analysis process, it was determined that homing in higher frequency bands was necessary for countermeasure discrimination in the littoral, and that based upon an iterative assessment of available technologies a paste-over array could be added to the existing array to achieve necessary enhancements at minimal cost.

Software development performed in the UWDO environment allows the real-time evaluation of the embedded software's capability to utilize the technologies in the new weapon system. Software is developed in an open architecture to facilitate upgrades as we transition to a completely new array that is improved over its entire lifecycle.

The SwampWorks torpedo development effort employed a menu-driven motor design tool to assess electric and thermal propulsion candidate systems. This design tool seamlessly interacts with thermal, structural and electromagnetic models to provide rapid assessment of system feasibility. For thermal propulsion systems, the design baseline is integrated with a thermodynamic model of engine performance that predicts cylinder pressure levels obtained from the burning fuel in the combustion chamber. The two models together predict the unsteady torque generated by the engine and transmitted directly into the propulsor. The design baseline is also used to predict the structural transfer functions of the housing, mounts and couplings. A third model, the NUWC developed Vehicle Acoustic Signature Tool (VAST) provides an acoustic assessment of the system that takes the unsteady vibration information and the transfer functions and predicts the in-water radiated noise signal that results. A similar process is initiated for electric propulsion in which analytical predictions of the electromagnetic forces are used to develop unsteady structural forces. Based upon the analytically predicted capabilities of candidate technologies and the mission requirements, it was found that the first generation of this new weapon system was best served with a traditional thermal propulsion system (Figure 4). This decision was primarily driven by the system constraint on vehicle length. However, the models indicate that, if the length requirement is relaxed, as new energy sources and motor designs emerge, a hardware refresh may be beneficial to introduce electric propulsion using new concepts such as the Integrated Motor Propulsor (IMP).

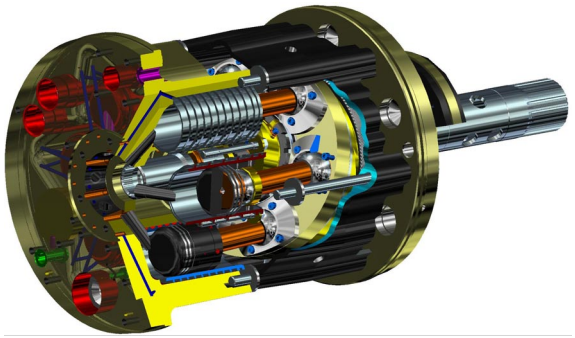

Figure 4. Solid Model of Baseline Undersea Vehicle Thermal Engine

Reduced and featureless noise signatures greatly increase the effectiveness of torpedoes and other vehicles; therefore, the reduction of radiated noise for undersea vehicles is always a major requirement in its development. Similarly, reductions in self-noise improve vehicle sonar performance. The reduction in vehicle length reduces the distance from the propulsion system to the sonar array and, thus, the self-noise is higher at the array than for the conventional thermal propulsion system. The VAST tool integrates acoustic source and transfer function information to support the rapid tuning of mounts, couplings and hulls based on vehicle signature goals for both radiated and self-noise performance (Figure 5). VAST can be used to perform parametric studies in a fraction of the time it would take to evaluate system through an actual test program. Using these tools, new midbody shell and isolation techniques were developed to ensure that the self-noise levels at the array were less than for the conventional heavyweight torpedo in spite of the reduced length. In a future phase of development, Design for Manufacture (DFM) techniques, coupled with in-water testing will utilize these models to drive the further optimization of the system and the reduction of maintenance requirements. Further gains will be achieved prior to production by applying the models to support targeted Condition-Based Maintenance (CBM) plans that focus on critical system components.

In some cases, system-level optimization strategies must be utilized to tune component properties over the lifecycle of the system to achieve stated performance goals. If a design does not emerge that meets all of the requirements, a set of achievable design characteristics is returned to the warfare analysis assessment tools to evaluate the impact of relaxing specific requirements. If no design evolves to meet the minimum goals for the weapon, a design concept is developed that will enable the seamless integration of new processors or hardware as technologies emerge to meet the long-term weapon requirements. This concept is embedded in the APB and HTRI processes for spiral transition of enhanced capabilities to the Fleet. Successful implementation requires a product model and database that are sophisticated and persistent for the weapon's total lifecycle. Preplanning a spiral development path that introduces enhanced capabilities as they evolve ensures that the weapon system does not become obsolescent over time. The SwampWorks torpedo described here is a spiral evolution of the Common Broadband Advanced Sonar System (CBASS) torpedo and will evolve to the next generation sonar array through these processes.

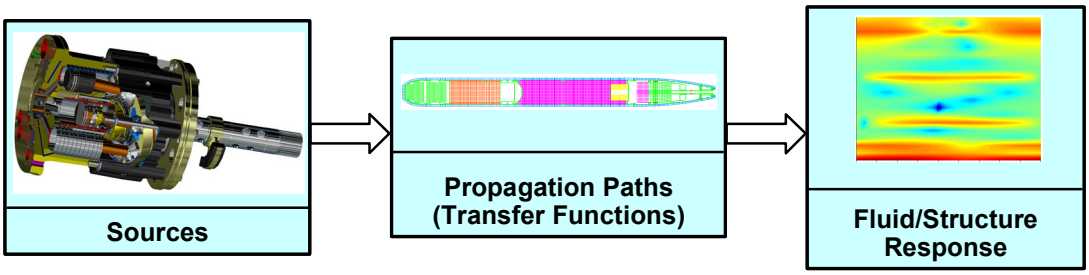

Figure 5. Results from Integrated Solid, Thermal and Acoustic Models

Total Ownership Cost Reduction

Once an acceptable technology demonstration has been accomplished, the design will pass to the lifecycle analysis tools for further assessment. Still working in a simulated environment, the solid model vibration predictions of system components can be used to statistically predict critical component life to failure. By ordering components by how likely they are to fail, and how critical they are to the successful operation of the weapon, the system designer is able to identify high risk components and seek design options for improved reliability. In addition, a CBM plan can be developed to monitor the components most likely to prevent the weapon from completing its mission, Gauthier, et al (6). A CBM plan is critical to reducing the operational costs, and in turn the Total Ownership Cost (TOC), of a weapons system. The Navy currently rebuilds its torpedoes following each run. With the next generation torpedoes, we will be able to implement gas-and-go propulsion and a smarter turnaround system that tests the vehicle for the performance of certain parts and determines whether or not the parts are to be replaced. Feedback from this evaluation also supports system redesign to mitigate design features prone to produce high failure rates.

An SBD approach has been utilized to effectively reduce the developmental costs of the new weapon system by eliminating the need for costly cycles of prototype design and fabrication. Simulated parametric studies also reduce the need for costly performance evaluation test series and prototype system modifications. Both of these steps work to reduce the prototype development costs. To lower lifecycle and maintenance costs, a SBD approach can be used to pinpoint problematic components and to estimate life to failure. To use this data in a CBM program, the "intelligent" nature of advanced technologies can be utilized as a component monitoring system. Integrated sensors needed to implement advanced silencing and propulsion technologies can be used to monitor component output, such as bearing vibration, prior to an exercise to indicate the component's condition and need for replacement. Eventually it may be possible to monitor component performance during the actual exercise, and eliminate the need to run separate diagnostic testing altogether. It is anticipated that these techniques will be implemented as the development cycle continues.

Once the baseline detailed design is validated a design for production phase will begin. In this phase, using standard commercial DFM analysis, material and manufacturing processes are selected to reduce production costs and maximize use of COTS components. The design for production process is executed using the same models and tools developed in the prototype design phase. Additional UWDO components are used to conduct analysis of system thermal, vibration, and shock survivability to meet ship loadout requirements. During production, the developers and the production team will be able to use the common product model to discuss and resolve production issues and rapidly produce units that have high probability of compatibility with existing Fleet systems. In addition, since logistics associated with multiple weapon configurations is a major driver for lifecycle cost, sophisticated design and analysis tools will be used to assist in evaluating deployment options to minimize the number of system variants that must be deployed.

Summary

Using the UWDO environment, the prototype next generation torpedo was designed and fabricated in a period of sixteen months and will be evaluated through in-water runs during April of 2003. The test data will be evaluated to verify that the predictive models accurately characterized system performance and met the UWDO evolved technical requirements. The effective utilization of modeling and simulation was a critical contributor to the significant reduction in development time and cost associated with development of a next generation

torpedo. The modeling and analysis was also critical in developing the confidence and approvals required for the unprecedented live fire of an ONR first prototype.

The same capabilities and knowledge management that drove the rapid development of the SwampWorks prototype can be extended to the production and deployment of the system as a Fleet weapon. Significant ownership cost reductions will be achieved through the use of these tools to optimize the production units and to sustain an APB and HTRI process driven by technology insertion, cost reduction and reliability improvement.

References

1. ACEM Sub-on-Sub Engagement Simulation; Computer Source Code; NUWC SBD Laboratory; https://sbd.npt.nuwc.navy.mil/acem.

2. NUWC Torpedo Program Plan; "Torpedo Advanced Processing Build (APB) and Hardware Technology Refresh and Insertion (HTRI) Program Process"; 2002; Prepared for PEO(SUB) PMS 404.

3. Frits, A., Weston, N., Pouchet, C., Kusmik, W.A., Krol, W., Mavris, D.; "Examination of a Torpedo Performance Space and its Relation to the System Design Space"; 2002; 9th AIAA/NASA Multidisciplinary Analysis and Optimization Conference.

4. Duarte, C., Krol, W., Kusmik, W.A.; "Cooperative Agent-Based Design for Undersea Weapon Design and Optimization (UWDO)"; 2003; NUWC Technical Memorandum 03-049.

5. Kusmik, W.A.; Glass, R.; "Neural Network Implementation for Torpedo Design and Optimization"; 2002; 9th AIAA/NASA Multidisciplinary Analysis and Optimization Conference.

6. Gauthier, B.J., Gomes, J.T., Kusmik, W.A., Griffin, J.S.; "Simulation Based Design as an Enabler for Condition-Based Mainframe and Total Ownership Cost Reduction for Undersea Vehicles"; 2000; 54th Meeting of the MFPT Society.