Mk48 ADCAP Torpedo High-Assurance Testing

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Abstract

The Mk48 ADCAP torpedo is the US Navy's premier heavyweight submarine-launched torpedo and is widely recognized as the world's most capable anti-submarine weapon. ADCAP is a wire-guided, thermal torpedo launched through the full submarine's depth and speed profile. Following ADCAP's initial fleet introduction in 1988, software upgrades were begun to improve torpedo performance in the presence of countermeasures, under the artic ice canopy and against high speed submarine targets. The ADCAP program has produced an extremely reliable and capable weapon system through over 16 years of development. Since ADCAP is a software controlled weapon, most performance enhancements require no hardware modification, can be made quickly and at low cost. Obviously, software enhancements must undergo testing before fleet introduction. This paper describes the ADCAP torpedo, the problems encountered during development and current status of the Mk48 ADCAP torpedo testing program.

Introduction

The Mk48 ADCAP torpedo is an advanced heavyweight submarine-launched torpedo employed by the US Navy. ADCAP is a software-controlled, embedded system. Software quality assurance is essential since ADCAP is launched from a manned platform, employs a high-speed underwater vehicle and carries a powerful warhead. Ongoing testing assures improved performance as well as launch platform safety.

The Mk48 ADCAP eventually replaces the Mk48 torpedo originally developed in the 1960's. The Mk48 is a hardware-only, analog torpedo. Obsolete technology coupled with the inability to reprogram the guidance and control unit made necessary a new, digital software controlled torpedo.

Mk48 ADCAP torpedo developmental began in the early 1970s with prototypes. Design, technical evaluation and prototype efforts continued until the mid-1980s when approval was granted for initial production. Extensive testing and development continued through the mid-1980s.

By 1988, ADCAP was approved for limited fleet use. A software block upgrade program began immediately in order to continue software improvements to the original ADCAP program. Software upgrade block I was introduced in 1988 and block II followed in 1993. Software block upgrade III for the baseline ADCAP torpedo began concept exploration in 1993 with fleet introduction planned for 1997.

The ADCAP MODs torpedo provides hardware upgrades that improve radiated noise emission and increase processing power. In 1995 Block IIA software together with the ADCAP MODs torpedo hardware passed its final operational evaluation. Initial fleet introduction is scheduled for 1997. Block IV software for the ADCAP MODs is currently under development and scheduled for fleet release in 1998. COT-DV is an ADCAP commercial off the shelf guidance and control upgrade currently under development and scheduled for fleet introduction in 1999.

ADCAP Hardware Development

Table 1 provides a comparison of hardware and software used as the Mk48 ADCAP has evolved.

Torpedo Type =>	ADCAP	ADCAP MODs	COT-DV
Guidance and Control (throughput) Software	Custom (1.1 MIPS) CMS-2	68040 8085 (5.5 MIPS) Ada	PC603 (COTS) (11.8 MIPS) Ada
Sonar (throughput)	Custom (90 MFLOPS)	DSP32C (250 MFLOPS)	C40 (480 MFLOPS)
Fleet Exercise Section	8085 Assembly	8085 Assembly	8085 Assembly
Warhead Electronics	80186 Assembly	80186 Assembly	80186 Assembly

Table 1 : Mk48 ADCAP Hardware and Software Implementation

Previously, custom-made torpedo processors and non-portable computer languages limited the expansion of torpedo processor capacity. Commercial off-the-shelf components allow rapid, low cost processor upgrades. The U.S. Navy standard computer language enforces software engineering discipline and provides for software portability. Common processors and computer languages will provide synergy between related torpedo programs.

The Mk48 ADCAP torpedo hardware developers have faced the challenging requirements listed below in Table 2. Low cost development is an important consideration with recent defense budget cuts. Rugged, shock-resistant construction is critical for a submarine launched torpedo. Full up around capability, a harsh operating environment and high reliability requirements have been imposed along with a maintenance overhaul life cycle of five years. Lightweight construction provides for higher torpedo speed with given engine horsepower output. Torpedo electronics hardware must fit into the smallest space possible inside the ADCAP torpedo to allow as much internal space as possible for fuel (to maximize torpedo range) and explosive (to maximize explosive yield).

Hardware Requirement	ADCAP Solution
Low Cost	Open System Architecture (COT-DV), Commercial off the shelf components, plug in more powerful processors as available.
Rugged (Shock Resistant)	Reduced Parts Count, rugged circuit cards and cage (ADCAP MODs)
Lightweight	Reduced Parts size/count, special materials (ADCAP MODs, COT-DV)
Small Space	Miniaturized Electronic Components, Open System Architecture (COT-DV)
Shallow Water Performance	State of the Art Processor (MODs, COT-DV)
Reduced Radiated Engine Noise	Quieted Afterbody (TPU, MODs)

Table 2: Requirements and Solutions for ADCAP Hardware Development

ADCAP Software Overview

ADCAP torpedo software controls all internal torpedo functions including navigation, dead reckoning, depth keeping, sonar processing and search logic. ADCAP software is about one million lines of computer source code. Blocks I, II and III are written in CMS-2 and Block IIA and IV are written in Ada as shown in Table 1.

The recent advances in available computer processing power have allowed torpedo designers to consider more computationally intensive algorithms, that are more effective in shallow water regions. For the Mk48 ADCAP program, torpedo software development begins at the Applied Research Laboratory at Penn State University (ARL). ARL has focused research efforts on improved shallow water antisubmarine warfare (ASW). ARL created a torpedo test system for torpedo software development. This system uses a common set of software to perform either Mk48 ADCAP (heavyweight torpedo) or Mk50 (lightweight torpedo) attack. The vehicles, the General Test Vehicle (GTV) and the Experimental Test Vehicle (XTV), are used to evaluate innovative signal processing and tactics technology.[1] Periodic in-water firings targeting U.S. fleet submarines help researchers evaluate these innovations.

The GTV / XTV guidance and control hardware uses mainly commercial off the shelf processor boards which interface with a VME standard backplane. The VME backplane allows the widest commercial variety of real-time boards for hardware upgrades. Adoption of commercially available components serves as a model for future torpedo hardware development. A magneto-optical disk recorder stores in-water data for subsequent post run analysis. Post processing of element level acoustic data affords laboratory analysis at ARL.

The ARL development environment allows evolution of the tactical software within the VAX environment. Software is ported directly to the micro-VAX on a VME card on board the GTV / XTV. The micro-VAX runs the DEC VMS real-time operating system. This method allows signal processor and interface code to be developed on Sun computers. Almost all guidance and control system code is written in Ada including the autopilot. The signal processor code, the only Ada exception, is written in 'C'. GTV / XTV provides a testbed for software commonality and Open System Architecture (OSA) implementation in operational fleet torpedoes.

Once ARL's advanced tactical and signal processing algorithms are validated in water and reach sufficient maturity, they are passed to the Naval Undersea Warfare Center (NUWC), Newport, RI. ADCAP software, under development by a team of about 20 programmers, implements ARL algorithms in the fleet torpedo software.

Table 3 addresses the software problems encountered during ADCAP software development. The Ada programming language is the U.S. Navy standard computer language. Ada reduced software life cycle costs by enforcing software engineering standards within the language. The Ada tasking function provides a machine portable software executive. Lower costs for development will be provided by common torpedo architecture for all U.S. torpedoes. Lower cost testing is afforded by Weapons Analysis Facility (WAF) simulation especially for shallow water firings. Enhanced shallow water performance and algorithm development is ongoing at ARL using the GTV / XTV vehicles.

Software Requirement	ADCAP Solution
Reduce Life Cycle Costs	Ada, Rigorous Configuration Control
Software Compatibility with Hardware Upgrades	Portable Software Executive Using Ada Tasking
Low Costs	Common Development Process for all US Torpedoes Common Torpedo Architecture, Ada
Low Cost Testing, Limited Fleet Services	Hardware in the Loop WAF Simulation Piggyback Testing on Fleet Exercises
Shallow Water Performance	Ongoing GTV / XTV Testing at ARL

Table 3: Requirements and Solutions for ADCAP Software Development

The Torpedo Software Commonality Team was chartered by the Program Executive Officer (Underseas Warfare) in Washington, D.C. to study ways to combine disparate torpedo development efforts. The team proposed long-term solutions to resolve these problems by using Open System Architecture, as opposed to the custom-made hardware systems used in the past, to reduce development costs and provide for system expansion as well as software portability. The Torpedo Software Commonality Team concluded:[1]

- Commonality is technically feasible and needed since all U.S. ASW torpedoes perform similar missions.
- Commonality will reduce infrastructure costs because software and system engineering efforts could be accomplished by a unified effort for both lightweight (Mk50) and heavyweight (Mk48 ADCAP) ASW torpedoes.
- The common architecture for future weapons should be developed using the Open System Architecture approach.

The architectural definition for future torpedoes will be developed by a joint industry / Navy Integrated Process Team.

Testing Overview

Mk48 ADCAP torpedo software testing requires extremely high software quality assurance. An extensive testing program has evolved since the program began. To date there have been over 2,000 ADCAP in-water test firings and 18,000 ADCAP simulation runs. Critical isssues that require testing include; prevention of premature warhead detonation, validation of torpedo performance in adverse environments, launch.

Torpedo software testing employs a four-step process; unit testing, integration testing, ADCAP Software Testbed (AST) and Weapons Analysis Facility (WAF) testing. The last two phases of testing involve hardware-in-the-loop facilities at NUWC, Newport.

WAF testing uses the state-of-the-art supercomputer torpedo simulation facility at Naval Undersea Warfare Laboratory in Newport, RI. Torpedo runs can be simulated for less than one percent of the cost of an in-water run and take only twenty minutes. In-water testing requires torpedo range and open ocean launches from US submarines using US submarines targets. Extensive planning and logistic resources are required for this type of testing. Each torpedo must be returned to the intermediate maintenance and overhauled prior to reuse. Costs run approximately $50,000 per torpedo for this type of testing.

Laboratory Testing for ADCAP Torpedo Software

ADCAP software is under development at the Naval Undersea Warfare Center (NUWC) in Newport, RI. A team of 20 programmers develops and maintains torpedo software. Enhancements, such as improved signal processing algorithms, are originally developed at the Advanced Research Laboratory (ARL) at Penn State University and tested using special torpedo test vehicles at the Naval Undersea Warfare Detachment in Keyport, WA. Once new concepts reach the proper level of maturity at ARL, they are implemented in torpedo software by the NUWC programmer team.

ADCAP software developers sift through fleet feedback to understand torpedo problems observed in-water. Operational Trouble Reports (OTR) document fleet feedback and performance problems discovered during post-run analysis. A Software Trouble Report (STR) is written to document problems related to torpedo software. STRs are used to track and correct known software deficiencies. An STR must be written and approved to correct any software deficiency. The STR system is integrated together with the ADCAP software configuration control system to ensure a new software version number is assigned whenever changes are made. Normally changes are made in batches when a new software version is created.

Torpedo software testing employs a four-step process; unit testing, integration testing, ADCAP Software Testbed (AST) and Weapons Analysis Facility (WAF) testing. Unit testing tests individual software modules that are new or newly modified. Peer reviews ensure coding meets standard guidelines. Normally a test harness is built and used to ensure all functional points work properly at the boundary conditions. Integration testing follows next when a new module or group of modules is added.

Testing of the fully integrated software package is next tested on the AST. This is a torpedo hardware-in-the-loop facility that tests all aspects of torpedo performance using a simple environmental model. ADCAP torpedo components are cabled together and hooked up to a minicomputer. The torpedo software runs through full tactical mission profiles from launch to shutdown. Software integration bugs are worked out at this stage.

Torpedo Simulator Testing

ADCAP torpedo software is tested at NUWC, Newport WAF. This facility is a hardware-in-the-loop testbed with an ADCAP guidance and control unit connected to the TC-2000 computer. Operational torpedo software runs on the torpedo guidance and control (G&C) unit hardware. The TC-2000 provides the "environmental simulation". Torpedo echo ranging signals from the sonar array face enter the environmental simulator electronically, and the simulator feeds acoustic echo returns back to the sonar array in real time. The

G&C processes the acoustic returns and sends the appropriate commands to the autopilot to control the torpedo vehicle's motion through the water.

Software regression testing is also performed on the WAF to ensure proven capabilities are not degraded as new features are added. For regression testing, new versions of torpedo software are run in a 61 element matrix. The mission score for the new version must compare closely with previous versions to allow software release. Full regression testing and several in-water proofing runs are required for each new version of software before allowing an ADCAP launch from a manned submarine target.

The WAF simulator has a graphic user interface front end to help analysts understand torpedo performance data. This interface runs on Silicon Graphic IRIS workstations that will replay any portion of the torpedo run for in-depth analysis. This visual analysis tool allows the analyst to step through simulator data slowly and zoom in on any particular portion of the torpedo run.

Tactics development for the ADCAP is ongoing using the WAF simulator as well. Analysts set up challenging torpedo runs and then observe torpedo performance. Improved torpedo software algorithms and torpedo employment tactics emerge from this process. In-water torpedo run data can also be replayed in the WAF simulator. Comparisons between in-water runs and simulation help improve simulator fidelity by allowing validation of the environmental model.

Final torpedo software approval involves a internal Torpedo Control Group (TCG) at NUWC, Newport followed by a Mission Control Panel (MCP) review in Washington, DC. These final steps involve a detailed review of laboratory testing from a safety standpoint. All aspects of laboratory testing and initial in-water firings are examined with respect to launch submarine safety.

In-Water Software Testing

The final and most convincing proof of torpedo software performance comes from in-water exercise firings. Other exercise torpedo targets are available in the U.S. inventory, but for ADCAP testing, a U.S. submarine target provides maximum operational realism. A manned submarine target is operated in a manner similar to the anticipated threat submarine. The exercise torpedo is fired so that it will acquire and home in on the target submarine. Data is recorded and stored on board the ADCAP for subsequent laboratory analysis.

In the early stages of developmental work, the attack scenarios for in-water testing are simple, canned exercises using preprogrammed geometry. As the software matures and fleet introduction approaches, ADCAP is employed in exercises closer to actual battle conditions called freeplay exercises.

A recent ADCAP torpedo exercise was held near the Channel Islands off the coast of California. This exercise provides the reader with an example of a typical torpedo firing test. Twenty-four ADCAP torpedoes were prepared for testing with four different versions of software. Three versions of ADCAP block upgrade III software loaded for a side-by-side comparison of new acoustic signal processing algorithms. The forth version was ADCAP block upgrade IV running in an open loop (non-homing) mode in the ADCAP MODs torpedo guidance and control unit. The open loop gather element level acoutic data for subsequent laboratory post-processing. These data are critical to further refinement of advanced signal processing in acoustically harsh environmental conditions.

A 688-class U.S. submarine based in San Diego provided four days of target services in the operating area. A launch craft (YTT-10) based in Keyport, WA provided launch services for the exercise since no other US submarines were available. The YTT is a special purpose range ship with two submarine torpedo tubes. Since this was a developmental test, the YTT and the submarine used pre-planned positioning for all 24 firings. Coordination of the exercise was critical because submarine service time is limited. Firing geometry and other coordinating information were passed via special brevity codes.

At the completion of each torpedo run, the positively bouyant exercise ADCAP floated to the surface. International orange paint on the normally green torpedo allowed the recovery crews to spot the ADCAP floating nose up. Torpedo recovery employed three UH-3 heavylift helicopters working in tandem. Each of these helos was equipped with a specially designed torpedo lifting cage for recovery and transport of the torpedoes to a nearby recovery ship. The lifting cage has an open, tapered wire basket at one end for dropping on top of the floating torpedo and a narrow closed end for holding the nose of the torpedo once it is lifted out of the water. Helo recovery is the best way to quickly recover ADCAP torpedoes in open ocean. In one day, as many as ten exercise ADCAPs have been launched and recovered using these techniques.

A civilian plane from a local airport was hired for marine mammal protection. Torpedo firings were immediately suspended when whales or other marine mammals were sited nearby. No injuries or disturbance of animal habitat resulted from this exercise. This effort was required to comply with federal environmental law. The light plane also served as an excellent torpedo spotter. Radio communications between the light plane, YTT-10 and the helos facilitated coordination for rapid torpedo recovery. Several ADCAPs were recovered in as little as ten minutes after shutdown.

Data recorders were installed on each exercise ADCAP torpedo. Following torpedo recovery, data extraction and analysis revealed just how well the torpedo performed. In open ocean, the torpedo run profile was reconstructed from data recorder information, launch platform GPS data and submarine position records. For this exercise, four new high capacity data recorders were installed to record element level torpedo acoustic data. Laboratory post-processing of this data will allow software developers to continue improving signal processing algorithms. In-water torpedo data goes back to the software development laboratory and the cycle begins again. Roughly four in-water exercises per year are required to continue ADCAP software development.

Future Plans

Greater use of modeling and simulation to reduce costly in-water testing is planned for the future. Excellent fidelity of the environmental model continues to improve in support of this initiative. In-water acoustic data gathered from torpedo exercises such as the example described above allows for continued comparison of WAF results with in-water firings.

An ADCAP-WAF accreditation intiative is currently underway. The goal of the WAF accreditation process is to perform operational validation and gain approval for Block III Deep Water simulation for DT/OT and Operational Evaluation. The WAF modeling and simulation environment represents the "at-sea weapons environment" to replace in-water torpedo testing.

An industry standard process is used to guide the development of the Verification, Validation and Accreditation (VVA) plan. Four major steps are required for WAF hardware-in-the-loop VVA.

1) Concept Validation - Analyis of model assumptions, derivations and interfaces.

2) Model Verification - involves corroboration of the validated model.

3) Operational Validation - comparison of model results with "real world" results. Common test cases are run in simulation and in the real world environment. Results are compared.

4) Support System Verification - Examination of software configuration management and software quality assurance as well as compliance with the accreditation plan.

The Mk48 ADCAP torpedo continues to evolve in response to the evolution of worldwide submarine submarine warfare. Proliferation of advanced submarine technology to littoral nations continues to pose a threat to peacekeeping forces. ASW in littoral regions requires enhanced survivability and better torpedo performance in shallow water. Current Mk48 ADCAP torpedo development efforts demonstrate outstanding success in both of these areas. The US Navy continues to support the development of advance submarine ASW weapons and will continue to improve their performance to match the challenging mission requirements of littoral and open ocean warfare.

References

[1] *Final Report of the Torpedo Software Commonality Team*, Program Executive Officer (Undersea Warfare), Feb 8, 1995, pp 5-6.