Undersea Weapon Design and Optimization

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Abstract

This paper provides an overview of the Undersea Weapon Design and Optimization (UWDO) program sponsored by the United States Navy's Office of Naval Research (ONR). Progress, status, and future research directions of the UWDO program are presented. The objective of the UWDO program is to develop computational tools and simulation-based methodology to optimize undersea weaponry system designs with respect to cost and performance. The design tools and environment developed in this program continue to be improved and implemented in the ONR Torpedo Guidance & Control, Undersea Warheads/Explosive, Torpedo Stealth, and High-Speed Supercavitating Undersea Weapons programs. Specifically, the design tools and collaborative design environment are used for the design of torpedo sonar system, new warhead configurations, virtual acoustic design using active control techniques, cost analysis, and simulation of high-speed supercavitating weapons in the virtual environment. Lastly, recommendations and future research directions in UWDO are provided.

Introduction

The objective of the UWDO program is to develop computational tools and simulation-based methodology to optimize undersea weapon system designs with respect to cost and performance. UWDO is the infrastructure that is being developed to support the design of various undersea weapons as shown in Figure 1. The weapons include the High-Speed Quick Reaction, Torpedo Defense, Coordinated Attack, Long Range Stealth, and Advanced Weapons. These undersea weapons cover close-in and extended range scenarios, with affordability as the key requirement.

The UWDO program is based on the Simulation Based Design (SBD) approach. As shown in Figure 2, SBD spans the design, prototyping, acquisition, and operations of undersea weapons. Specifically, it is used in the simulation-based design and engineering, virtual manufacturing, virtual testing [1], training simulations, operations and logistics simulations, and warfare analyses.

The UWDO system architecture (as depicted in Figure 3) consists of four major components-- multi-user access server, design tools, simulation environment, and life cycle factors. The multi-user access server is the project data manager that communicates and interacts with the other three components. The design tool consists of analytical and numerical models, computer codes, and technology object library that supports product design and development. The simulation environment provides performance simulation and virtual training, testing, and tactics evaluation. The life cycle factors component deals with logistics modeling, cost modeling and analyses, and manufacturing process modeling

The ONR UWDO team consists of members from the Naval Undersea Warfare Center- Newport Division, Pennsylvania State University/Applied Research Laboratory, Naval Surface Warfare Center-Indian Head Division, Science Application International Corporation (SAIC), SRI International, Georgia Institute of Technology, and University of Maryland.

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Technical Challenges

Affordable Science & Technology (S&T) product development, acquisition, and support for future undersea weaponry requires a software driven simulation based design process that provides:
1) improved (reduced time and cost) product development, 2) a good cost and benefit estimate of new technologies to meet future war-fighting needs, and 3) efficient transition of technology to the end users. The UWDO program develops the infrastructure that supports the development of undersea weapons in torpedo guidance and control, warhead, propulsion, stealth, and torpedo defense technologies, as well as advanced weapons system concepts such as the high-speed supercavitating weapons. This program establishes a modeling and simulation environment that integrates the United States Navy's S&T with Engineering Development efforts in undersea weaponry. The goal of the UWDO project is to develop a system that determines the design that gives optimal performance with a minimal Total Ownership Cost (TOC).

Some of the key technical challenges and S&T issues include:
- Interface of the various design tools and computer codes
- Connectivity of multi-users in a collaborative design environment
- Affordable, optimized designs
- Effective visualization of large amounts of data

Collaborative and Distributive Design Environment

The UWDO program focuses on the development of system architecture and design tools for the collaborative and distributive design environment. Design tools such as a virtual prototype design, Multidisciplinary Optimization (MDO), and cost/performance analyses are emphasized. Cost and performance trade-off studies are conducted by applying the methodology and tools to rapid prototyping of a torpedo upgrade, a new capability, or a new weapon system design. Figure 4 illustrates the virtual prototyping of a torpedo. Given overall system attributes in speed, depth and range, the designers can select the subsystems in power, guidance & control, propulsor, hydrodynamics, shell and structures, and payload. Cost analyses and simulated engagements are then performed to determine the optimal design.

Connectivity needs to be developed for disparate languages, Computer Aided Design (CAD) systems, performance models, external libraries, and users. Boyars et al. [2] identified connectivity among designers and users as one of the key requirements for the collaborative and distributive design environment. The design and optimization process involves building the SBD architecture using physics-based models to provide data for process/mechanical/environmental simulations, which, in turn, forms the basis for the vehicle subsystems, and creates a virtual prototype system design that can be used for performance, cost, and quality assessment. As an example, a web based collaborative and distributive design environment was used to design a torpedo sonar array (Figure 5). Engineering analyses and design were performed by geographically dispersed designers/users.

Multidisciplinary Optimization

Multidisciplinary Optimization (MDO) helps the users and designers to gain the understanding of the interaction among the various components to make effective and efficient tradeoff decisions. Kusmik [3] used MDO, and Belegundu et al. [4] used attributed-based MDO to design undersea vehicles. MDO needs a rapid convergence on optimal system-level design using the various models, simulation tools, and information management systems. Considering the conflicting requirement of the various sub systems and components, such optimization is indeed very complicated. Research efforts in Interval Programming and Probabilistic Methods are underway to develop effective and fast algorithms for optimization.

Multi-objective MDO is being used for a new warhead design (Figure 6). Given the design requirements, and objectives and constraints, the optimizer interacts with the warhead server, torpedo shell analyzer and lethality evaluator to produce the optimal warhead design. In this optimization, warhead lethality, radiated noise, and probability of kill (P_k) are considered simultaneously.

In the electric propulsion design and analysis, thermal and structural analyses are performed simultaneously to optimize motor design. As shown in Figure 7, thermal analysis and finite element analysis are integrated in the motor design.

Cost Analysis

Total Ownership Cost (TOC) has become one of the critical criteria in the weapon system acquisition process. TOC consists of costs from: 1) research and development, 2) production and manufacturing, 3) operation, and 4) maintenance. There are commercial parametric cost estimating software and cost models, e.g., PRICE, CORBA, for cost analyses [5]. Typical cost estimation requires inputs such as design, schedule, and deployment information. The outputs of cost estimation consist of total program cost, cost by phase, cost by type, and cost by category. The cost by category includes drafting, design, system engineering, project management, prototype, production, tooling & test equipment, general & administrative, and overhead. Maintenance cost is one of the most challenging cost estimations, in particular when there is a lack of repair records or cost data.

Virtual Design Environment

Recently, substantial progress has been made in virtual reality and scientific visualization to translate large amounts of data to visual representation. Aukstakalnis and Blatner [6] defined *Virtual Reality* as " a way for humans to visualize, manipulate and interact with computers and extremely complex data." The virtual design environment provides visualization techniques that designers can see design changes and their impact on the overall system.

Virtual reality and collaborative design environment is used for the development of advanced undersea weapons. Specific interests and focus are on torpedo stealth, warhead design, and high-speed supercavitating weapons. For example, the Virtual Reality Laboratory at the University of Maryland is developing the active noise and vibration control techniques [7] for stealth torpedo using this approach (Figure 8). Numerical results from the finite element model of the torpedo shell are displayed in the virtual environment. The animated structural noise radiation can be heard using the sound system and the vibration of the shell can be felt with the touch glove.

With the virtual environment, designers can select a range of subsystem technologies to assemble a conceptual design. This virtual prototyping capability dramatically reduces development time and total ownership cost. The virtual environment provides simulation and modeling capabilities, as well as evaluation of realistic operational scenarios.

The immersive visualization facilities at the Penn State University/Applied Research Laboratory, Virginia Tech, and University of Maryland, are utilized together with basic and applied research related to supercavitation physics, torpedo silencing and warheads to develop a unique integrated design environment. The three virtual reality sites are connected to form a collaborative design cluster among UWDO team members. The capability to visualize real-time simulations of the high-speed supercavitating weapons has been demonstrated at the Penn State University's Applied Research Lab. Modeling and simulation capabilities are augmented with the capability to generate immersive simulations from a synthesis of individual subsystem designs. Collaborative design architecture, multi-disciplinary optimization scheme, cost analysis tools and other relevant subsystem synthesis methods are incorporated into this virtual design environment. The advanced weapon designs are evaluated in operational scenarios modeled using the concept of operations requirements from the operational Naval community. Standard protocols are utilized so that the conceptual designs can be evaluated in warfare simulation involving real players. This virtual design environment provides a *faster*, *more effective, and affordable* design space to develop undersea weaponry to meet future threats.

Recommendations and Future S&T Directions

Simulation Based Design (SBD) is an effective approach for system design and product development. The UWDO environment provides the foundation for timely, information-based engineering and programmatic decision-making.

Future S&T directions should focus on *Multidisciplinary Optimization, cost analysis, and virtual environment for simulation*. Specifically, the following areas should be of great interests:

- Efficient optimization schemes
- Fast convergence algorithms
- Accurate cost analyses
- Representation and interaction with large amounts of digital data in the virtual environment
- Interfacing design tools and computer codes

References

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[2] Boyars, A. B., Kusmik, W. A., and Yukish, M., *Collaborative Engineering Across Organizational Boundaries*, ASNE Conference, April 2002.
[3] Kusmik, W. A., *Optimization in the Simulation Based Design Environment*, ASME DETC Paper, Pittsburgh, PA, September 2001.
[4] Belegundu, A. D., Halberg, E., Yukish, M. A. and Simpson, T. W., *Attribute-Based Multidisciplinary Optimization of Undersea Vehicles*, AIAA Paper 2000-4865, 2000.
[5] Yukish, M., *Cost Analysis*, 54th MPFT Meeting, Virginia Beach, VA, April 2000.
[6] Aukstakalnis, S. and Blatner, D., *Silicon Mirage: The Art and Science of Virtual Reality*, Peachpit Press, Berkeley, California, 1992.
[7] Akl, W. and Baz, A., *Design of Quiet Underwater Shells in a Virtual Reality Environment*, AIAA Paper, Atlanta, GA, September 2002.

Paper #49
Discussor's Name: Professor Ramana Grandhi
Author's Name: Dr. Kam W. Ng

Q: You are doing research in multidisciplinary optimization and also in probabilistic mechanics. Are you doing any work where the probabilistics is combined in MDO or reliability optimization or MDO based on stochastic finite element analysis?

A: We do multidisciplinary optimization, and modeling using the various numerical techniques including finite element analysis. We also use probabilistic methods in the undersea weapon design. Our design methodology is based on integrated system approach. Accordingly, we combine the various numerical techniques, computer codes and tools in the multidisciplinary optimization.

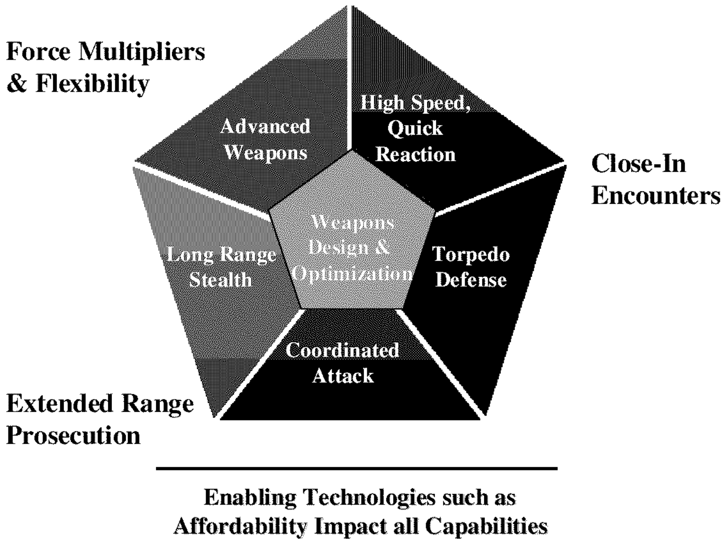


Figure 1. Capabilities of Undersea Weapons

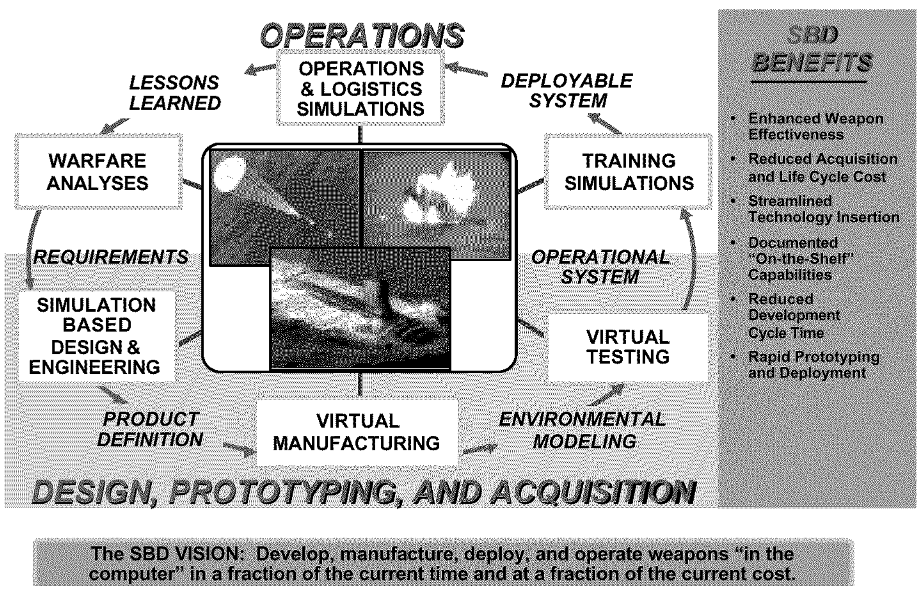


Figure 2. Simulation Based Design (SBD) Vision

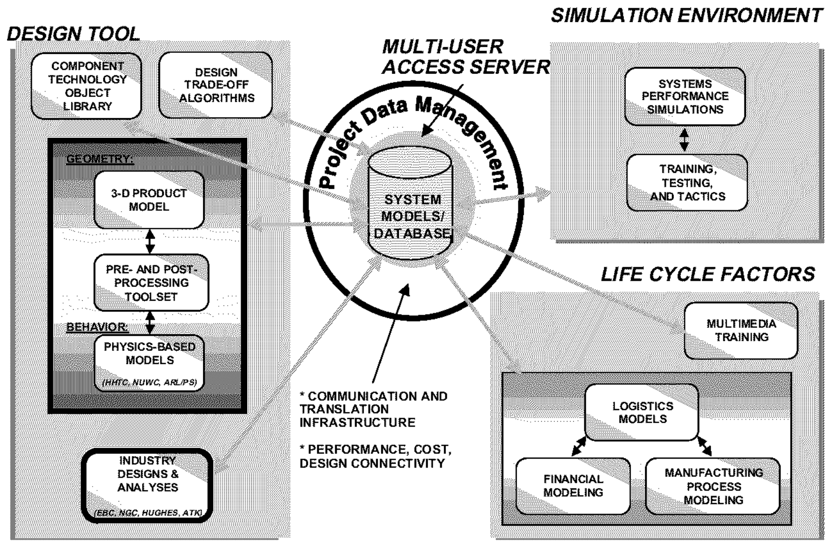


Figure 3. Design System Architecture

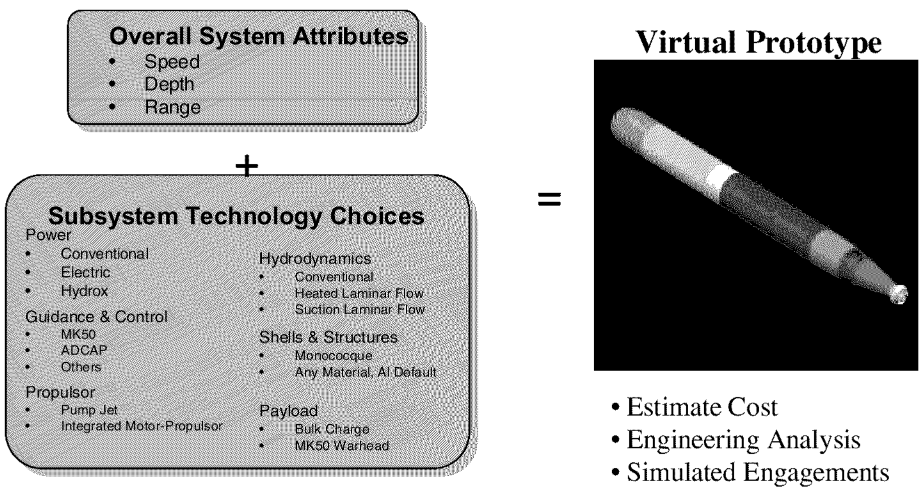
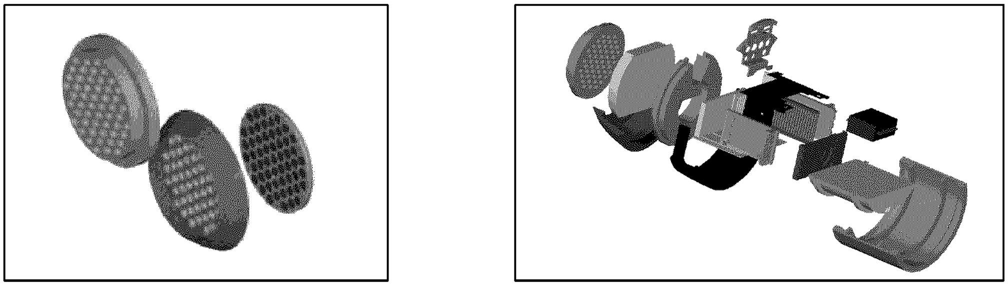


Figure 4. Undersea Weapon Design

- **Establish a web based collaborative environment for distributed team access to program data**
  - — Design
  - — Analysis
  - — Technical data
  - — Program schedules and correspondence
- **Modeling services applied for design development**
  - — Thermal
  - — Structural
  - — Solids Based Design
  - — Shock
- **Geographically dispersed design reviews**
- **Implement paperless processes**
- **Web based program management and workflow**
- **Model transitions to life cycle support functions**



Virtual Reality Modeling Language (VRML) design model with intelligent web based interface

Figure 5. Application to Torpedo Sonar Design

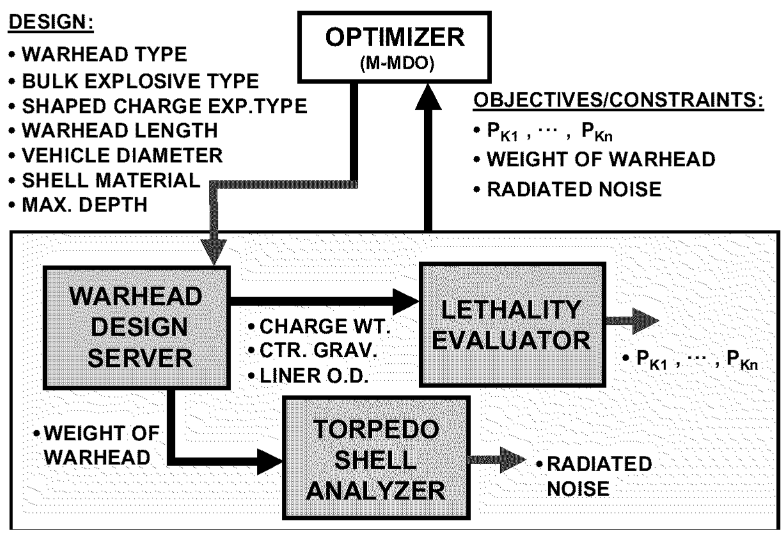


Figure 6. Multi-Objective Multidisciplinary Design Optimization for Warhead

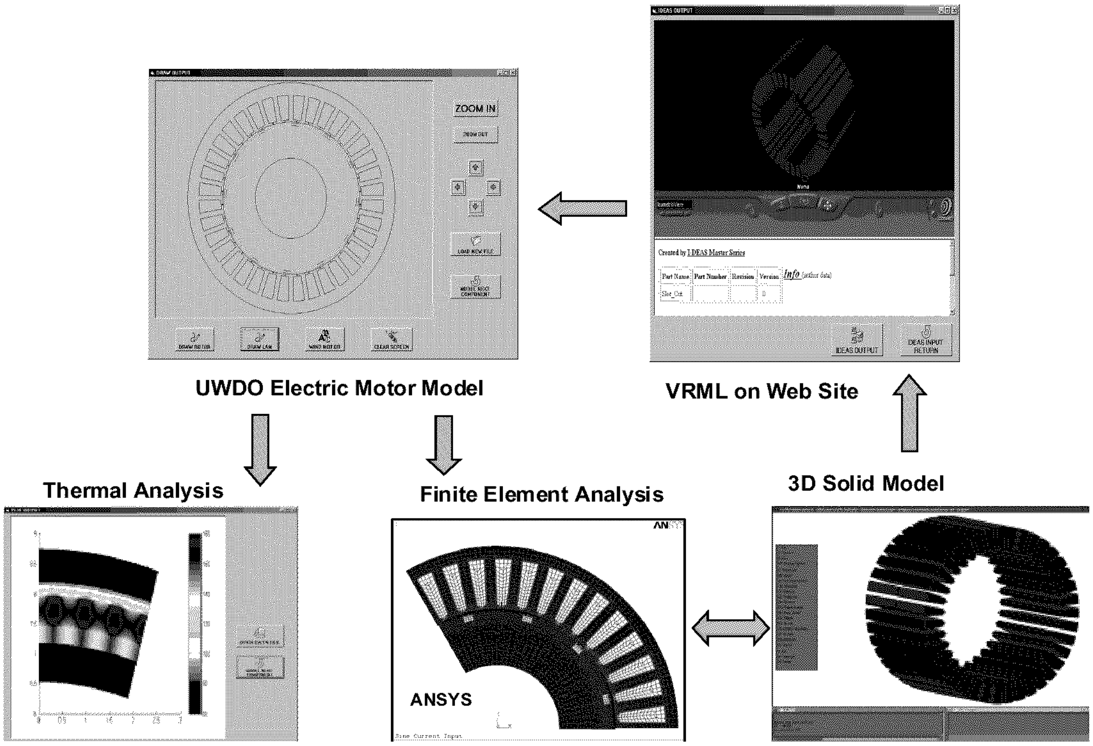


Figure 7. Electric Propulsion Design and Analysis

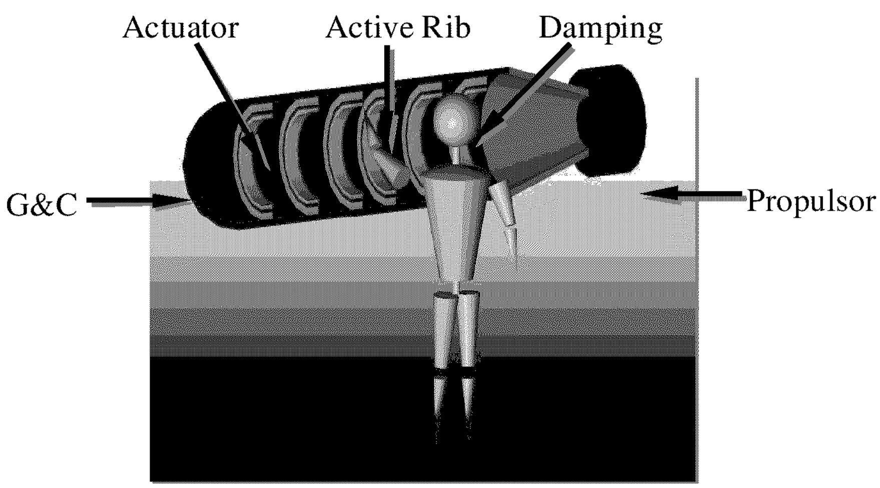


Figure 8. Virtual Acoustic Design of Torpedo Hull