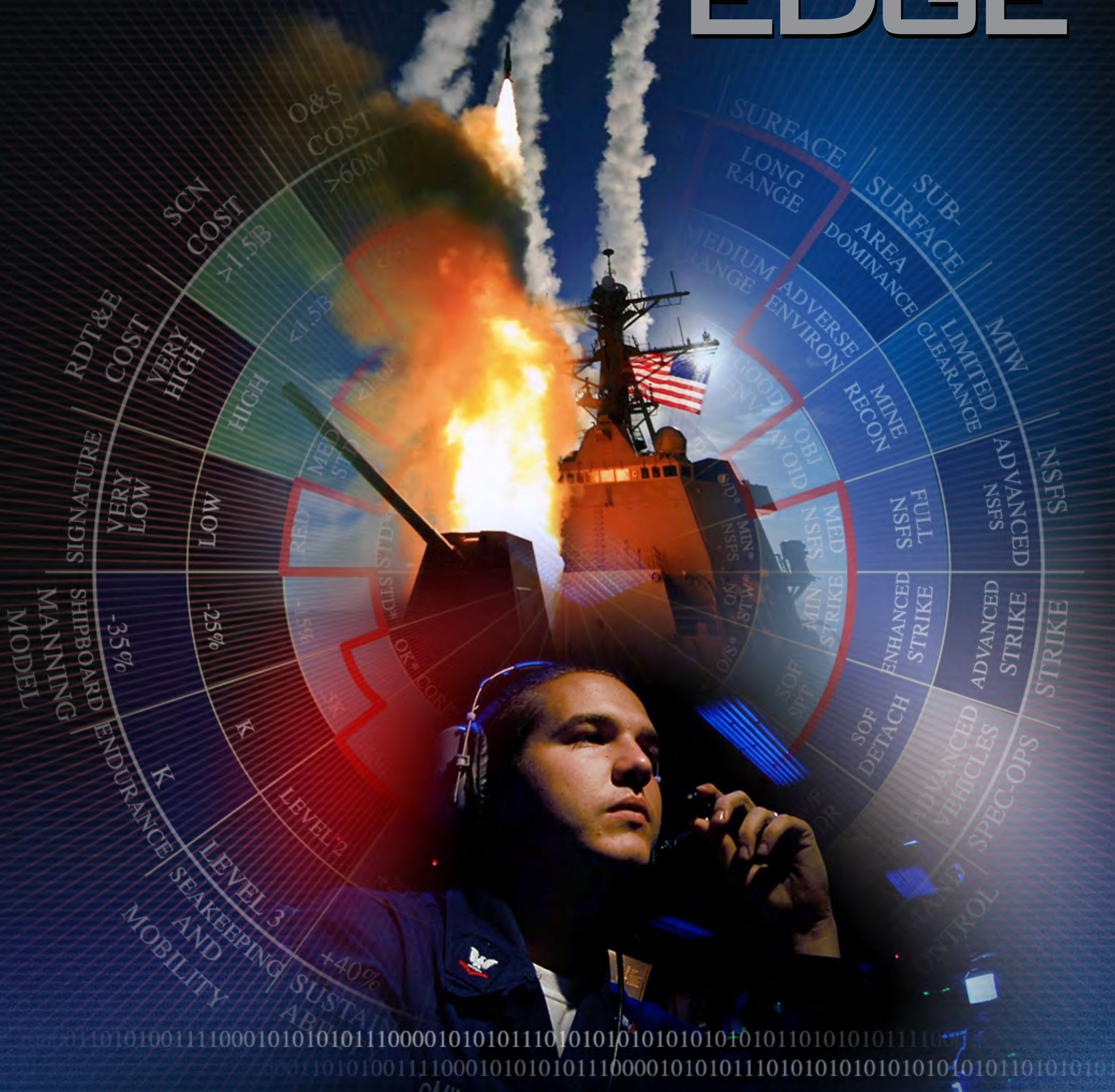
LEADING EDGE

February 2013



CSE&I

COMBAT SYSTEMS ENGINEERING & INTEGRATION

NAVSEA WARFARE CENTERS DAHLGREN

LEADING EDGE

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Leading Edge magazine—produced by the Naval Surface Warfare Center, Dahlgren Division, Dahlgren, Virginia— is an official, authorized publication of the Naval Warfare Center Enterprise. The purpose of the publication is to showcase technical excellence across the Warfare Center Enterprise and promote a broader awareness of the breadth and depth of knowledge and support available to the Navy and DoD.

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NSWCDD/MP-13/22
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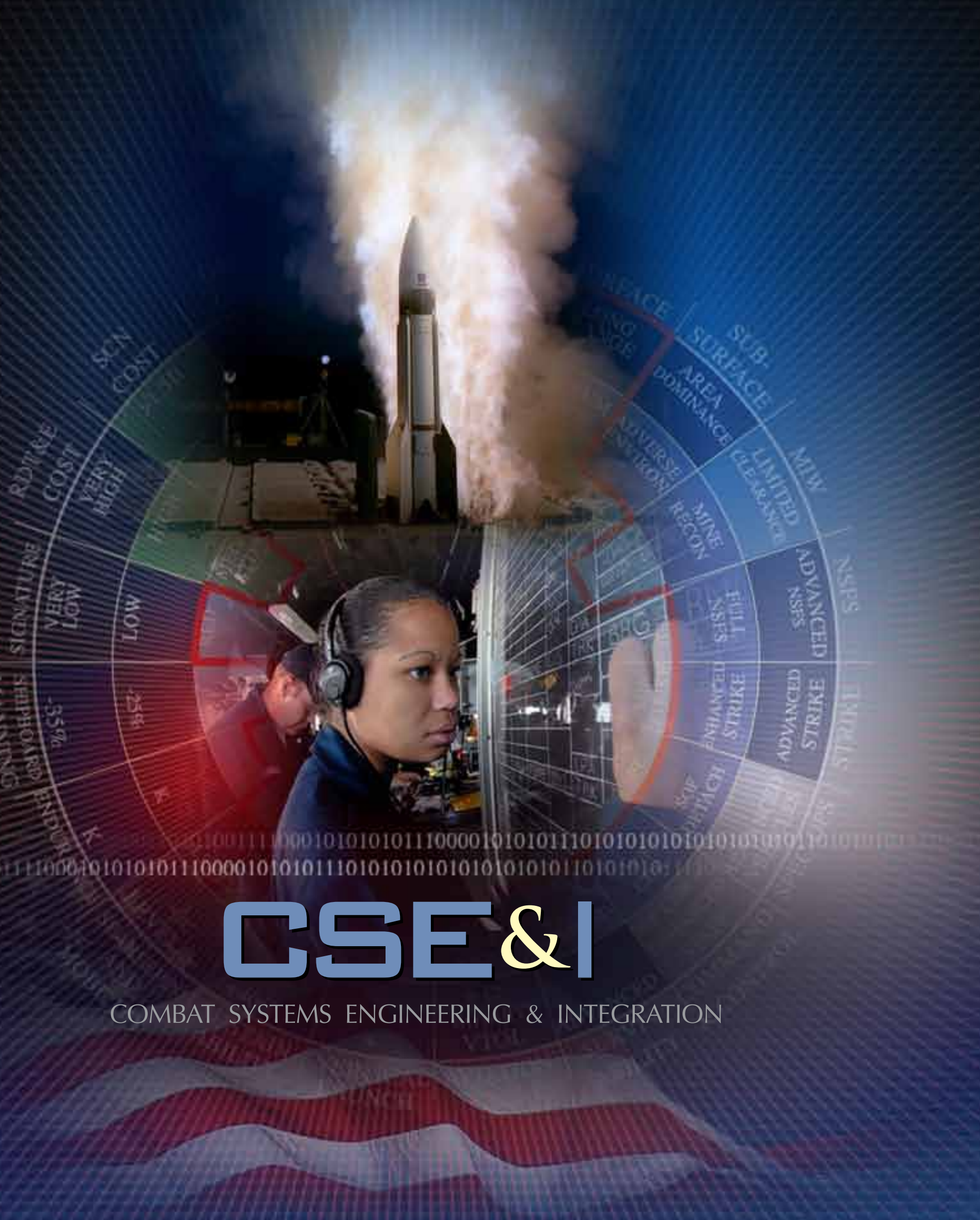


CSE&I

COMBAT SYSTEMS ENGINEERING & INTEGRATION

Introduction

Leading the Way Through Excellence in Combat Systems Engineering and Integration

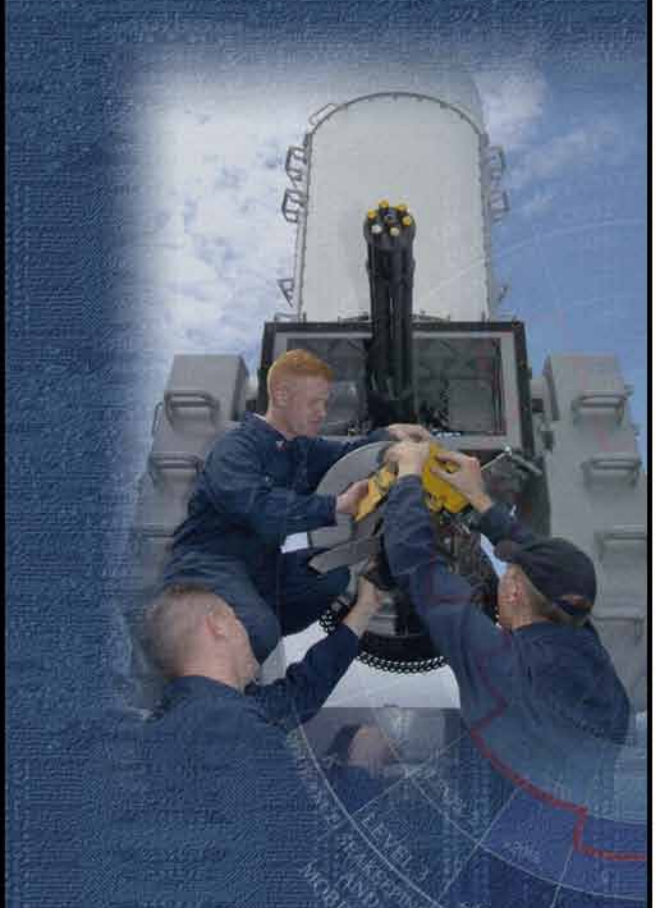
Captain Michael H. Smith, USN
Commander, NSWCDD

Naval Surface Warfare Center, Dahlgren Division (NSWCDD) has a long heritage of integrating increasingly more complex systems into the warfighting capability for the nation. With an enduring technical professional development program, NSWCDD has successfully shown the value of engineering rigor within the systems hierarchy (i.e., components, systems, platforms, and missions). Our scientists and engineers are experts in translating needed mission capabilities into engineering solutions and are committed to providing the Navy's core technical capability for the integration of sensors, weapons, and their associated weapon and combat systems into surface ships and vehicles.

Our goal is to provide leadership in large-scale, end-to-end systems engineering at the system level, system-of-systems level, and mission level. The articles in this Combat Systems Engineering and Integration edition of *Leading Edge* attest to this leadership and describe NSWCDD's work in pioneering integrated solutions for the surface Navy. Throughout this publication, you will follow the journey to solve incredibly complex problems and gain an insight into the innovative enhancements, analysis, and designs that are making a difference to ensure optimal support for the warfighter and the Fleet. You will learn more about the Navy's efforts in developing systems that are increasing flexibility and bringing advanced capability as we push the limit on power technologies and total ship integration.

The world will be different in the future and our warfighting capability needs to change with it. Limited footprint aboard ships will require more efficient use of available space. This edition of *Leading Edge* looks into the future with articles describing multifunction systems that will help us manage our topside requirements and deepen our magazines as well as next-generation systems. It also provides a look at the Navy's total-ship-enterprise approach and demonstrates how the approach is utilized by the Navy to support system integration to address the challenges in our 21st century Fleet.

I invite you to explore the Combat Systems Engineering & Integration edition of *Leading Edge* and learn about the exciting and important work NSWCDD and others are doing in support of integrated combat system solutions across mission domains. Given the wide array of contributions our team is making, I am proud to say that our Navy will continue to be protected from adversaries, now and in the future.



Introduction

Combat Systems Engineering and Integration Edition of *Leading Edge* Magazine

Mr. Dohn Burnett
Head, Warfare Systems Department
NSWCDD

Welcome to the Combat Systems Engineering & Integration (CSE&I) edition of *Leading Edge*. The area of CSE&I has undergone significant evolution in the past decade. In that time, the art and science of CSE&I has progressed from systems engineering at the combat systems level, to the systems-of-systems level and mission level. While these later areas are still rapidly evolving, many of the associated challenges have been recognized, characterized, and in some cases mitigated through recently defined processes and tools. Developing the competencies to engineer at these levels is critical to providing effective warfighting capabilities at affordable costs. At the same time, other aspects of CSE&I have evolved to address challenges such as computing technology insertion, cyber security, human/systems integration, and state-of-the-art computer program development. Overarching all of this is the need to reduce costs while ensuring the warfighters have the quality systems they need. Many of these vital subjects are explored in this edition. I encourage everyone who has a stake in CSE&I to read through the articles, engage in discussion with the authors, and help ensure our collective capabilities can respond to the continuing challenges we are facing.

Acknowledgments

There are many people who worked very hard to make this Combat Systems Engineering and Integration issue of *Leading Edge* a reality.

I would like to thank the Technical Information Services Office's (CX7) publishing staff and the NSWCDD Corporate Communications team (C6), who worked hard to produce this professional document.

My thanks also go to the authors who provided their expertise and talent and put key thoughts together in writing these articles.

I'd like to acknowledge the support of my chain of command—my Commander, Captain Mike Smith, and my Technical Director, Mr. Carl R. Siel, Jr.—who have been very supportive of our work in combat systems for the Navy, joint, and national needs areas.

Finally, I want to recognize Mr. David S. Richardson who led this effort for the Warfare Systems Department (W Department) and kept things moving forward. Mr. Richardson provided a critical review of all the articles and worked with many of the authors to ensure that the articles were current, relevant, and not redundant. He was also our Department liaison to Corporate Communications and the Command Public Affairs Office and is largely responsible for successful publication of this *Leading Edge* issue. I would also like to thank Mr. Neil Baron and Mr. Gil Goddin for their assistance in developing our theme and reviewing articles.

Introduction

Innovation Spanning All Levels of the Systems Engineering Hierarchy

Mr. Neil Baron
Distinguished Scientist / Engineer for Combat Systems
Warfare Systems Department, NSWCDD

Foundational to the framework of systems engineering for U.S. Navy combat capabilities is the notion of a hierarchical relationship spanning from the smallest of computer components to the immenseness and complexity of the Aircraft Carrier Battle Group. Technical requirements and operational definitions are specified at each level of the hierarchy through a structured approach of decomposition (down) for development/production and then aggregation and integration (up) to achieve a deployable combat capability. From the day that Marconi brought the first radio to sea until today — the age of the digital computer — the capabilities and complexities of naval combat systems have grown to truly span all the levels of the systems engineering hierarchy. The machine of war, U.S. Navy combat capability at sea, is defined, developed, produced, tested, certified, and deployed at each level of the hierarchy. This is certainly a technical challenge, but it is also a scheduling and fielding challenge as the continued flexibility of adapting to threat-driven changes is also enabled through the same technology. The combat capabilities of our systems, ships, aircraft and land vehicles, and our deployed aircraft carrier, expeditionary, and surface action battle groups are continually evolving throughout their service lives and deployment schedules.

To help gain an insight into each area of combat capability development, we have chosen to structure the articles in the Combat Systems Engineering & Integration edition of *Leading Edge* utilizing the systems engineering hierarchy that drives so much of our effort. The articles are categorized at the mission level, platform level, system level, and component (or element) level; they explore development of specific products for particular levels of the hierarchy as well as the application of engineering disciplines such as requirements, certification, or cost engineering at those levels.

By structuring our work through the systems engineering hierarchy, we are able to safely and effectively engineer and manage naval combat system developments. There is nothing more complex, more demanding of engineering mastery, more dominating the world over, and yet more sensitive to catastrophic system failure than the naval warship at sea defending our nation; yet that is what a warship is built to do.

Please enjoy this Combat Systems Engineering & Integration edition of *Leading Edge*.

The Importance of System-of-Systems Integration

by Alvin Murphy, David S. Richardson, and Terence Sheehan

It is evident from today's budget constraints that the Navy can no longer afford to build new and unique combat systems for each ship class. The Navy realizes that computing architectures in many of its systems are performance-limited and expensive to upgrade due to restricted, single-ship-class acquisition processes. The Navy is under intense pressure to control the rising costs of warfare systems and aging platforms and, at the same time, build a surface ship fleet capable of meeting emerging threats. To manage the various platform developments while keeping costs under control, the Navy must transition to managing this development within an enterprise portfolio of vessels. The Naval Surface Warfare Center, Dahlgren Division (NSWCDD), is uniquely situated and its employees are specifically trained to execute this transition.

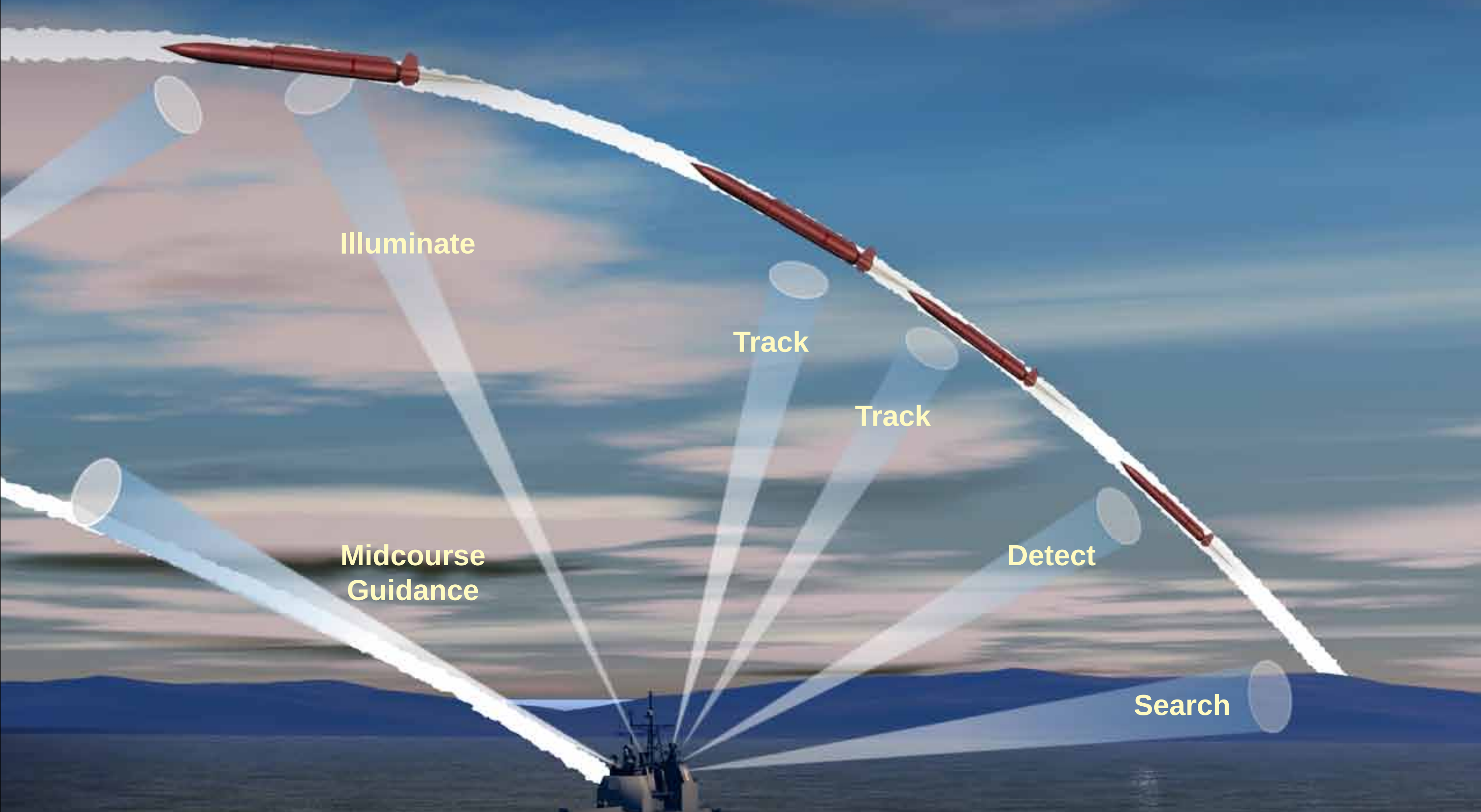


Figure 1. AWS Integrated Closed-Loop Fire Control

Origin of Integrated Warfare Systems

Development of the Aegis Weapon System (AWS) was a revolutionary implementation of integrated warfare systems engineering generated as a result of the Advanced Surface Missile System (ASMS) Assessment Group. The group evaluated weapon system alternatives reaction time, greater firepower, expanded coverage, and higher availability and reliability through systems integration. The decision was made, at the time, to design and develop the entire ASMS system, later to be named "Aegis," within a single project office where systems engineering methodologies could be applied to manage the requirements, allocate functions to system elements, and manage budgets across the system elements. Subsequently, Aegis has been able to deliver extremely capable, integrated systems that meet evolving requirements primarily by adhering to rigorous systems engineering and integration processes. The AWS integrated closed-loop fire control is shown in Figure 1.

Migration to System-of-Systems (SoS) Engineering

Eventually, the Navy needed to apply the integrated systems engineering process at the force level for increased interoperability and mission performance, especially given the advent of advanced communications and data sharing opportunities, such as the Cooperative Engagement Capability (CEC). NSWCDD, as a leader in combat systems engineering, subsequently became a leader in SoS engineering, establishing leadership roles on the Combat System Functional Allocation Board, Design Community of Practice, and Architecture Community of Interest. The Naval System of Systems, Systems Engineering Guide[1] provides this definition for SoS:

> The term system of systems (SoS) is used to describe an integrated force package of interoperable systems acting as a single system to achieve a mission capability. Typical characteristics include a high degree of collaboration and coordination, flexible addition or removal of component systems, and a net-centric architecture. Individual systems in the SoS may be capable of independent operations and are typically independently managed. An example would be an Expeditionary Strike Group acting to provide coordinated naval fires. The capabilities provided by each constituent system operating within the SoS are framed by the integrated force package architecture.

An SoS provides improved capabilities through network-centric operations. Designing, building, and managing SoS integration is an enormous task, given the entire set of systems, programs, platforms, and force compilations. Figure 2 depicts the complexity of Navy SoS integration overlaying the other services with similar integration challenges.

So, why is integration at the SoS level necessary? Mission analysis indicates SoS performance significantly increases performance. It engages more threats, uses ordnance expeditiously, experiences fewer blue-on-blue force (friendly fire) engagements, reduces collateral damage, and provides a number of other benefits including winning wars faster.

Surface Navy SoS Vision

Platform-specific systems are being replaced with a common core set of combat capabilities used across all surface ships. As a result, the differences among combat system capabilities across ship classes will be limited to unique mission capabilities. The benefits of a common core set of capabilities are many, including fewer systems serviced, consistent warfighting methods, cross-platform training, and reduced shore infrastructure costs. The vision for enterprise combat system solutions is the development of reusable product line components into a single combat system

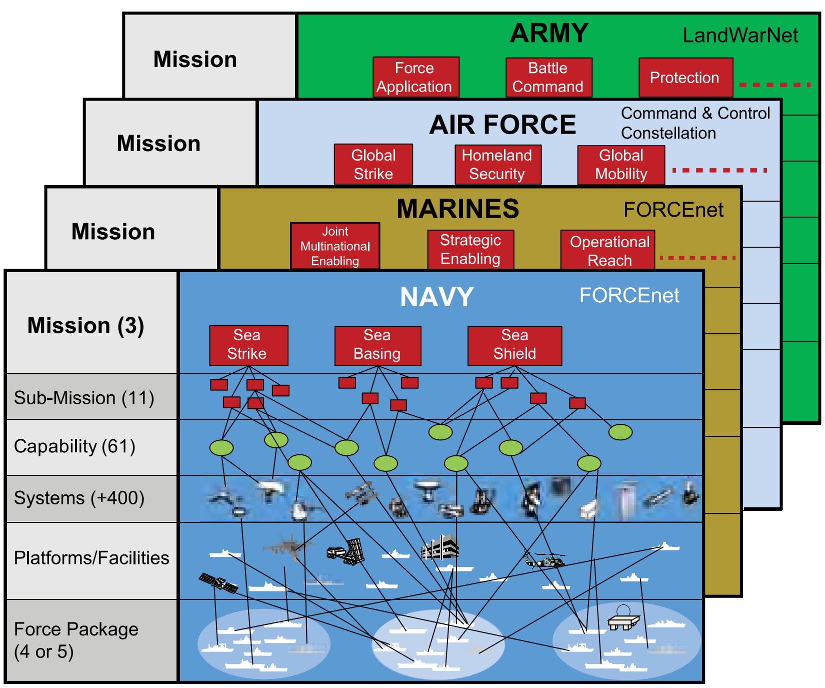


Figure 2. Department of Defense (DoD) SoS

architecture. NSWCDD, with its decades of experience, leads the definition and implementation of this product line architecture (PLA).

Implementation of the PLA increases competition and encourages a "best-of-breed" open business model based on the following five principles:

- Modular designs
- Competition and collaboration
- Interoperability through commonality
- Reusable software components
- Life cycle affordability using commercial off-the-shelf (COTS) and technology insertion processes

Based on these principles, and using an open business process, the Navy, via the leadership of NSWCDD, decoupled combat system design from ship design, developed modular combat systems, facilitated software and hardware reuse, and incorporated COTS open standard-based components for ease of upgrade, as illustrated in Figure 3.

Product Line Approach to SoS

A software product line is a set of software-intensive systems, sharing a common, managed set of features that satisfy the specific needs of a particular market segment or mission, and that are developed from a common set of core assets in a prescribed way.[2] Implementation of a product line approach for surface Navy SoS requires significant changes in how the systems engineering organization manages requirements, architectures, and detailed designs. NSWCDD is uniquely postured to support the warfighter and provide superior combat system capabilities by systems engineering the integration of SoS capabilities. In providing these capabilities, a product line approach is used. A product line approach requires integration and alignment of acquisition activities to realize the potential benefits of the approach.

In a document titled, *A Software Product Line Vision for Defense Acquisition*,[3] the author points out:

> Many DoD missions depend on systems for which requirements and enabling technology change and are deployed at multiple sites and versions. A separate or modified solution for every circumstance can be wasteful and time-consuming. Instead, missions could be better served if acquisition programs were to take a product line perspective to explore whether and how different needs, operational contexts, solution technologies, and potential changes could be anticipated and addressed through an ability to develop and deploy different solutions. By exploiting the similarity inherent in alternative solutions to perceived mission needs, a product line acquisition could create a capability for the rapid production, deployment, and evolution of multiple products, each customized to suit specific needs.

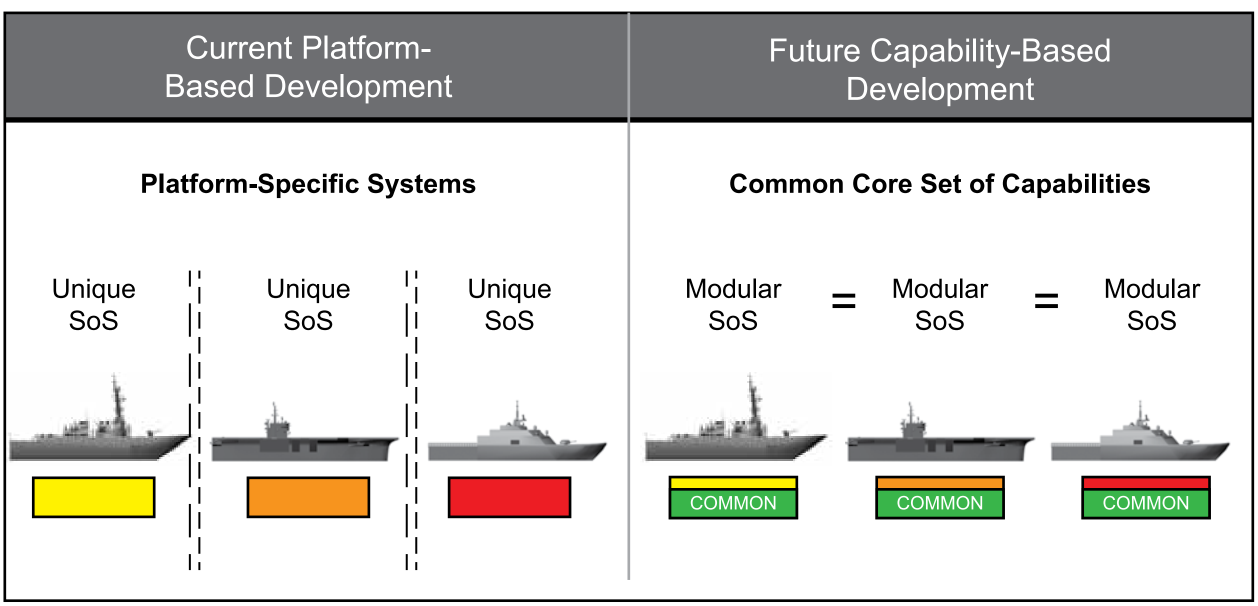
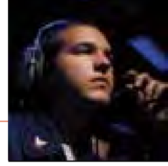


Figure 3. Surface Navy Product Line Vision



SoS Enablers

SoS enablers include technical competency, architecture, enterprise requirements, and a systems engineering management plan (SEMP).

Technical Competency

An understanding and an acceptance of the need to develop and maintain a foundational enterprise technical competency are both required for enterprise-level integrated mission systems. The Navy needs to nurture and sustain a cadre of technical experts in its warfare centers because those experts are in the best position to understand the operations, requirements, and system instantiations across ship classes (i.e., aircraft carriers, amphibious platforms, and surface combatants) and across system domains (e.g., combat system, C4ISR [Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance], aviation, hull, mechanical and electrical, and computing). SoS engineers (SoSEs) need broad experience working on different programs during their careers, and they need to have worked at the detailed technical level. Additionally, they need to be federal employees to facilitate access and visibility across programs. Multiple Program Executive Offices must be able to trust the SoSEs as honest brokers and technical authorities, especially when their recommendations sometimes contradict recommendations of subordinate program managers.

Architecture

PLA development is a critical enabler for moving to a product line approach. A common architecture consists of an enterprise architecture, system architecture, and software architecture. All are distinct, but interrelated levels compose the overall architecture. Enterprise architecture defines business structures and the processes that connect them.[4] It further describes the flow of information and activities among various groups within the enterprise to accomplish an overall business activity. A repeated theme from SoSE lessons learned is the need for a clear understanding of integration scope, end-user requirements, and a systems engineering management process across all stakeholders. System and software architectures describe the system elements and software components and the interactions of a complete system. In a product line approach, an architecture reference model is established first to ensure common understanding of terminology, functional allocation, and data flow among system components. The reference model is then mapped onto a reference architecture to define a PLA that is used to define specific system architectures. PLAs should address the evolution of the capabilities in order to address future requirements. Quality attributes, such as modifiability, extensibility, performance, etc., facilitate assessment of architectural options. Software patterns such as publish/subscribe provide well-known solutions to architectural problems, such as extensibility; however, it should be noted that various patterns may have negative impacts on related quality attributes, such as performance. Architectural relationships are shown in Figure 4.

Enterprise Requirements

The migration of existing programs to a product line approach may require significant effort to align platform mission system specifications. Figure 5 presents a notional approach for moving from multiple unique specifications to product lines for surface combatants, carriers, and amphibious platforms. NSWCDD manages requirements by functional domains, as well as by mission areas, to facilitate

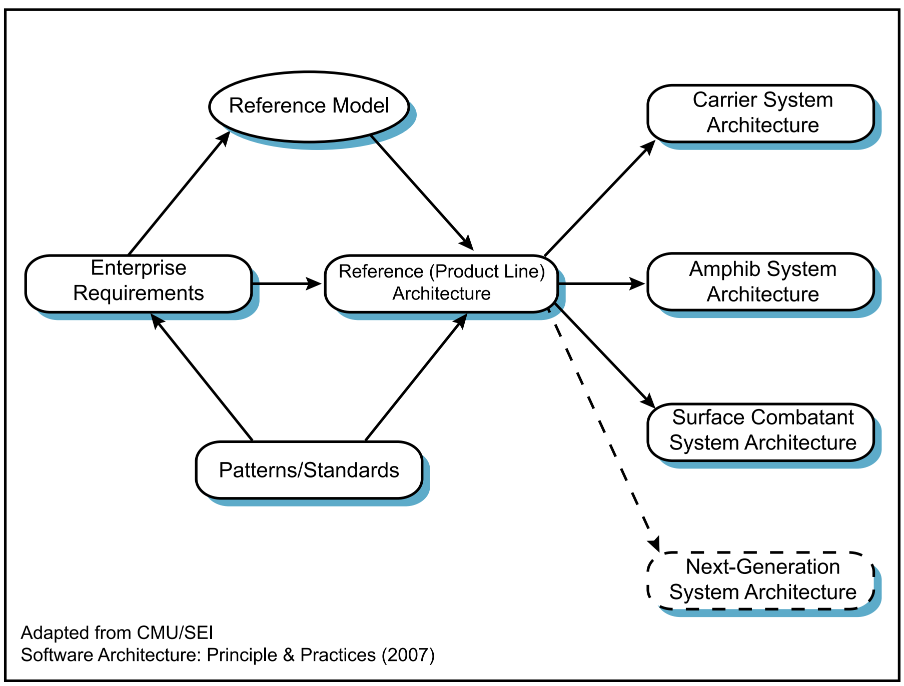


Figure 4. Architectural Relationships[5]

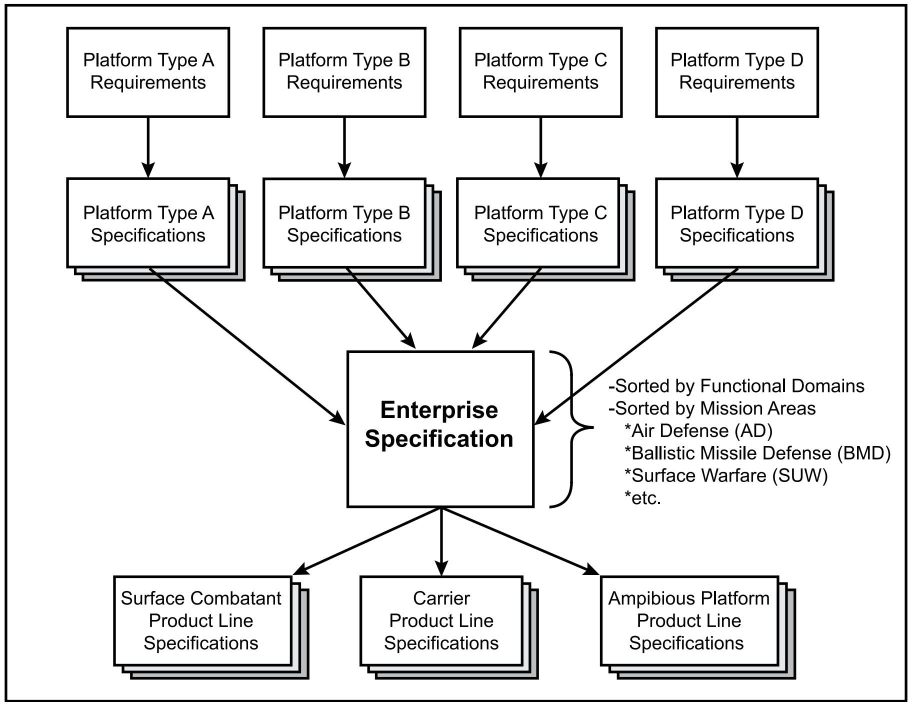


Figure 5. Mapping of Existing Requirements to a Product Line Approach

allocation to combat system elements within the architecture and to assess capabilities through mission area analysis to specific product line requirements.

Enterprise Systems Engineering and Management Plan

As defined by industry standards, such as *the Standard for Information Technology – Software Life Cycle Processes* (IEEE 2207),[6] establishment of an enterprise SEMP is critical for moving an organization toward a product line approach. The SEMP should provide (1) technical program planning, implementation, and control; (2) the systems engineering process; and (3) methodology for specialty engineering integration.

Challenges

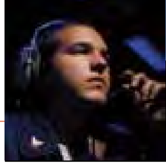
There are a number of challenges to the SoS approach; these include organizational, working with industry and academia, and political challenges.

Organizational

The Navy is organized for systems acquisition in a way that reflects our historical planning, funding, and acquisition execution (the verticals). Requirements are defined around platforms as opposed to product line capabilities (the horizontals) that can be employed across multiple platforms. Because organizations tend to reflect the environment in which they work, both the acquisition community and the customer side of the Navy are aligned to the vertical perspective. The most effective mitigating action to this challenge is to organize the requirements and budget infrastructure, including how appropriations are structured, to better reflect the benefits of the horizontally integrated enterprise.

Working with Industry

Industry must become a willing and effective partner. Businesses participate in procurement and evaluate their competitive position in relation to each other based on potential work, reward, and future opportunity—whereas NSWCDD supports integration plans that support healthy industrial opportunities as well as maintain maximum system performance for the sailor and value for the taxpayer. Under this new, open business model, opportunities for competition will increase within the industrial base, encouraging best-of-breed capability selection.



Working with Academia

Academia is a significant contributor in research and experimentation with new technology. It is important that NSWCDD includes academia in collaborations to continue to stay on top of the technology and implementation curve. It is also important that academia be kept current with the latest Navy SoS solutions and challenges so that future generations of engineers can be trained and prepared to replace the current work force. There is a variety of external challenges to overcome to achieve an open business model. We must capitalize on the forward-thinking and involvement that academia provides.

Political

Congress must be engaged as a willing partner and effective ally and have a clear understanding of the business model. The Navy will need to work with the Congress to clearly articulate the value and options to manage these within an enterprise construct.

Conclusion

The surface Navy requires a centrally managed, technically founded, large-scale SoS engineering capability at the cross-platform, combat system level to effectively manage combat system enterprise development. The approach to move toward an enterprise warfare systems environment for surface combat systems is centered on establishment of a product line approach for developing reusable components that can be assembled by the platform system integrators into systems that meet all the requirements of a particular ship class and enhance broad Navy warfighting. The focus, therefore, needs to be on key technical initiatives to enable this evolution. Notwithstanding, an enterprise organizational structure, continuity of leadership, and revitalization of government technical roles in the Navy's warfare centers enable this evolution. The need to transition the surface Navy's combat systems acquisition processes, technical underpinnings, and organization to a product line approach is pressing. The benefits to be derived from implementation of the new business model and enterprise systems engineering principles extend from tangible cost savings to rapid and effective integration of warfighter capabilities. The transition of the surface combat system acquisition enterprise to the new business model will be essential to Navy efforts to achieve its objectives for the size and strength of its surface combatant ship force.

NSWCDD has a long heritage of integrating increasingly more complex systems into the warfighting capability for the nation. With an enduring technical professional development program, NSWCDD has successfully shown the value of engineering rigor within the systems hierarchy (i.e., components, systems, ships, and force). Consequently, an aggressive yet paced reinsertion of NSWCDD as the prime integrator for targeted major weapon system acquisitions represents a sound Navy strategy.

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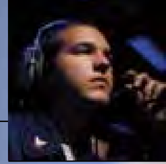
AEGIS



Product Line Systems Engineering (PLSE)

by Gilbert Goddin and Chris Knowlton

The Navy has long applied a product line-like approach to selected subsets of its overall warfighting capability. For example, the weapons control system for the Tomahawk cruise missile has been fielded in many configurations across several surface ship classes as well as in the submarine fleet. Adaptations were made to accommodate the needs of each host platform, but most of the weapons control software was taken from a common product line core. Similarly, the Aegis Combat System has been differentiated into many product variants tailored to multiple baseline variations across two classes of ships. Reapplication of common features that proved successful, while introducing new capabilities in later baselines, was an effective way to develop the product line over time. Treating the core combat systems across a wider variety of surface combatants as a single product line, however, is just beginning.

The concept of a product line is well established in the commercial sector where this approach has been used by car manufacturers, cell phone makers, and computer companies to create a variety of unique products tailored to specific applications, all based on a common core. The Boeing Company, for example, developed the 757 and 767 air transports as a product line. The parts lists for these two very different aircraft overlap by about 60 percent, thereby achieving significant economies of production and maintenance.[1] When this concept is applied to software, a product line is a related group of software-intensive systems developed from a set of common core components or a common source library. The rationale for doing this is typically to improve development time, cost, productivity, and quality.

Evolving Product Line Approach

As each surface Navy combat system moves towards a predictable, repeatable development cycle for fielding new capabilities in advanced capability builds (ACBs), it will become increasingly possible to coordinate development schedules across platforms and find opportunities for product line solutions supporting shared operational needs. However, a change in engineering methodology is required. Instead of stove-piped systems engineering focused on unique combat system programs, a product line systems engineering (PLSE) approach is being considered as the underpinning to the future surface combat system acquisition process.

The PLSE approach is very much a work in progress, but several characteristics are emerging. PLSE is clearly a system-of-systems engineering challenge, requiring the systems engineering organization to look across multiple ship classes as well as across multiple epochs when determining optimal plans and approaches for implementing new capabilities. PLSE makes use of the same systems engineering techniques and strategies that have become familiar in other complex software-intensive combat systems engineering projects. What makes PLSE unique is that it widens the aperture of what is considered a system to include an entire potential product line, rather than just a single ship combat system. The systems engineering approach remains familiar, however, and consists of the following:

- Multiplatform mission thread analysis
- Requirements analysis
- Architectural analysis
- PLSE management

Multiplatform Mission Thread Analysis

Multiplatform mission thread analysis is a technique that shows great promise for use in PLSE. In a conventional mission thread analysis, a particular operational problem or challenge is examined in detail from end to end to determine alternatives and best options for addressing that challenge. The multiplatform mission thread analysis extends conventional analysis by identifying shared operational needs across platforms and evaluating common product line solutions where appropriate.

To conduct a mission thread analysis, a detailed operational scenario is first established. This scenario should accurately describe the operational environment and the expected challenges for a particular mission area and for a particular timeframe. For combat systems, mission threads are often threat driven, so they should make use of accepted, and whenever possible, common representations of current and future threats and their associated environments validated by the intelligence community. The mission thread scenarios themselves should depict force-level employment of a system of combat systems to counter the threats under consideration, according to an accepted concept of operations, and from approved sources such as design reference missions for programs slated to receive the combat systems under analysis. Once a set of operationally relevant scenarios is selected for the mission thread analysis, the scenario is examined using current combat system capabilities and inventories. The expected performance of current combat systems is determined through analysis of operational effectiveness, including such measures as probability of kill, survival of the examined unit or force, or attainment of mission objectives over time. Often, this analysis will reveal weaknesses or capability gaps that should be addressed through future combat system product line upgrades. The results of this gap analysis lead to a more detailed statement of the operational problem and set the stage for identification of options for closing the operational gaps. The next step of mission thread analysis is identifying possible (or leading) options for product line upgrades.

Once a set of upgrade options is identified, it is further analyzed from the perspectives of performance, cost, schedule, and risk to find the preferred options for further systems engineering development and implementation. When applied to the combat system product line, one of the key goals of the mission thread analysis is to examine all of the surface combatants in the product line to determine how the new capability might affect each one of them. For example, many combat systems in the product line share a requirement to provide tactical air control for aircraft assigned to them, but only large-deck, aviation-capable ships like aircraft carriers require a full air traffic control capability to manage large numbers of aircraft in the immediate vicinity of the ship. Evaluation of these types of differences in mission are important drivers that will help determine which requirements are shared between members of the combat system product line and which are unique to a single platform.

Another key goal of the product line mission thread analysis is to examine the operational gaps and the resulting upgrade options from the perspective of the desired product line architecture for the combat system. When upgrade options are developed in this context, the proposed solutions are more likely to drive commonality into the product line over time. A product line mission thread analysis provides insights that drive requirements and architecture decisions. When the mission thread analysis reveals a need for common functionality across platforms, a set of upgrades and modifications to the product line architecture is defined. A description of the scope of each change is produced, including boundary conditions and major functionality to be included in each affected product line component. When performing this analysis from a cross-platform perspective, care must be taken to ensure that the functionality specified satisfies the minimum needs of the most stringent user. This analysis is performed at varying levels of detail until a detailed set of "design-to" and "build-to" functions result. These results can then be translated into detailed design requirements for the product line component at hand. Once again, care must be taken to ensure that the most stringent cases are considered to ensure that the resulting requirements satisfy the most stressing scenarios. Using this systems engineering approach, requirements and architecture are developed together at increasingly higher levels of detail until the system is fully designed. This approach also ensures an integrated design since all requirements are likewise defined using an integrated approach.

Product Line Requirements Analysis

Operational requirements for joint and naval forces are initially expressed in the form of very high level Mission Area Initial Capability Documents (MA-ICD) or other capstone statements of mission requirements. For example, a Theater Air and Missile Defense (TAMD) MA-ICD was developed in 2004 to describe desired operational capabilities and perceived warfighting gaps for naval TAMD forces. These desired force capabilities are inherently cross-platform requirements, with a variety of naval and joint platforms cooperating to meet the overall force warfighting need.

One of the first steps in upgrading individual combat systems, in response to the MA-ICD, is to extract the capabilities pertaining to a particular combat system and capture the subset of operational requirements for that specific combat system. For example, a platform-specific operational requirements document (ORD), capabilities development document (CDD), or naval capabilities document (NCD) is generated or updated to capture the operational capabilities applicable to the particular platform. A weakness in the current approach is that each platform performs its own analysis to determine how it should contribute to the overall force mission capability and extracts what it perceives to be the correct subset of MA-ICD capabilities for inclusion in its own platform-specific CDD or NCD. Each platform does this in relative isolation from other programs. The resulting CDD or NCD then becomes the primary driver for further system specification, architecture, and development. As shown in Figure 1, the current systems engineering process becomes platform-centric very early in the development process as each platform follows its own unique solution path.

A product line requirements analysis approach would help address this divergence as this approach takes advantage of the fact that the capstone MA-ICD already contains statements of operational capability that span a number of naval and joint platforms. As shown in Figure 2, the top-level operational capabilities common to more than one platform could be developed as (or at least should be considered as candidates

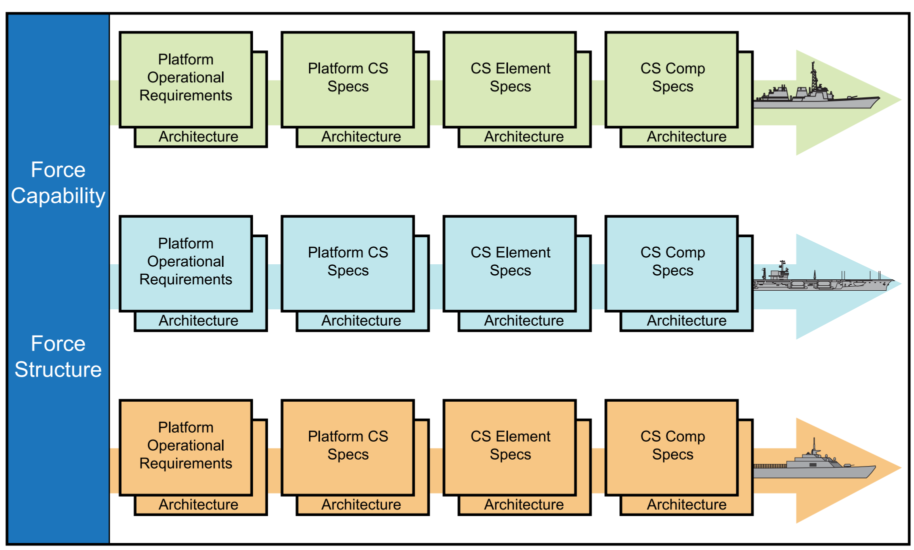


Figure 1. Platform-Centric Systems Engineering Approach

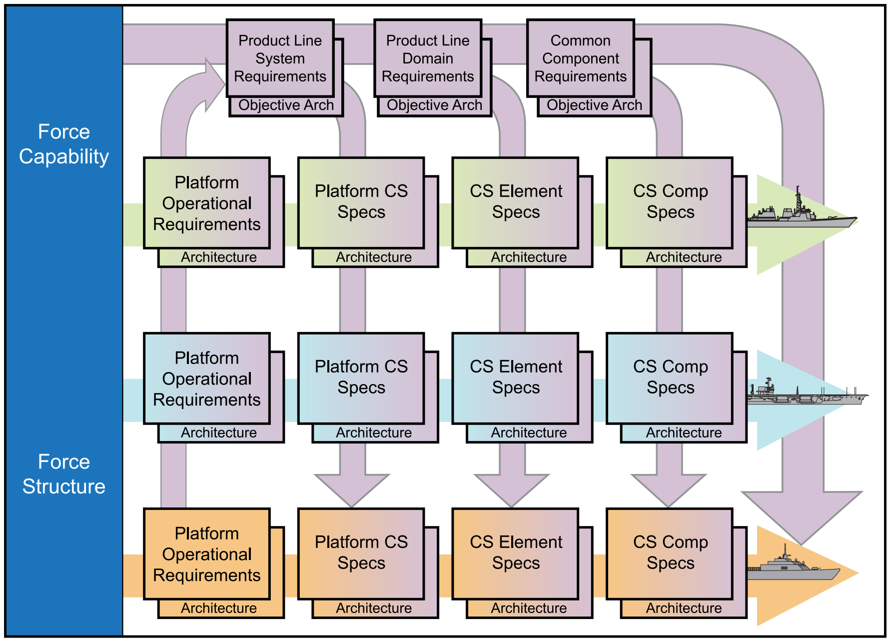


Figure 2. Product Line Systems Engineering Approach

for) common development using the product line systems engineering approach.

The first step in the PLSE approach is to perform product line requirements analysis on the top-level, cross-platform mission area requirements for a capability using the multiplatform mission thread analysis approach described earlier. This approach views the platforms as swim lanes for the analysis and high-level combat system functions allocated to these platforms in an end-to-end analysis. After a sufficient number of iterations and decomposition of this process, the aggregated functions are then translated into a set of operational requirements for each platform. In this manner, the operational requirements are integrated and deconflicted. Based on the resulting operational requirements (i.e., CDD, NCD), subsequent requirements analysis efforts focus at the system level to identify common versus unique combat system requirements. Therefore, in addition to allocating operational requirements to each affected system's CDD or NCD in a coordinated manner, those capabilities common across platforms are identified up front. All common requirements are then generated and included in a product line system requirements database that contains the common requirements in the context of the common architectural framework across all platforms. Platform-unique requirements continue to be defined by the individual programs. Accordingly, a full system-level requirements specification for each program consists of program-unique requirements and common requirements from the product line system requirements database.

Product line system requirements are best maintained using a modern requirements management tool such as IBM Telelogic's Dynamic Object-Oriented Requirements System (DOORS). The database contains both the requirements statements as well as attributes indicating the platform to which each is applicable. Initially, the product line system requirements database would be populated by drawing from the system specifications of existing combat systems. Although these individual system specifications were not coordinated, they contain similar requirements in many areas. Once all platform system specifications are available in a common database, the product line system requirements can be created by normalizing these requirements by grouping similar specifications and rewriting them as common statements of functionality and performance. When new warfighting capabilities are identified for addition to the combat system product line, the resulting common cross-platform combat system requirements could then be added to the product line system requirements database. Then, when individual platform combat systems engineers analyze their CDD or NCD to create their system-level specifications, they can draw requirements directly from the product line system requirements database for those capabilities that are common to more than one platform.

Product Line Architecture Analysis

Concurrent with the product line requirements analysis, the architectural impacts of integrating the new warfighting capability in the surface combatant fleet need to be analyzed. The goal of this architectural analysis is to provide a mapping of the operational requirements onto a system (or in this case, product line) that can deliver the desired capabilities. Conducting this analysis for the product line introduces several new challenges when compared to architectural analysis for a single ship combat system. These challenges include:

- Assessing and resolving architectural differences between members of the product line
- Developing and upgrading a common product line objective architecture
- Determining appropriate migration plans
- Integrating architectural plans and schedules between product line members

Architectural analysis and requirements analysis are conducted concurrently because the outputs of each analysis effort feed the other. At the cross-platform level of architecture analysis, one of the major goals is to map the required operational capabilities for the force as a whole onto the individual ship combat systems. The output of the architecture effort is a partitioned set of requirements, allocated appropriately across the platforms. These partitioned requirements can then be mapped onto each combat system's system-level architecture to come up with the appropriate partitioning of requirements at the system level. One of the key differences between product line architectural analysis and the traditional approach is the earlier point at which product line architectural analysis occurs in the systems engineering process.

Traditionally, force-level operational requirements are first allocated to individual ships before any architectural analysis begins. Architectural analysis is then conducted on just the set of requirements for that ship, and the resulting architectural decisions affect only that ship. In product line architectural analysis, the force-level operational requirements are assessed to extract the corresponding system-level requirements so that architectural impacts on the product line are identified as a whole, particularly on common product line components. These are determined prior to final allocation of system-level requirements to individual members of the product line. As a result, not only are system-level requirements allocated to the platforms but, when appropriate, technical solutions are allocated in the form of plans, specifications, and component-level architectures as well for components designed to meet the operational requirements for all members of the product line. These common, planned component upgrades then become a constraint on the receiving systems, which must be engineered into their respective platform architectures. Levels of architecture (and requirements) include cross-platform operational architecture, platform-level systems architecture, platform-level element architecture, and platform-level component architecture.

In general, surface combatants are multi-mission combatants. As a result, they participate in several mission areas at the same time. For example, an Aegis combatant supports integrated air and missile defense, undersea warfare, and strike warfare concurrently. The operational architectures for each of these warfare areas are different but must be woven together into a single, cohesive system design at the platform level. This introduces additional architectural considerations that must be addressed at the system level over and above those mandated when considering the mission operational requirements alone. For example, as ballistic missile defense operational capabilities are integrated, resource contention and multi-warfare interactions with other air defense requirements of the ship must be considered, as well as manning constraints and interactions with other mission areas. The level of maturity of the combat system product line must also be considered.

PLSE Management

Achieving the goal of developing all surface combat systems using a product line approach requires that a new governance and decision-making process be put into place for product line systems engineering management. This new management process must address several new issues that have emerged when all combat systems are viewed as a system of systems. Product line questions that must be answered include:

- Which platforms share common operational requirements?
- Which capabilities should be developed as part of the common product line and which are unique?
- Which platform should develop the common products?
- When should these common products be introduced onto the host combat systems?

Clearly, managing a product line systems engineering process demands significant coordination and communication, because it involves systems engineering organizations at the overarching product line level – the individual platforms, the systems engineering agent contractors for each of the platforms, and possibly third-party contractors and organizations assigned responsibility for development of common components and capabilities. Production schedules for all of the platforms in the product line have to be communicated, assessed, and deconflicted to enable coordinated cross-platform development, particularly when there are critical path interactions between programs and platforms. The understanding of requirements, specifications, and technical characteristics of combat system component designs must be exchanged reflecting several levels of detail. Cross-platform and overarching product line governance structures and technical interchange forums need to be established to ensure alignment.

Because the surface Navy combat system product line is a system of systems produced by a variety of organizations over time, the communication of technical plans and schedules between programs is critical to ensuring effective coordination. This communication across and among related combat system contributing programs is beginning to take the form of a Capability Phasing Plan (CPP). The CPP is a concise summary of planned upgrades to a subsystem, component, or element, and include several key features:

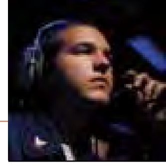
- A listing of upgrades planned for the system
- A brief description of the upgrades
- A time-phased plan for rolling out the upgrade, preferably tied to particular ACBs for the targeted host combat system(s)
- Any known dependencies or relationships between these upgrades and those planned for other related systems, particularly if upgrades must be delivered together as a package to a combat system platform
- Funding profiles related to the upgrade

Although a final format for the CPP has not been defined, the content listed above has been useful in coordinating acquisition activities across the system of systems. One way to maintain and exchange information is through the war room approach, in which all combat system feeder programs contribute and maintain their upgrade roadmaps to a common space that all other programs can access. Coordination across programs then can take the form of formal and informal visits and reviews of the technical and programmatic information compiled in the war room to ensure consistency and synchronization between efforts and, when warranted, to spark more detailed follow-on discussions between combat system constituents. In addition to maintenance of a physical war room facility as a focal point for cross-program roadmap information, this data needs to be made available to all stakeholders through an integrated development environment with adequate controls to protect program data while making roadmap changes and updates available to all interested parties.

Implementing Product Line Systems Engineering

Implementing product line systems engineering for surface combat systems requires a fresh look at the traditional government and industry roles and responsibilities in the acquisition process. The responsibility for systems engineering of naval surface combat systems is a shared task, with the government providing program oversight, program management, and technical review of systems engineering efforts for the affected combat systems. An industry prime contractor provides much of the technical analysis and detailed systems engineering effort. This model has worked well because each platform's combat system has been maintained as a separate entity associated with a dedicated prime contractor.

Moving toward product line systems engineering and acquisition will require many important systems engineering decisions affecting multiple combat systems and industry partners. These decisions include determining whether to develop or procure particular upgrades, which programs should be funded to develop a common capability that will later be shared between programs, and other procurement-sensitive systems engineering decisions. These types of product line combat systems engineering decisions are best made within the government, although the government will continue to rely on the technical expertise of its combat system contractors. That said, the government must increasingly develop and rely on its own technical resources for product line systems engineering in key areas of high-level system architecture definition and planning and combat system requirements management. This includes system-level specification development and maintenance of the program roadmaps for all combat systems, contribution elements, feeder programs, and the product line itself.



NSWCDD's Role in PLSE Process Development

The Naval Surface Warfare Center, Dahlgren Division (NSWCDD), has been a significant contributor to the Program Executive Office for Integrated Warfare Systems (PEO IWS) in conceptualizing and documenting key systems engineering processes for PLSE. These processes span the systems engineering spectrum from early capability planning and programmatic support through development and fielding of capabilities on individual platforms. The approach taken to define and capture these evolving processes and their associated business rules is to apply a use case modeling approach using the Unified Modeling Language (UML). Figure 3 shows several use cases identified as functions of PEO IWS in executing PLSE, external agencies that interact with PEO IWS in carrying out these use cases, and primary areas of interaction.

For each of these use cases, more detailed activity diagrams were generated to further define the use case. Each organization involved, both inside and outside of PEO IWS, is assigned a vertical swim lane, which contains the process steps (i.e., activities) performed by that organization. Figure 4 is an example of one such activity diagram for the use case "Conduct Enterprise Systems Engineering," which focused on the cross-platform, product line aspects of the systems engineering process.

These activity diagrams provided a convenient mechanism for describing both the processes and the organizational roles and responsibilities for PLSE. This approach captured the process knowledge as it was evolving, and it served as a way to communicate the current state of understanding with other process stakeholders who then provided valuable inputs for extending and refining the activity diagrams to reflect their particular areas of expertise.

NSWCDD used the results of this PLSE process modeling effort to generate the PEO IWS Systems Engineering Concept of Operations (SE CONOPS). The SE CONOPS defines the PEO IWS Product Line Systems Engineering Process and the Concept of Operations for Combat Systems Engineering across surface Navy platforms, which is applied to all programs and projects within PEO IWS. The initial release of the SE CONOPS was signed by RDML Benedict in April 2010. (PEO IWS Systems Engineering Concept of Operations, Version 1.0, dated 22 April 2010). NSWCDD is leading efforts to further define and update the PLSE processes to be included in this forthcoming revision. Figure 5 identifies the planned activity diagram updates.

Conclusion

The Navy's approach to product line systems engineering across surface combat systems is still a work in progress. PLSE is not an attempt to make the combat systems on all ships the same, but rather, a disciplined engineering methodology to reduce overall acquisition cost by deploying common core capabilities across platforms and by developing unique functionality for individual ships where necessary to fulfill unique system requirements. In order to achieve the goal of delivering new capabilities using PLSE, a new governance and decision-making process is required. Key to success is collaboration

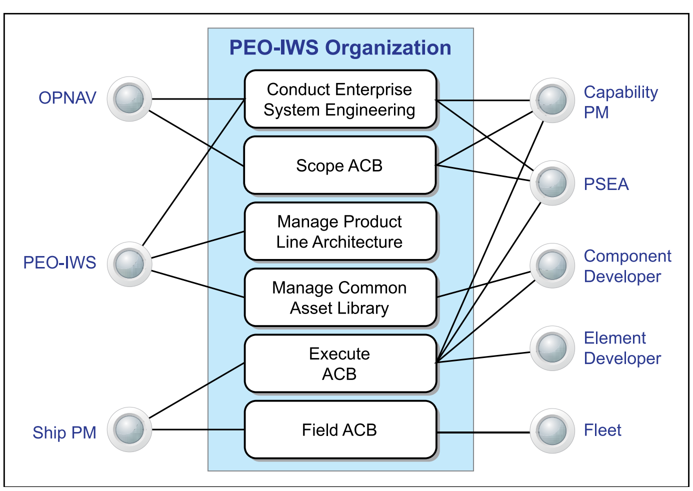


Figure 3. PLSE Use Case Diagram for PEO IWS Product Line Systems Engineering

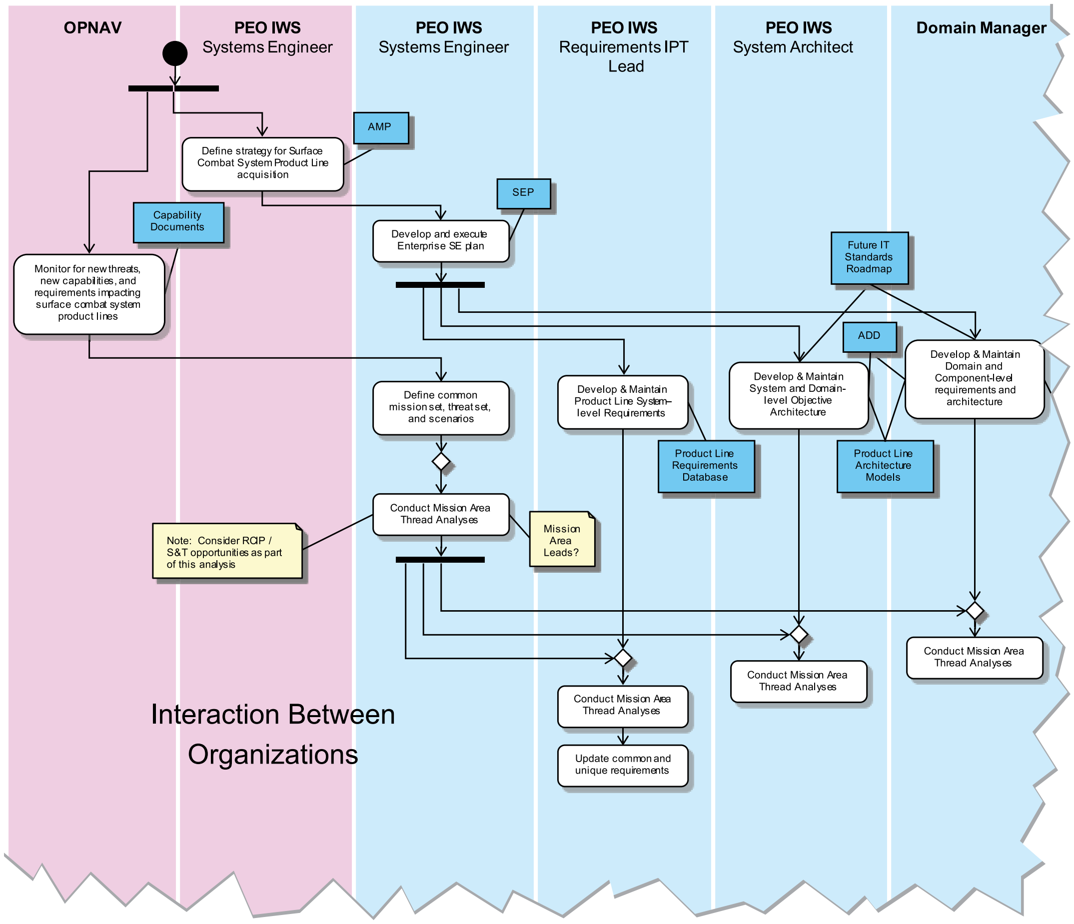


Figure 4. Activity Diagram for PLSE Process

by resource sponsors, program managers, ship integration program managers, platform systems engineering agents, and participating acquisition resource managers across multiple ship classes in government-led requirements definition. PLSE needs to commence with operational requirements and continue until the system-level requirements are complete for each combat system in the product line. Institutionalizing this rigorous product line requirements and architecture analysis approach undoubtedly will lead to common system requirements, further leading to the development of common components for all surface combat systems supporting future Navy warfighting needs.

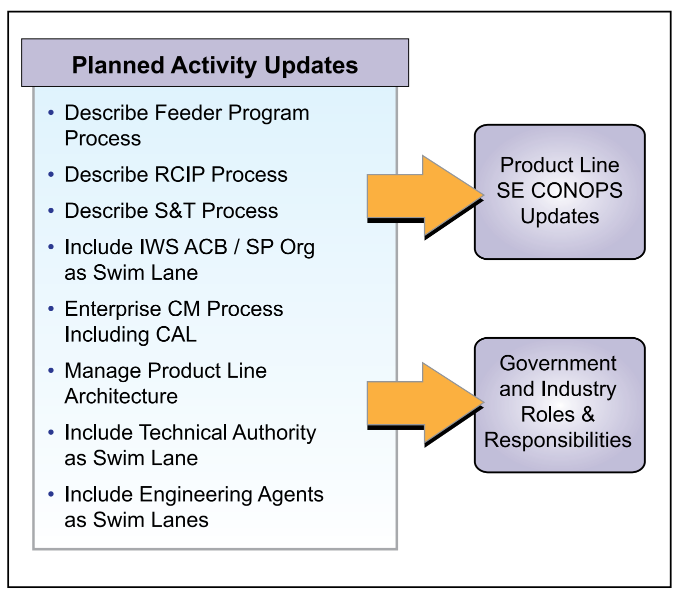


Figure 5. Planned PLSE Process Updates

Acknowledgment

Warren Lewis (Strategic Insight Inc.) contributed to this article.

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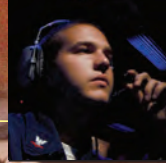


Naval Integrated Fire Control – Counter Air Capability-Based System-of-Systems Engineering

by Jeffrey H. McConnell and Lorra L. Jordan

"Understanding the environment in which a system or system of systems (SoS) will be developed is central to understanding how best to apply systems engineering (SE) principles within that environment."[1] Since 1996, the Naval Integrated Fire Control – Counter Air (NIFC-CA) project has been striving to develop an SoS capability to defeat overland cruise missile and Over-the-Horizon (OTH) air warfare threats. Lacking the luxury of a "directed" SoS SE organization with component systems subordinated to the overarching SoS, the NIFC-CA project has utilized the "acknowledged" SoS SE methodology. This approach empowers an SoS SE team to work collaboratively with independent component system SE teams to achieve SoS capabilities and objectives. The NIFC-CA SoS SE approach has been very challenging but also rewarding and is viewed by the Deputy Under Secretary of Defense for Acquisition and Technology (DUSD(A&T)) as a pilot model for future SoS acquisition programs. With the successful completion of all critical design review (CDR) milestones in 2009, a review of the NIFC-CA SE environment, approach, and accomplishments is timely and instructive for similar developmental programs.

NIFC-CA Background

In a letter dated January 11, 1996, Mr. Paul Kaminski, then Under Secretary of Defense for Acquisition and Technology (USD(A&T)), and the Vice Chairman, Joint Chiefs of Staff (VCJCS), Admiral W. A. Owens, initiated action to address the emergence of the overland cruise missile threat.[2] Very challenging situations are presented by this threat when the detection and illumination of cruise missiles, that can also change course and speed, become blocked by the Earth's curvature, coastal hills, mountains, and varying types of terrain.

Beginning with the 1996 letter, technologies and acquisition programs were given direction or guidance to ensure emerging developmental systems would include capabilities supporting the resultant Overland Cruise Missile Defense (OCMD) SoS. Specifically, OCMD was to be supported by the development of the Army aerostat program (known today as the Army Joint Land Attack Cruise Missile Defense Elevated Netted Sensor (JLENS)), improvements to the Navy E-2C and Air Force E-3 early warning aircraft, and advanced interceptor seeker development.

In 2002, the OCMD program was officially recast as the NIFC-CA project in a joint ASN(RDA) and VCNO letter.[3] This recasting documented the growth of project scope to defeat the OTH manned fighter and OTH anti-ship cruise missile (ASCM) threat in addition to the original OCMD mission. The letter also directed Program Executive Officer – Integrated Warfare Systems (PEO IWS) to establish a NIFC-CA Systems Engineering and Integration Project Office to "integrate across the elemental programs in support of the development and acquisition of a NIFC-CA Capability." NIFC-CA was to execute as a capabilities-based acquisition project, levying minimal requirements onto the component systems while deriving SoS capability from the union of these independent systems.

In 2010, NIFC-CA resolved into an advanced Family of SoS (FoS) engineering project that is working to combine multiple sensors through IFC-compliant combat systems to support extended range active missiles. The NIFC-CA FoS officially includes three complete SoS known as "killchains" as illustrated in Table 1. Each SoS killchain consists of elevated and surface sensor(s), a sensor network, a weapon control system and an active missile. The balance of this paper will concentrate on the FTS killchain.

The NIFC-CA SoS SE Environment

"Control your own destiny or someone else will." – Jack Welch – former CEO of General Electric

An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities.[4]

The ability to control the outcome of any SoS development is a function of the authority available to the SoS manager or SoS integrator. In all SoS acquisition programs, the developmental environment is a key driver of what can be accomplished, how the systems acquisition and systems engineering will be performed, and whether the ultimate outcome is successful or not.

The SoS "type," as described below, dictates how much authority and control is available to the SoS manager and systems engineering team to achieve SoS objectives. The type further addresses SoS component system independence and the manner in which the component systems are aligned, either by direction or cooperation, to achieve SoS capabilities.

Table 1. The NIFC-CA Family of System of Systems

SoS (Killchain)	Remote Sensors	Sensor Network	Weapon Control System	Active Missile
From-the-Air (FTA)	E-2D F-18 E/F	Link-16	F-18 E/F	AMRAAM
From-the-Sea (FTS)	E-2D JLENS	CEC	Aegis ACB12	SM-6
From-the-Land (FTL)	E-2D JLENS TPS-59 G/ATOR	CTN	CAC2S	- None - Currently TBD

AMRAAM - Advanced Medium Range Air-to-Air Missile (AIM-120D)
CEC - Cooperative Engagement Capability
CTN - Composite Tracking Network (CEC Network hosted on USMC land-mobile vehicles)
CAC2S - Common Aviation Command and Control System
G/ATOR - Ground/Air Task-Oriented Radar

Table 2. SoS Types

Virtual	A virtual SoS lacks a central management authority and a centrally agreed upon purpose for the system of systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain it. The DoD net-centric policies and strategies that connect all DoD systems to virtual networks for information sharing are creating a virtual SoS.
Collaborative	In a collaborative SoS, the component systems interact more or less voluntarily to fulfill agreed upon central purposes. The Internet is a collaborative system. The Internet Engineering Task Force works out standards but has no power to enforce them.
Acknowledged	An acknowledged SoS has recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the component systems are based on collaboration between the SoS and the component system.
Directed	A directed SoS is one in which the integrated SoS is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central, managed purpose.

SoS Type

The DUSD/A&T Systems Engineering Guide for SoS describes the four types of SoS typically seen across DoD and industry. Table 2 lists all four types with a short description of each to help delineate and define the "acknowledged" SoS approach utilized by NIFC-CA.

The virtual and collaborative types are not utilized for the development of SoS that have the intended purpose of delivering lethal force. The more intentional systems engineering processes inherent in the acknowledged and directed types of SoS are essential to lethal systems development.

The Missile Defense Agency (MDA) is a contemporary example of a directed SoS type. On January 2, 2002, the Secretary of Defense refocused and reorganized the existing Ballistic Missile Defense (BMD) program into the newly formed MDA with the mandate and authority to manage all aspects of the component systems as a synergistic whole. This SoS type is very attractive but a rarity, typically mandated at the secretariat level for national priority programs such as the Strategic Systems Program, the National Reconnaissance Office, and the MDA.

NIFC-CA is an example of and a USD pilot project for the "acknowledged" type of SoS. NIFC-CA is charged with bringing together independent major defense acquisition programs (MDAP) as component systems of the NIFC-CA SoS. These programs have their own operational requirements, specific funding lines, independent developmental timelines, and staggered deployment schedules. The mandate to collaborate with and support the NIFC-CA project management and systems engineering team has been communicated from senior USD, ASN, and Navy leadership but still presents a tough balancing act for all program managers involved.

NIFC-CA Acquisition Leadership and Management

Successful management of acknowledged SoS SE projects requires reaching across organizational boundaries to establish an end-in-mind set of objectives and the resourced plan for achieving those objectives. The acknowledged SoS type increases the complexity, scope, and cost of both the planning process and systems engineering, and introduces the need to coordinate interprogram activities and manage agreements among multiple program managers (PMs) as stakeholders who may not have a vested interest in the SoS.

Through 2002, as the Navy solidified its programmatic approach to NIFC-CA development, the organizational structure depicted in Figure 1 evolved. This picture was completed in 2006 as PEO IWS-7, the NIFC-CA Project Office, established a collaborative government/industry systems engineering integration & test (SEI&T) team that is primarily

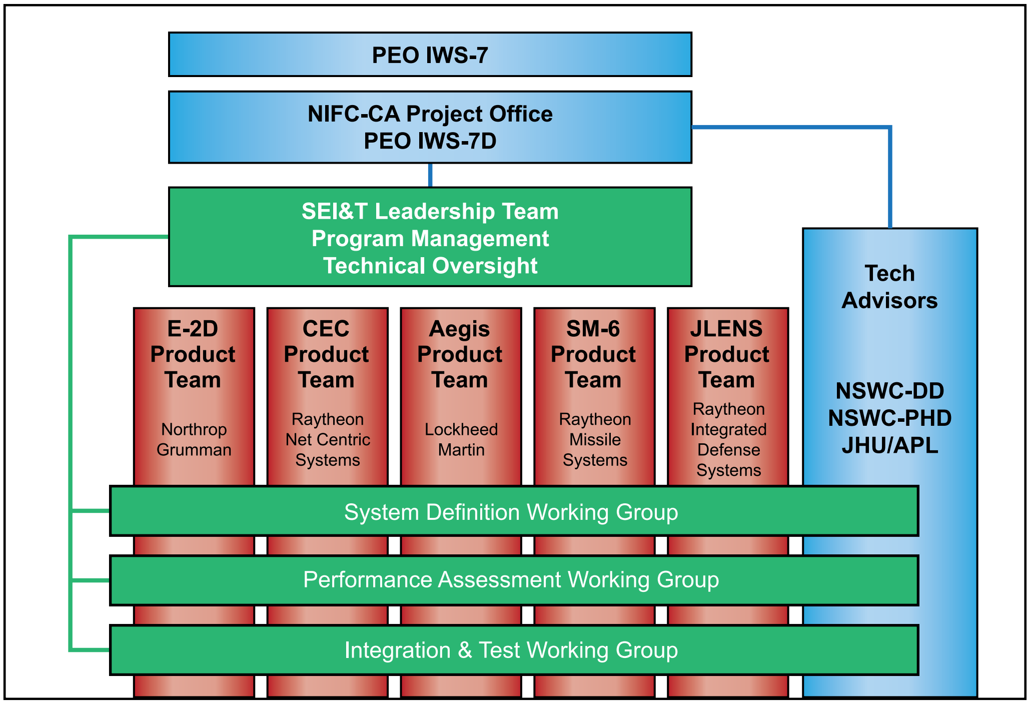


Figure 1. NIFC-CA SoS Management

composed of personnel from the NIFC-CA Project Office, government laboratories, academia, and industry (with team members from each component system).

The task of the NIFC-CA SEI&T effort is to ensure the component programs are integrated to achieve a viable SoS by matching individual system contributions to SoS performance goals. The NIFC-CA capability is not derived from a set of initial requirements leading to component program selection. Rather, the NIFC-CA capability is derived from the SoS performance predictions via analysis and/or SoS models and simulations that describe the expected performance of the component systems.

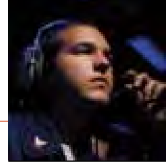
NIFC-CA Capability Acquisition and SoS Engineering

Over the past decade, the NIFC-CA government/industry team has made significant accomplishments across the acquisition spectrum both at the FTS SoS killchain level and within the supporting component systems. Figure 2 illustrates the disciplines, processes, tools, and products that have been executed throughout the development of the NIFC-CA Capability.

The challenge lying before the SEI&T team working with the component systems' engineering teams is summarized in the following basic statements:

1. The Aegis combat system was designed in the 1970s and has evolved and expanded dramatically ever since.
2. The Aegis combat system provides a self-contained, highly engineered anti-air warfare system with a dedicated phased array multifunction radar; a robust, time-critical command and decision system; and a semiactive interceptor (SM-2) that is tightly controlled all the way to intercept.
3. For IFC engagements, the SEI&T team was charged with uncoupling and distributing this single-system killchain across independent pillar systems consisting of multiple nonorganic sensors, connected via the CEC network to the Aegis Combat System so that it can control the SM-6 missile until it goes below the horizon, becoming active and independently concluding the engagement.

While Figure 2 takes on the form of the familiar Systems Engineering "V," the individual steps and functions performed within the chart may not seem familiar. Based on a limited budget and the acquisition/engineering management environment described so far, this chart describes the analyses and engineering deemed essential to reassemble the distributed killchain, automate remote sensor and interceptor management, and ensure performance against a wide range of threats in many theaters and scenarios.



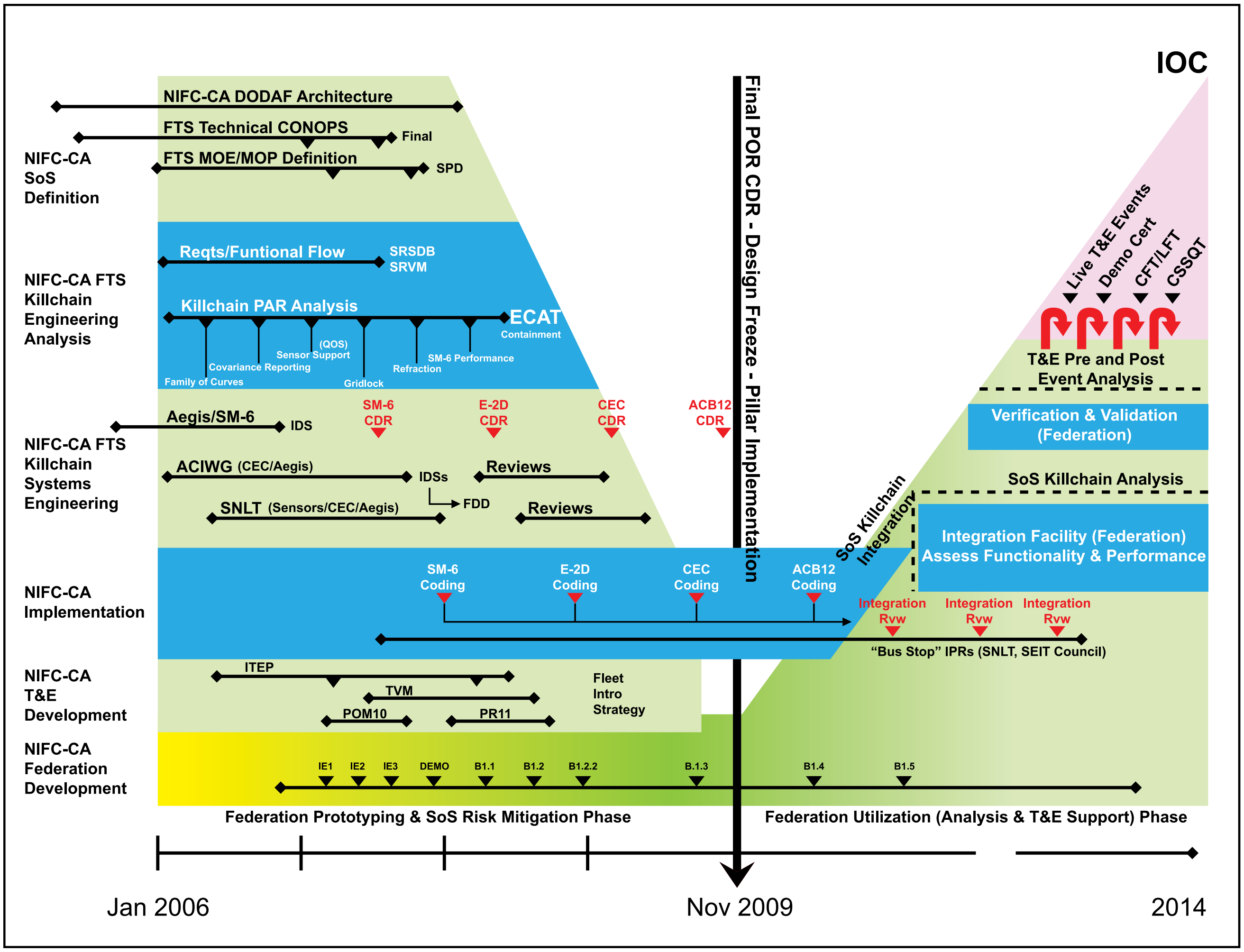


Figure 2. NIFC-CA Capability Acquisition and SoS Engineering

The key timeline drivers within this chart are the four CDRs listed that each component system was scheduled to meet within its system acquisition timeline. The challenge for the SEI&T was to execute and finalize all NIFC-CA analysis, functional allocation, and design documentation in time to support each CDR for each component system. The transition from analysis and engineering to implementation, integration, and T&E is denoted at the bottom of the V, marking when the final component system CDR took place in November of 2009. The following sections of this paper will discuss several of the processes performed on the left side of the V.

System Architecture Development

For NIFC-CA as an acknowledged SoS type, it became apparent that a good system architecture would be essential to NIFC-CA development. In 2002, NSWC Dahlgren began working with pillar program offices, FTA killchain system engineers, and prime contractors to develop a NIFC-CA DoD Architecture Framework (DODAF) architecture.

In 2006, with the establishment of the SEI&T industry team, architecture development drove toward a complete architecture with enough insight at the component systems level to validate NIFC-CA functional allocations and information exchange requirements (IERs) across the entire killchain. Details of the SoS functionality were added as killchain analyses and design work were conducted for each pillar. This effort ensured the allocated design fulfilled the operational architecture.

The NIFC-CA architecture has been utilized as the authoritative source of information to guide system engineering tasking as well as high level discussions with other military services, the Joint Integrated Air and Missile Defense Office (JIAMDO), and other organizations. The NIFC-CA DODAF architecture has proven to be a powerful tool for capturing the functionality, communications, and essential information of the

NIFC-CA SoS. It has fostered communications across the killchains and within the component pillar systems while documenting the requirements for incorporation of future sensors, weapons, and combat systems supporting IFC as well as future functionality and capability spiral evolution.

NIFC-CA FTS Killchain Engineering Analysis

As described earlier, the key engineering challenge within NIFC-CA FTS has been the decomposition of a tightly integrated real-time killchain and subsequent reallocation of that killchain across independent component systems. Killchain Engineering Analysis is an essential part of ensuring that the resultant distributed killchain will perform effectively and safely across all SoS component systems.

Within the collaborative environment of the government/industry SEI&T team, the entire FTS SoS killchain was reviewed and performance-critical and/or time-critical functions identified for detailed analysis. Performance Assessment Report (PAR) plans were developed and assigned to small teams partnering different prime contractors and government personnel to analyze these critical functions. Two examples illustrate the scope and importance of this analysis:

- The Containment PAR analyzed the maximum size error basket that would be required from the remote sensors via the CEC network in order to support SM-6 missile active seeker performance.
- The Sensor Support Quality of Service (QOS) PAR defined the attributes and parameters that would be requested by the weapons control system in order for CEC to find and provide remote sensors meeting that QOS request.

NIFC-CA FTS Killchain Systems Engineering

Based on the findings of the killchain engineering analysis and guided by the NIFC-CA DODAF architecture, working groups were formed to address specific killchain systems engineering topics. In order to engage component system program offices and engineers within the broader Navy IFC community, collaborative groups were created to facilitate engineering tasking and information exchange in the form of Interface Working Groups (IWGs) and Technical Interchange Meetings (TIMs).

Due to the staggered nature of the CDRs for each of the component systems and the early CDR date for the SM-6, an Aegis/SM-6 IWG was the first group to gather and develop the specific documentation artifacts for the interface between the Aegis ACB12 combat system and the missile. This is a historic working relationship going back several decades for all variants of the Standard Missile family. Even so, the SM-6 is a major upgrade in capability, and significant design and interface tasking had to be accomplished.

The Aegis/CEC IWG (ACIWG) was established next in order to design and document several CEC-to-Aegis interfaces. In order to allow many current and future sensor types to support SM-6 engagements, the Aegis WCS is being built to be “sensor agnostic”; essentially it will not know the specific characteristics of remote radars, just the real-time characteristics of their tracking information. To support this uncoupling, CEC was tasked to take on the function of finding and providing remote sensors that are able to meet Aegis Quality of Service (QOS) requirements for each engaged target. Therefore, the ACIWG took on the challenge of creating and documenting a new paradigm for IFC sensor support.

In mid-2006 it became apparent that a larger forum including engineers and leadership supporting CEC, Aegis, and all sensors was needed to discuss and document the detailed engineering that supports the overall NIFC-CA architecture. This forum was established as the Sensor Netting Leadership Team (SNLT). This team, working closely with the ACIWG, took on the challenge of fleshing out the mid-level architecture (IERs, functional allocation, operational sequence diagrams) and, eventually, the low-level integration agreements that are generally invisible outside of contractor development facilities. This latter category basically came down to discussions and agreements between two companies on either side of an interface regarding topics such as 1) data unit interpretations, 2) mathematical matrix transformations, 3) matrix rotation conventions, etc. This function of the SNLT was needed because this kind of coordination historically would have occurred within a single prime contractor. With a distributed SoS killchain, a pseudo-government forum had to be established to enable and capture this kind of discussion between prime contractors on either side of an interface.

NIFC-CA SoS SE Accomplishments

With the successful completion of the Aegis ACB12 CDR in November 2009, a very capable, flexible, and extensible IFC design was established across the pillars of the NIFC-CA FTS capability. The FTS SoS detailed design is being implemented by each component system as this article is being written. The resultant product will allow the Fleet to engage any target from the near-horizon to the maximum kinetic range of the SM-6 and future interceptors utilizing a variety of sensors.

At a less apparent level, the NIFC-CA engineering teams took the opportunity to apply basic systems engineering principles to distribute the NIFC-CA killchain across component systems and establish a solid foundation for rapid evolution of future IFC capabilities. Key system engineering and software engineering techniques, including modularity, abstraction, and information hiding, were applied during the functional allocation and distribution process resulting in a system that is far more extensible, allowing dramatic evolution and innovation in the future. The following are examples of SoS SE innovations applied during the NIFC-CA design process:

1. Sensor Agnostic WCS: In order to accommodate a variety of remote non-SPY sensors, the ACB12 Aegis baseline was chosen as a point of implementation for a new Reduced State Estimator (RSE) WCS filter design. This design does not rely on hard-coded knowledge of sensor type and performance (information hiding) but is designed to accept basic covariance data describing the sensor track error basket and dynamically apply that data within the filter. This breaks the hard coupling across the interface between WCS and sensors (better modularity), allowing for many different sensors to become providers for engagements without any modification to WCS design or code.
2. CEC Best Sensor Selection (BSS): Early in the NIFC-CA design process, the decision was made to institute basic network-centric principles by assigning NIFC-CA remote sensor selection and management to the CEC network. This decision provides full support to the decision to uncouple WCS from remote sensors and moves sensor management closer to the actual sensors while ensuring WCS accuracy and timing requirements are met. Based on a QOS requested by WCS for each target, the new CEC BSS function will find from one to several sensors capable of meeting the QOS and make contracts with each sensor to provide data for the engagement. Per these contracts, CEC will provide one or more sensor track data streams to WCS, where final filtering and multistream fusion are performed to guide the interceptor flight.
3. Active Seeker Technology: This technology uncouples the hard connection and dependence between the ship and the interceptor. The ship will retain control of the interceptor for the majority of the flight, but the ship's radar and illuminator horizon is no longer a hard floor limiting the flight of the interceptor. Control and illumination from any source is not required for the final seconds before intercept as the missile goes active and independently finds the target. The entire battlespace from interceptor operating ceiling down to the land or sea surface and from ownship out to interceptor maximum kinematic range is now available to Fleet operators for engagement of all threats.

These are just a few major examples of the systems engineering accomplishments during NIFC-CA system development. These accomplishments support higher level DoD acquisition objectives for IFC by enabling a growing diversity of DoD airborne and surface-based sensors to support OTH engagements. This uncoupling and opening of interfaces will lead to industrial innovation of both tracking sensor and active missile capabilities and to further improvement in overall military capability.

Conclusion

SoS systems engineering provides great opportunities to leverage national investments in defined-purpose military systems in order to achieve unique and powerful capabilities at the SoS level. It is apparent that most future military SoS acquisition and engineering programs will be of the acknowledged type. Based on this brief overview of NIFC-CA SOS SE, it is hopefully apparent that the acknowledged type of SoS SE environment is full of opportunities and challenges. It will require flexible, creative, and active program leadership, and systems engineering leadership that is mindful of the fundamentals of systems engineering while encouraging and guiding collaborative engineering teams toward SoS-unique objectives. Within that type of leadership framework, the collaborative community consisting of SoS systems engineers working with the diversity of the component systems' engineering teams can produce innovative, extensible, and powerful solutions.

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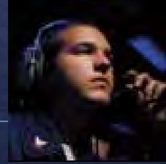

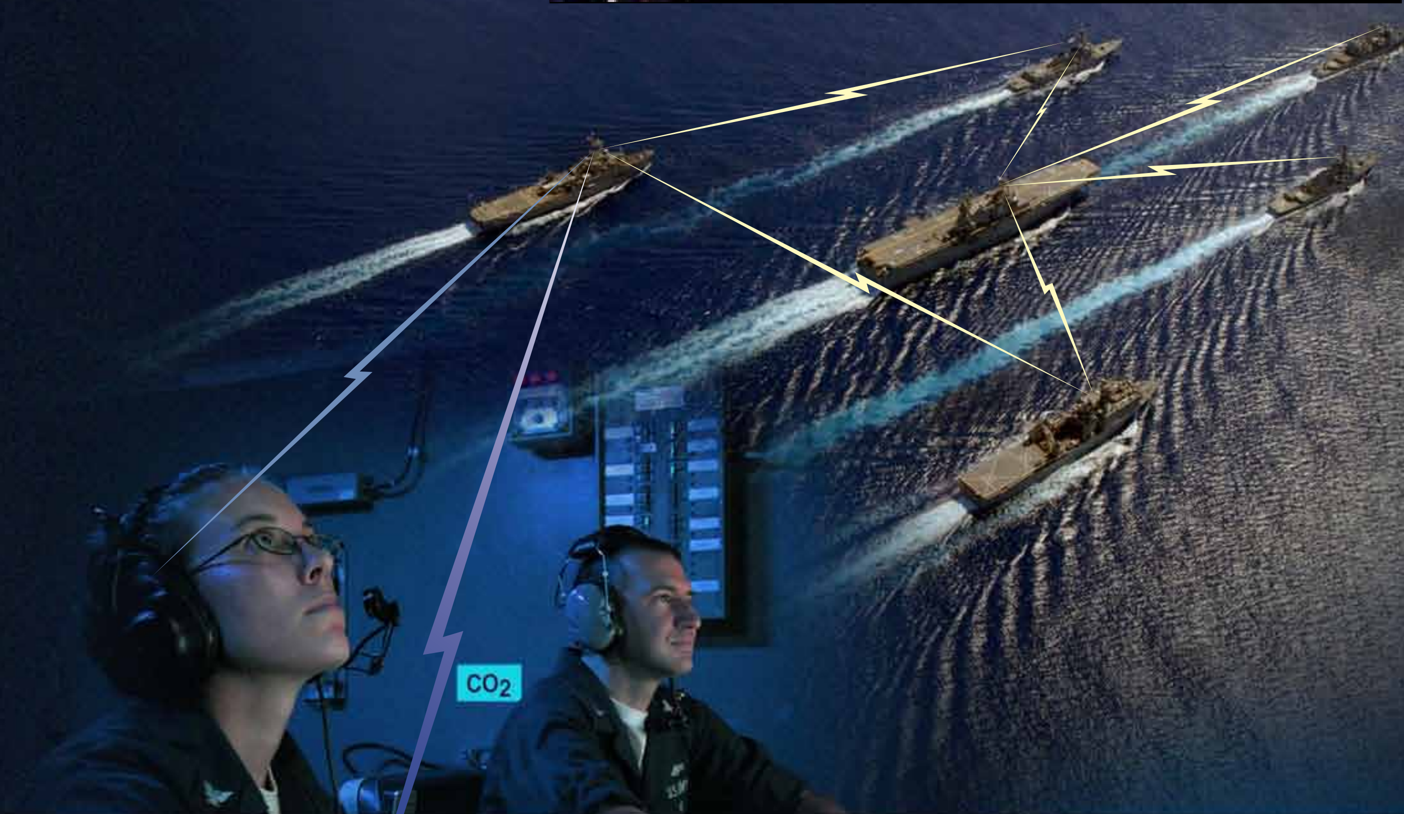

On the Leading Edge of Interoperability

by Phillip Hall and Gerrick Rosado-Vega

Over the years, warfighter reliance on Tactical Data Links (TDLs) has increased exponentially. When initially implemented, the simple exchange of basic radar contact information via Link-11 in a sector air warfare environment was deemed a success. Today's TDL employment encompasses all warfare areas and phases from detection and dissemination to engagement and kill assessment. TDL interoperability has been and remains a critical consideration necessary for warfighters to achieve mission success.

Joint guidance concerning interoperability states that "systems, units, and forces shall be able to provide and accept data, information, materiel, and services to and from other systems, units, and forces and shall effectively interoperate with other U.S. forces and coalition partners."[1] Interoperability is best understood by considering the principal function of a shipboard Combat Information Center. Each unit, through the use of radars and other sensors, collects, processes, and displays tactical information for evaluation and action. Multiple units within a strike force follow the same process and exchange their tactical information using a number of TDLs. The TDLs provide decision-makers with a coherent and common tactical picture to use to conduct a particular operation. Accordingly, what warfighters see on local tactical displays needs to correctly represent the tactical environment and reflect essentially the same information displayed on every other unit participating on the TDLs.

In the mid-1970s, Naval Surface Warfare Center, Dahlgren Division (NSWCDD) engineers began supporting development efforts that resulted in the introduction of the first Aegis cruiser, USS *Ticonderoga* (CG 47) into the Fleet. At that time, Link-11 was the primary means of tactical data exchange among carrier battle groups. Link-11, also known as TDL-A, is based on 1960s technology and is a relatively slow TDL. It normally operates on a polling sequence architecture where network participants transmit tactical data when called upon, as shown in Figure 1.

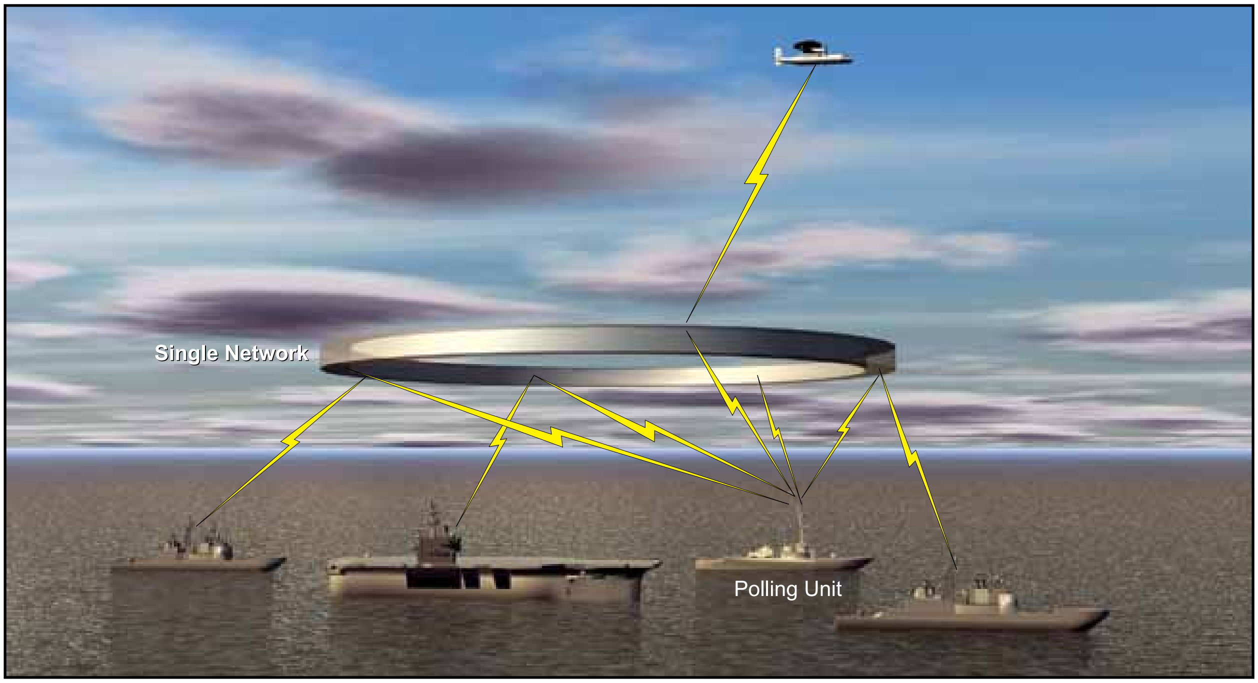

Figure 1. Link-11 High-Level Architecture

As mission needs evolved and technology advanced, the need for a more capable and robust TDL was identified. This led to the development of Link-16, also known as TDL-J, which provided the warfighter the technical and operational improvements needed to meet evolving mission needs. Link-16 is a secure, jam-resistant, line-of-sight TDL that allows network participants to exchange tactical data based on predetermined time slots, which results in a significant increase in the rate of data exchange over Link-11. A high-level Link-16 architecture is depicted in Figure 2.

As operational missions continued to evolve, the requirement was identified for a communication system capable of tactical data exchange with other units Beyond Line-of-Sight (BLoS). Multiple variations of satellite communication systems were developed to

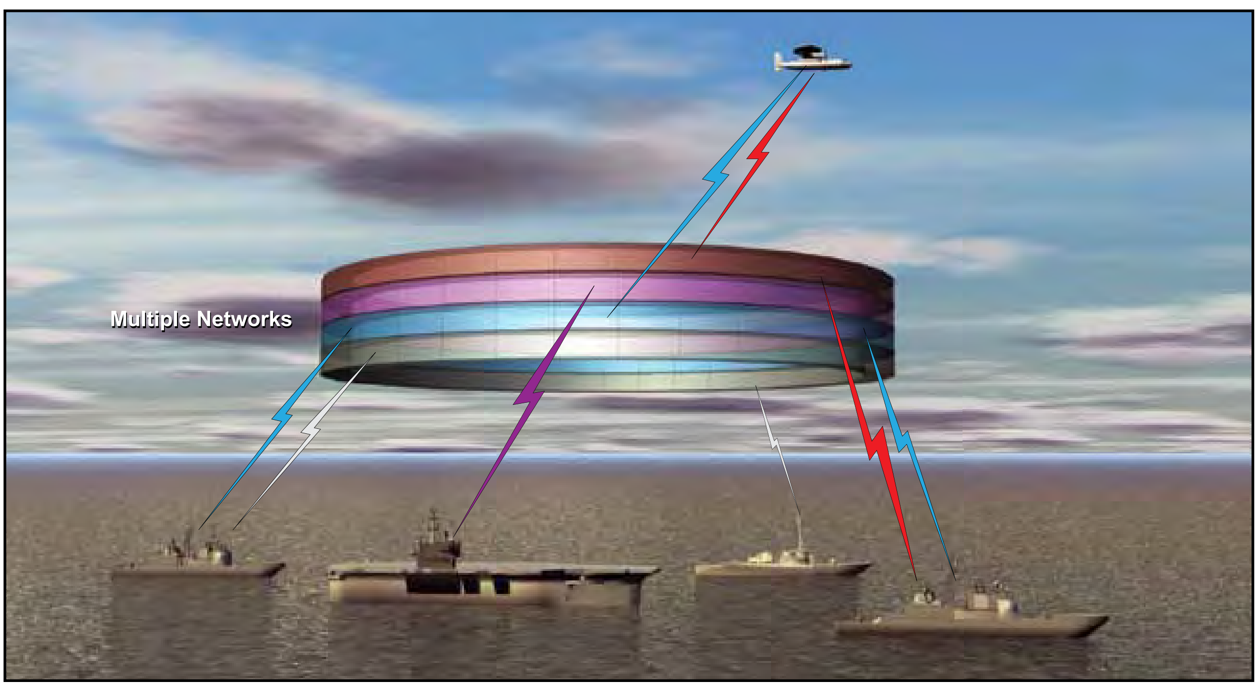

Figure 2. Link-16 High-Level Architecture

satisfy these requirements. Satellite Link-11 (S TDL-A) and Satellite Link-16 (S TDL-J) were the first satellite systems used for BLoS TDL communications. While they provided the capability to exchange tactical data with BLoS network participants, the number of participants and the speed at which data could be exchanged were limited because of the data rate constraint of the satellites used. As technology continued to advance, faster and more capable satellite systems were used for BLoS TDL communications. The Joint Range Extension Application Protocol (JREAPS) capability, which provides added security, improved speed, and an increased number of network participants over S TDL-A and S TDL-J, is the latest satellite TDL capability implemented by the Navy. A high-level BLoS TDL architecture is depicted in Figure 3.

Adhering to Military Standards

The TDLs mentioned earlier are governed by a series of Military Standard (MIL-STD) documents that identify implementation requirements that combat systems must meet to be interoperable with other combat systems. Interoperability is made possible by consistent implementation of MIL-STD requirements on applicable combat systems. Prior to fielding, each combat system must be certified to validate that it meets the applicable MIL-STD requirements.

The MIL-STDs are dynamic documents that are under continual review and changed as necessary to satisfy the operational community's requirements. The change process for the NSWCDD Data Link engineering team begins with listening to the needs of the operational community and program offices supported.

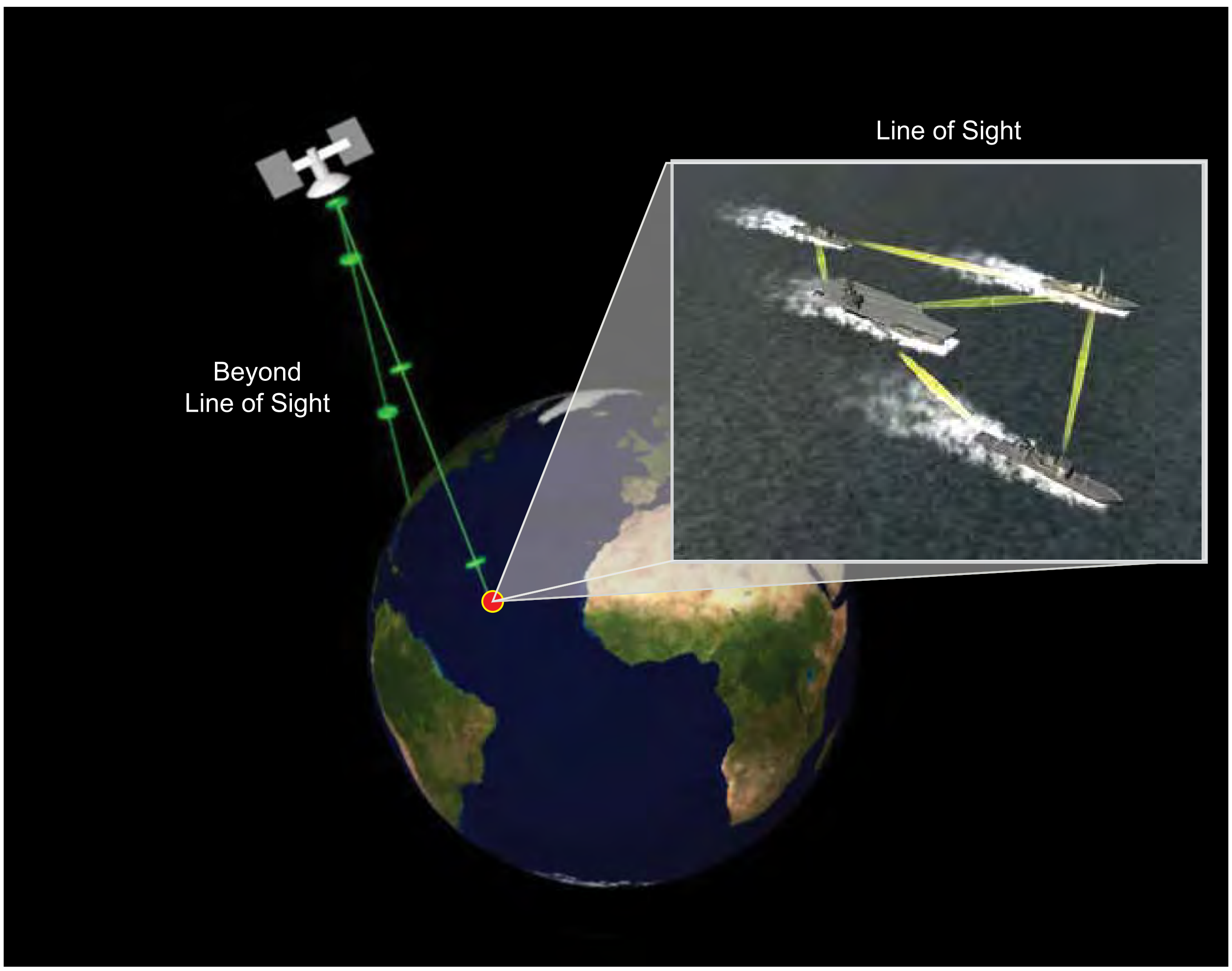

Figure 3. BLoS High-Level TDL Architecture

Examples of this input include post-deployment reports, Fleet feedback, Fleet trouble reports, and the introduction of new capabilities by the respective program offices, such as the new Mode 5 Identification Friend or Foe capability. With an understanding of the requirements, NSWCDD engineers begin developing a proposed modification or addition to the various MIL-STDs, termed Interface Change Proposals (ICPs). An ICP can range from a few pages to a document several hundred pages in length as it details the proposed technical solution for the implementation of an operational requirement.

Following development and subsequent internal reviews, the proposed ICP is provided to the Navy technical standards section of the Space and Naval Warfare Systems Command (SPAWAR) Systems Center (SSC) Pacific Code 59. This organization (formerly known as the Navy Center for Tactical Systems Interoperability) then distributes the ICP to various other program offices and activities for review and comment. The ICPs are then presented by the proposing agency at a regularly scheduled Technical Interoperability Standards Group (TISG) meeting. The TISG, chaired by an SSC Pacific Code 59 representative, has a voting membership made up of representatives from multiple Navy program offices and engineering activities. At the TISG, the technical merits of the ICP are discussed, and the ICP is either approved as written, modified to address the requirements and concerns of other users, or disapproved. Following Navy approval, ICPs then make their way to a review by the other services, and in some instances, to the North Atlantic Treaty Organization for review and approval.

Interface Change Proposal Process

The ICP development process is not unique to the NSWCDD community and, as voting members of the TISG, NSWCDD representatives are responsible for reviewing and commenting on ideas brought forth by other Navy and joint service activities. This requires an understanding of how the other systems operate and how the proposed changes might impact the systems NSWCDD supports. The ICP process, from origination to incorporation into the applicable MIL-STDs, can take years as nations, services, and individual technical communities provide insight and recommend changes on the way to the final technical solution.

Once ICPs are formally approved, the NSWCDD Data Link engineering team begins the process of determining how best to implement the ICPs into the applicable combat system programs such as Aegis, Aegis Ballistic Missile Defense, DDG 1000, Littoral Combat Ship, and the Common Aviation Command and Control System. NSWCDD engineers study the risks associated with cost, schedule, and performance, and provide recommendations to the respective program offices to determine which of the proposed changes will be scheduled for incorporation. The goal is to implement approved ICPs as quickly as possible on all applicable combat system programs; however, incorporation may be delayed due to available funding and delivery schedules. This applies to all program efforts across the services and, as a result, contributes to some of the interoperability issues our warfighters face today.

Once ICPs are approved for incorporation into a given combat system, NSWCDD engineers continue to coordinate with the program office and developers to ensure the required changes are incorporated. This process involves working with the design activity to develop and evaluate the combat system Specification Changes (SCs) that incorporate the ICP and detail the changes to the Command and Control System functions and displays. These SCs can be very complex as they typically affect multiple elements and/or functions within the combat system.

Once SCs are reviewed and approved, the developers code and deliver the updated combat system programs. During this process, depending on the combat system supported and the stage of development, NSWCDD engineers take the lead in testing and validating the ICP implementation or assist other agencies as required. This process can involve the development of test plans and procedures, test conduct, post-test data analysis, and reporting.

Tactical Datalink Interoperability Certification

Throughout the combat system development effort, NSWCDD engineers work with the program office to determine the best approach for obtaining TDL/interoperability certification for the combat system. There are three phases in this process: Navy TDL/interoperability developmental testing, Navy TDL/interoperability certification testing, and joint TDL/interoperability certification testing.

Navy Tactical Data Link Interoperability Developmental Testing

Typically, a developmental test is conducted for all new and updated combat systems. Developmental tests are conducted while the combat system is still in development but mature enough to support testing in which interoperability performance can be assessed. Developmental tests are also conducted early enough in the development process to allow time to effect change should problems be identified during testing. During a developmental test, NSWCDD engineers work with the Navy service-level test agent, the SSC Pacific Code 59 System Test, Integration, and Certification Branch. This testing usually takes three weeks and delves into all aspects of CS TDL/interoperability functionality using a certified link simulation system, the Multi-Link System Test and Training Tool (MLST3), to simulate remote TDL participants. NSWCDD engineers function as the combat system test agent and assist the SSC Pacific test director and staff during the event. Following the test, the SSC Pacific and NSWCDD test teams conduct independent assessments of the test results and discuss these finding in a Navy Analysis Review Panel (NARP). At the NARP, SSC Pacific and NSWCDD representatives discuss the issues identified during test and analysis, adjudicate the priorities, and provide mitigation for the concerns where appropriate. Following the adjudication process, those issues deemed to be critical or high-priority by both parties are captured in a "must fix" list. If not corrected, these issues could prevent the combat system from achieving its Navy TDL/interoperability certification or accomplishing all mission requirements once deployed. Following the NARP, NSWCDD engineers work with the program office and design activity to ensure the necessary computer program corrections are implemented prior to proceeding to the Navy TDL/interoperability certification effort. Figure 4 is a photo of NSWCDD engineers performing console operations during a test event.

Navy Tactical Data Link Interoperability Certification Testing

Once all of the TDL/interoperability-related combat system upgrades or corrections have been delivered and validated, the official Navy TDL/interoperability certification test is scheduled. This effort is similar to the developmental test in that the same test procedures, test bed, and simulators are used. Any high-priority issues discovered during this test could result in failure to obtain Navy TDL/interoperability certification. This certification is one of the key criteria taken into consideration by the Combat System Certification Panel for the combat system under test.

Figure 4. NSWCDD Engineers Performing TDL/Interoperability Certification Testing

Joint Tactical Data Link Interoperability Certification

Once a combat system has been Navy TDL/interoperability-certified, NSWCDD engineers work with SSC Pacific test agent personnel to prepare for the joint interoperability test conducted by the Joint Interoperability Test Command (JITC) located in Fort Huachuca, Arizona. Like the Navy TDL/interoperability certification event, the goal of the joint TDL/interoperability certification event is to ensure the combat system meets MIL-STD and operational TDL requirements. The main difference between the two is that Navy certification is conducted with a link-certified simulator (MLST3) representing the remote TDL participants, and the joint certification event is conducted with multiple joint combat systems exchanging tactical data over simulated TDL networks. Testing in this manner allows the engineers to gain insight into how the combat systems interact with each other when exchanging data over the TDLs. At the completion of this test event, NSWCDD engineers analyze the issues provided by JITC and other test participants, discuss their findings, and mitigate identified issues at a Joint Analysis Review Panel. This board, composed of representatives from JITC and the other services, discusses the issues observed during the test and decides whether or not to approve or disapprove that particular system's joint interoperability certification.

Deploying Group Systems Integration Testing

In addition to the Navy and joint interoperability certification processes described above, NSWCDD engineers participate in at-sea test events, such as deploying group systems integration testing, which is conducted by all carrier strike groups and expeditionary strike groups prior to deployment. These events provide an opportunity to assess combat system interoperability performance in a tactical environment, evaluate interoperability changes and upgrades, and receive Fleet feedback on combat system capabilities and performance, which is then fed back into the process to identify new Fleet requirements.

Meeting Interoperability Requirements

Meeting interoperability requirements is a challenging task. The demands for exchanging, processing, and displaying information over the TDLs are ever increasing. To meet the challenges of implementing current and future interoperability needs, NSWCDD engineers not only must be knowledgeable of their respective combat systems from an interoperability perspective, but also well-versed in the capabilities and limitations of other systems, the requirements of operators, and the systems engineering process from design through test and evaluation. Despite these challenges, NSWCDD engineers continually deliver capabilities on the leading edge of interoperability that are necessary for ensuring that naval warfighters have the tools they need to achieve mission success.

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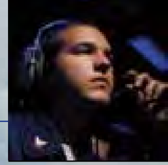


Mission Analysis in the Combat Systems Engineering Process

by Stephanie Hornbaker and Sean Chapin

Mission analysis is performed at multiple stages of the combat systems engineering process and is a technique used to estimate mission effectiveness under different operational concepts. In other words, mission analysis is the evaluation of multiple approaches to achieving a given mission, or goal, and the selection of one that provides the best performance.[1] Mission analysis is employed early in system design to identify capability gaps and evaluate approaches to close those gaps. It is also used for evaluating the impact on performance of new technologies and operational tactics. The performance analysis then drives the creation of requirements and the development, design, and deployment of a system.

Beginning with a well-defined mission or need is critical. Analysts must first determine if the sponsor is looking for an answer to an acquisition, tactical, or technological question. The type of question will drive the design of an appropriate mission analysis study. Analysts initially might only be provided with high-level requirements for a system and may need to work with the customer to flesh out the specific threats and scenarios necessary to perform an appropriate analysis. For example, a customer may want to know how to configure multiple defense systems on a ship to achieve the best self-defense performance. Analysts would need specification on the types of systems, the measures of effectiveness most important to the customer in defining self-defense performance, and the types of threats to test against the ship. If the goal is not correctly defined in the beginning of the mission analysis process, the ultimate solution will not solve the customer's problem. Once the mission has been accurately defined, the analyst must identify a set of architectures, approaches, and subsystems that represent the trade space. Mathematics, analysis, and simulation techniques are used to provide a quantitative justification for building or employing a combat system in a specific way. This article discusses the Naval Surface Warfare Center, Dahlgren Division's (NSWCDD's) established mission analysis process and tools.

Mission Analysis Process

The mission analysis process begins with an acquisitional, technological, or operational question from the sponsor. The problem could involve a single ship or battle groups of ships performing multiple missions, such as anti-air warfare (AAW), ballistic missile defense (BMD), integrated air and missile defense (IAMD), or surface warfare (SUW). Typically the problem centers on making a decision among several combat system configurations or deciding if the addition of a new combat system element improves the ability of the overall combat system to perform its mission. Each configuration is defined by a control system, a sensor suite, and a weapon suite. For example, one configuration could consist of the Ship Self-Defense System (SSDS) control system with the Rolling Airframe Missile (RAM) and the SPQ-9B radar. A second configuration could share the same control system and sensor, but with an Evolved Sea Sparrow Missile (ESSM) instead. Thus, this mission analysis process would provide insights into the relative performance differences between the two configurations. A schematic of the mission analysis process is shown in Figure 1.

Once the problem definition is complete and understood by all analysts involved, tactical situations are designed that can be simulated in weapon, sensor, and control system models. The threat, sensor, and weapon models can be run independently of one another and their performance data fed into a control system model. Alternatively, the models can be integrated into a single end-to-end simulation of the engagements. The modeling process often involves simulating a raid of threats, such as cruise missiles or ballistic missiles attacking a U.S. Navy ship or a battle group. The threats are defined by the trajectories they fly, radar cross sections, and seeker characteristics. The threat characterization is passed to the sensor and weapon models to evaluate the performance against the threats. The sensor models produce measures of performance, such as probability of maintaining a track as a function of range for each threat trajectory, or detailed histories of when the threat is in track and when it is not. Networked sensors, such as those in a battle group, can be modeled to produce a common track picture available to multiple ships when running a battle group simulation. The weapon models produce lethality data for

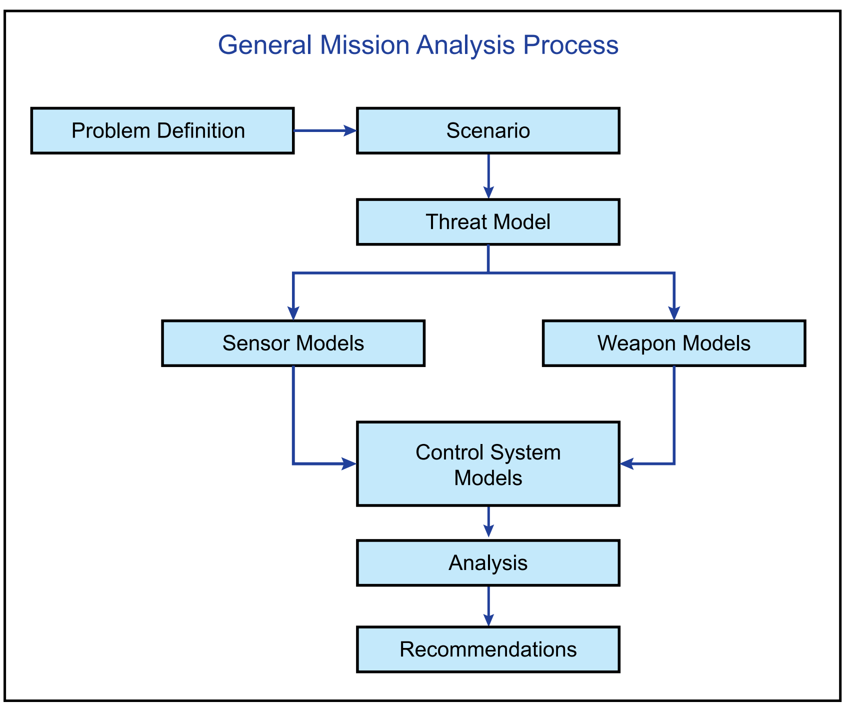
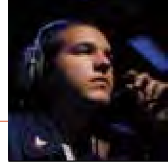


Figure 1. Schematic of the Mission Analysis Process



the threat showing the single-shot probability of killing the threat as a function of range for any shooting ship against any threat in the scenario. The data from the sensor and weapon models are then fed into a control system simulation that models the sequence of events from detection of the threat by various sensors to its engagement by different weapons. The simulation includes scheduling algorithms for ship assets involved in the engagements. This includes launcher and illuminator scheduling and coordination of multiple shooting ships in a battle group. The battle simulation can be repeated hundreds of times generating a number of outcomes during which key events and statistics can be recorded. Sample outputs from a mission analysis simulation for three combat system configurations are shown in Figure 2.

In the mission analysis context, a measure of effectiveness (MOE) is designed to estimate how combat system performance changes across the configurations considered in the analysis. The MOEs are based on the statistics collected from the control system simulation and are used to underpin the analysis. Examples of MOEs include the probability of defeating the entire raid of threats, probability of defeating a particular threat, percentage of threats defeated, and weapon expenditures.

The final and most important step is to analyze the data and develop an understanding of overall system performance and interactions. Control system simulations can reveal important interactions between elements of the combat system by generating many possible outcomes of a battle depending on sensor threat detection timeliness, weapon performance, and the resulting effects on scheduling engagements. These interactions are not always obvious upon cursory examination and are used to inform acquisition decisions. For example, at first glance a new sensor that extends the range at which firm track is obtained on a threat might appear to be a simple way to improve a ship's self-defense performance. However, if weapon performance is poor at the extended firm track ranges provided by the new sensor, overall system performance may not be improved. This would represent a situation where the additional cost of a new sensor might not be justified unless it provides other benefits to performing the mission deemed too important to ignore. Mission analyses designed to explore the trade space are essential for providing these insights to decision-makers.

Another example of insight that mission analysis can provide is showing the impact of radio frequency propagation conditions on a radar's ability to maintain firm track on a threat.

Option 1		Battle 1	Battle 2	Battle 3	...	Battle 200
	Firm Track Range	17	14	15	...	19
	Intercept Range	9	3	4	...	11
	Threat Defeated?	N	N	Y	...	Y
	Probability Ship is Hit: 0.84					

Option 2		Battle 1	Battle 2	Battle 3	...	Battle 200
	Firm Track Range	22	18	21	...	24
	Intercept Range	12	9	11	...	13
	Threat Defeated?	N	Y	N	...	Y
	Probability Ship is Hit: 0.97					

Option 3		Battle 1	Battle 2	Battle 3	...	Battle 200
	Firm Track Range	14	9	17	...	16
	Intercept Range	4	2	6	...	5
	Threat Defeated?	Y	N	N	...	N
	Probability Ship is Hit: 0.64					

Figure 2. Sample Mission Analysis Simulation Outputs

Meteorological conditions impact the paths of the electromagnetic waves emitted from the radar resulting in regions where the radar cannot see a threat. It is possible for the radar to track a threat for a period of time, lose track on the threat, and regain track on the threat again at a later time. This phenomenon can impact weapon effectiveness and the ability of the control system to schedule an engagement of the threat. Mission analysis enables exploration of a range of environmental conditions and impacts on overall combat system performance. While such variables cannot be controlled under operational conditions, analysts can systematically estimate their impacts and pass that information to decision-makers and the Fleet.

Once the mission analysis process is completed, a package of information is delivered to sponsors detailing how system performance varied over the trade space. The analytical approach, assumptions, conclusions, and driving factors must be clearly and concisely explained, suitable for a wide audience. That information is then fed back into the overarching alternatives analysis process, which also considers cost and risk analysis. The result is an analytically rigorous decision on a combat system configuration or operational approach that meets the warfighter's requirements. System design and specification or updates to tactics or technologies can then commence.

Conclusion

NSWCDD has a long history of performing mission effectiveness studies and alternatives analysis studies for the Chief of Naval Operations, for the operational Navy, for the Program Executive Office for Integrated Warfare Systems (PEO-IWS), and for other sponsors including foreign navies. Subject matter experts in sensors, weapons, threats, electronic warfare, and control systems across NSWCDD partner with mission analysts to produce authoritative assessments of combat system performance. As pressure on the Navy to produce combat systems that both perform their missions and are affordable persists, mission analysis plays a vital role in the combat systems engineering process.

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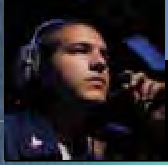


A Systems Engineering Approach to Requirements Commonality Across Surface Ship Combat Systems

by Diana Kolodgie, Karen Shuttleworth, and Greg Albertson

Today, the surface Navy designs and implements combat systems that are typically targeted for a particular class of ship (e.g., CG, DDG, LCS, CVN, and LPD) without adequately considering the larger family of systems implications. Requirements development and design approaches vary across ship classes and platforms and are, in effect, conducted independently. Commonality in cross-platform requirements analysis and development has the potential to increase the use of common components across designs of combat systems and to facilitate commonality in test and certification. Commonality among combat systems may reduce the complexity of family-of-systems design and of integrating platforms and their combat systems into highly effective and efficient operational task forces. This has great potential to achieve significant savings by reducing the cost of designing, developing, producing, training, maintaining, and updating capabilities, while increasing the ability to quickly incorporate new or updated capabilities into the Fleet.

Currently, there is no formal process to analyze, allocate, and coordinate requirements development between and within ship classes. As a result, platform requirements are developed independently of one another. This is further compounded by individual ship programs and systems having similar yet uniquely tailored requirements development. This has led to system-level requirements being decomposed from specific operational requirements in isolation and creating a stove-piped development approach. Having limited to no cross-platform development communication often causes the same operational need and functionality to be defined differently in system-level requirements and architecture. This approach inhibits commonality as requirements are decomposed down the requirements hierarchy. Thus, there is the potential to miss opportunities for common requirements and the total ownership cost benefits associated with commonality.

A solution to the lack in commonality is the engineering of combat systems as a common product line. Applying a systems engineering approach across platforms will allow for the identification of combat system components that can and should be common while preserving the option of platform-unique solutions where appropriate. This paper focuses on the integral role common requirements play as part of the systems engineering process as applied to surface Navy combat systems. A common approach to requirements development is provided as well as how common requirements contribute throughout the systems engineering process to the development of a common product line.

Application of Systems Engineering

A combat system product line develops commonality, utilizing a common set of reusable requirements across the family of surface Navy combat systems. What makes these product lines part of a family are some common elements of functionality. Functional and nonfunctional requirements capture the intended behavior and constraints of the system. This behavior may be expressed as services, tasks, or functions the system is required to perform (functional) and the constraints describe how well a function is to perform (nonfunctional) and are largely consistent across the family. Adding platform-unique constraints on the system's behavior in the form of nonfunctional requirements produces the aggregate set of requirements for the system. This approach establishes a consistent and common decomposition of the operational requirements across multiple ship classes while preserving a platform's unique requirements. Future and upgraded platforms will leverage a common set of product line requirements to which platform-unique requirements can be applied to compile a complete set of combat system-level requirements. To establish a set of product line requirements, all existing legacy platform requirements will be analyzed and further normalized to produce a superset of common requirements. Product line requirements will be applicable to future platforms and platform upgrades throughout life-cycle development by using a central repository for all surface Navy combat system requirements.

Establishment of Common Product Line Requirements

There are three main aspects to the overall product line requirements development process. The first focus is to establish the initial set of common product line requirements that will set the framework for all future requirements development. From that common set of requirements, future platforms can incorporate platform-unique requirements to develop a Combat System Requirements Document (CSRD). The final aspect is full life-cycle management of the product line. Future requirements will be reviewed and evaluated for incorporation into the common set. These future requirements will factor in platform and warfighter capabilities that evolve and are identified as a result of the campaign level of analyses conducted by the Office of the Chief of Naval Operations.

Establishment of Initial Common Product Line Requirements

The process described herein proposes the development of the initial common set of combat system-level requirements. Figure 1 provides a graphical representation of the following steps to develop the initial common set of requirements:

1. Establish requirements database
2. Compile source references
3. Review and sort requirements
4. Determine common versus platform-unique requirements
5. Perform normalization

This development process is designed to establish the initial set of product line requirements based upon legacy combat system requirements. Incorporation of future platform-unique requirements and life-cycle management of the product line are defined in separate processes later in the text.

The proposed requirements development process is implemented using a requirements database. This will allow for a defined structure and for attribute definitions. Using an integrated database will enable systems engineering and facilitate data collection as well as provide a collaborative environment to review and modify requirements in one central location.

Step 1. Establish Requirements Database

An integrated requirements database is established to facilitate a systems engineering process throughout requirements development. A database will support the development of the product line requirements and maintain

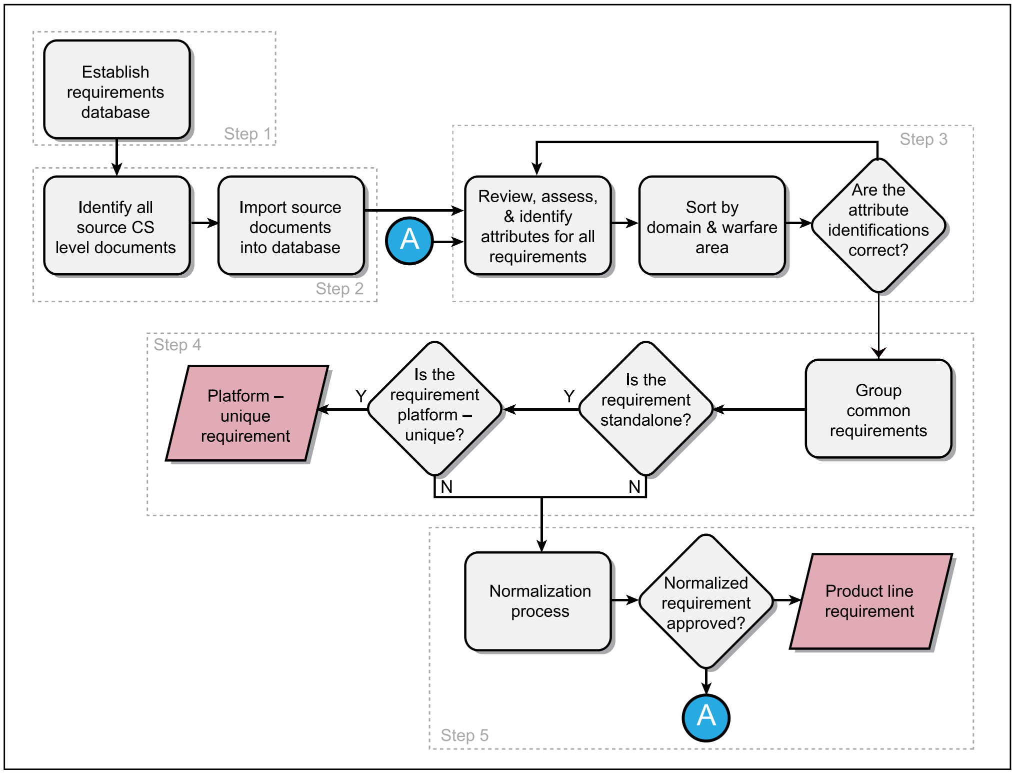


Figure 1. Product Line Requirements Development Process

all combat system-level requirements for the development life cycle. An integrated database will allow for traceability among higher level requirements as well as to the defined product line architecture and platform-unique architectures.

Along with capturing the requirements text, it is critical to define multiple attributes to provide a clear understanding of each requirement. In a specialist task, such as defining a product line that requires multiple sorts and unique information to be captured, each requirement can be tagged with an unlimited number of attributes allowing for easy selection of subsets of requirements.[1]

Table 1 provides examples of attributes that will be defined and utilized during the initial product line requirements development process. Additional attributes may be added throughout development as appropriate.

Step 2. Compile Source References

The next step in producing the initial combat system product line requirements is to compile a list of combat system requirements currently developed for legacy platforms. This list of requirements will be developed from available source combat system references, such as Aegis A-Specs, DDG 1000 Segment Specifications, and Precommissioning Unit (PCU) Gerald R. Ford (CVN 78) Performance and Capability Requirements. Additionally, applicable statutory and regulatory instructions will be compiled, such as information assurance, safety, and Naval Sea Systems Command (NAVSEA) guidance and policy on combat system and combat system element training safety precepts and design requirements. While these instructions may not contain the true "shall" requirements language, they do contain the governance and oversight that ensure stakeholder requirements are met and provide rationale for nonfunctional "ility" requirements. All current combat system-level requirements are compiled without modification into the established database.

Step 3. Review and Sort Requirements

The next step in the development process is to review and assign all compiled requirements with initial attributes. The assignment will allow for the sorting of requirements into local groupings, which provides a mechanism for a manageable review and facilitates the normalization process, based upon the functional and nonfunctional requirements common across all combat systems as derived from operational, statutory, and regulatory requirements. Proposed groupings include domain, mission area, and nonfunctional.

The domains, as defined in the PEO IWS *Surface Navy Combat Systems Software Product Line Architecture, Architecture Description Document (ADD)* (2009),[2] provide a means to functionally group the requirements. The domains are not meant to be a physical representation of the deployed system (PEO IWS 2009). Domain mapping will provide an avenue for functional analysis and allocation. There are multiple

Table 1. Initial Database Attributes

Attribute	Definition
Object Identifier	Unique number applied to each object (requirement) within the database
Object Text	Paragraph text to provide the requirements statement
Classification	Classification of the Object Text
Requirement	Yes/No field to identify if the Object Text contains a "shall" statement (Shall = Yes)
Rationale	Paragraph text to provide intent of Object Text
Domain	Allocation to a combat system domain
Mission Area	Allocation to a mission area
Platform	Applicability to specific platform(s)
Product Line	Yes/No field to identify common requirement
Nonfunctional	Allocation to a nonfunctional group ("ility," inherent capability)

mission areas across the numerous platforms. Each platform's specific mission areas and nonfunctional groupings (potential inherent capabilities) are defined in its operational requirements document. Table 2 provides examples of potential domain, mission area, and nonfunctional mappings.

All requirements are first sorted by domain with the mission area and nonfunctional attributes providing amplifying information to assist in requirements analysis and normalization. Mission area attribute mappings will also assist in allocating the level of work to warfare area subject-matter experts (SMEs). The SMEs are consulted during this step to review and assess the requirements to ensure attributes were identified correctly. Their assessment and participation continues throughout the normalization process.

Step 4. Determine Common versus Platform-Unique Requirements

Once requirements are sorted into manageable groupings, they are further analyzed for commonality. This step allows for further analysis of the requirements to ensure normalization is performed correctly. SMEs will review current requirements within domain groupings and amplified with mission area and nonfunctional attributes for like requirements. All like requirements, those having the same or similar meaning, are identified as common. Those requirements that are standalone (i.e., do not have any other requirement with the same or similar meaning) are identified as "platform-unique." Platform-unique requirements are identified as such with the product line attribute (i.e., "no") and not normalized. The requirements identified as common, with the product line attribute identified as "yes," are then normalized into product line requirements.

Step 5. Perform Normalization

Once all current combat system-level requirements have been identified as like or platform-unique, the compiled list of like (potential product line) requirements can be normalized to produce the initial product line requirements.

The goal of the final step, normalization, is to standardize all common requirements. This step is necessary because of the differences among current requirements writing approaches taken across platforms. All common requirements will be reviewed and rewritten to be consistent, with respect to style and requirements writing standards.

It is critical in the normalization process that requirements are thoroughly reviewed to ensure sound requirements are produced without losing the original intent. There are many different requirements aspects to review to ensure consistency and quality requirements writing.

In addition to the provided requirements characteristics, it is vital that quality requirements writing be utilized when creating the superset of common requirements. There are many guides to writing quality requirements. In summary, Buede (2000)[3] provides some guidance for quality requirements writing.

Table 2. Initial Attributes for Sorting

Domain	Mission Area	Nonfunctional
External Communications	Ballistic Missile Defense	Survivability
Display	Antiair Warfare (AAW)	Information Assurance
Vehicle Control	Surface Warfare (SUW)	Safety
Weapon Management	Undersea Warfare	Mobility
Sensor Management	Strike	Reliability
Track Management	Information Operations	Maintainability
Combat Control	Antiterrorism/Force Protection	Availability
Support		
Training		
Navigation		
Infrastructure		

1. A statement of requirement includes the use of the word "shall."
2. A requirement statement should only include one "shall."
3. Requirements statements shall include a subject (the relevant life-cycle system), the word "shall," a relation statement (e.g., less than or equal to), and the minimum acceptable threshold with units.
4. Use appropriate grammar.
5. Avoid compound predicates and negative predicates.
6. "And/or" colloquialism is inappropriate.
7. Requirements statements should not start with "If…" statements.
8. Requirements statements should be unambiguous.
9. Common verbs that are not specific should be avoided (e.g., maximize, minimize, and optimize).
10. Adjectives and adverbs are a major source of ambiguity.

Like requirements are reviewed and rewritten, using quality requirements writing, into common requirements. These common requirements become the product line requirements used for future platform requirements development and legacy upgrades.

Following the normalization process, we are able to see that object IDs 1 and 3, as currently worded for their platforms, contain the same functional requirements and can be reviewed and rewritten into common product line requirements. Table 3 provides the original object text along with an example of new, normalized object text. The normalized object text is the new requirements language developed from the two original platform requirements and rewritten into a standardized requirements language, based on applying the guidance described above. The new text is then included in the superset of common product line requirements to be utilized by all future platforms.

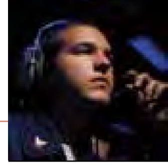
Establishment of Future Platform CSRDs

Once the initial common set of combat system-level requirements (product line requirements) have been developed, system-level documents can be quickly and commonly produced. Future combat system requirements document development will leverage the existing applicable common product line requirements. The proposed process of common product line requirements establishes a requirements database that facilitates the development of CSRDs. A future platform can simply sort the product

Table 3. Examples of Normalized Requirements

Object ID	Object Text	Normalized Object Text
1	The engagement system segment shall suspend an engagement upon receipt of cease-fire or hold-fire commands from Command, Control, Communications and intelligence (C3I).	The combat system shall perform cease fire on engaged targets upon receipt of automatically initiated and operator-initiated cease-fire orders. The combat system shall perform hold fire on engaged targets upon receipt of automatically initiated and operator-initiated hold-fire orders. The combat system shall perform break engage on engaged targets upon receipt of automatically initiated and operator-initiated break-engage orders.
3	The combat system shall accept and execute operator orders to cease fire, hold fire, or break engage.	

Note: Definitions for cease fire, hold fire, and break engage that are derived from statutory and regulatory requirements will be required to ensure proper allocation and decomposition to lower-level requirements.



line requirements based on their stakeholder-defined mission areas to obtain an initial set of requirements. The product line requirements will then be augmented with a platform's unique requirements deemed necessary to achieve its aggregate combat system requirements.

Significant savings and commonality across platform combat systems development, integration, testing, and deployment can be realized by utilizing product line requirements to establish the majority of its requirements base needed to fulfill the platform's missions.

Life-Cycle Management of Product Line Requirements

The final aspect to implementing a full combat system product line is the ability for life-cycle management of all system-level requirements and documents. Once the initial set of common requirements has been developed, the next step is to document a process to integrate potential new additions to the common set of requirements as well as expand the current database into a fully integrated surface Navy combat system requirements database.

As new operational requirements are defined by stakeholders, new system-level requirements are derived and will need to be evaluated as potential additions to the common product line superset. If new requirements are deemed common, they will then impact the scope of legacy upgrades as well as all future platforms.

A fully integrated surface Navy combat system database will incorporate not only the common product line requirements but all future platform-unique requirements (clearly identified as such with attributes) and traceability links back to platform-specific operational requirements. This fully integrated database will create one central repository for all system-level requirements development. This central database will encompass all system-level requirements, documents, and architecture, providing a clear mechanism for consistency and commonality.

At this point in the process, configuration management would need to be addressed and initiated to ensure quality control of defined configuration items. Product line control boards would be established to approve all new additions to the common set of requirements.

Establishment of Common Product Line Architecture

Similar to the establishment of a common requirements repository, the development of a common functional architecture would assist in alleviating the problem of the loss in commonality in the translation of operational capabilities into the requirements and design of the combat systems. A common functional architecture can be developed through functional analysis and allocation of requirements. The functional architecture serves as the bridge between the common product line requirements and the common product line components. Those requirements that are allocated to components outside of the common core set are platform-unique.

As new operational requirements are developed for future ship platforms, requirements and functional analyses will be performed to determine the common components that satisfy the new requirements. The platform will use the applicable functionality and allocations from the common functional architecture as determined from the analysis performed. The final architecture for each future platform will be a combination of common components and platform-unique components as depicted in Figure 2. The common requirements database would then be updated with the traceability to the applicable functions and components.

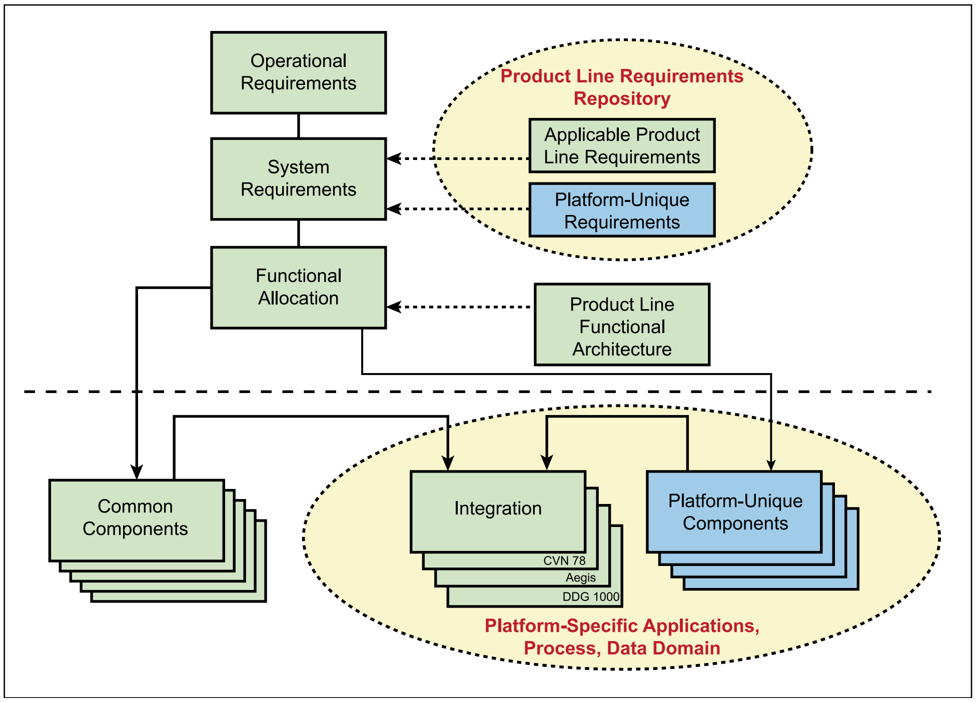


Figure 2. Combat System Systems Engineering Process

Conclusion

The common product line requirements development process focuses on the development of a superset of combat system requirements across all surface Navy platforms. The five-step process described above should alleviate the problem of the loss in commonality in the translation of operational capabilities into the requirements for and design of the combat systems. Combined with architecture, a common product line requirements development process is critical for determining where common components may be used in the combat systems across surface Navy platforms. This proposed systems engineering approach will support the awareness of and coordination in allocating and decomposing requirements from capability development documents to ship classes and contribute to the development of the system design specification. If done properly, this approach will facilitate test, verification, and certification of combat systems, as well as achieve cost saving across surface Navy combat systems development and training.

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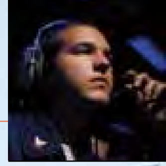
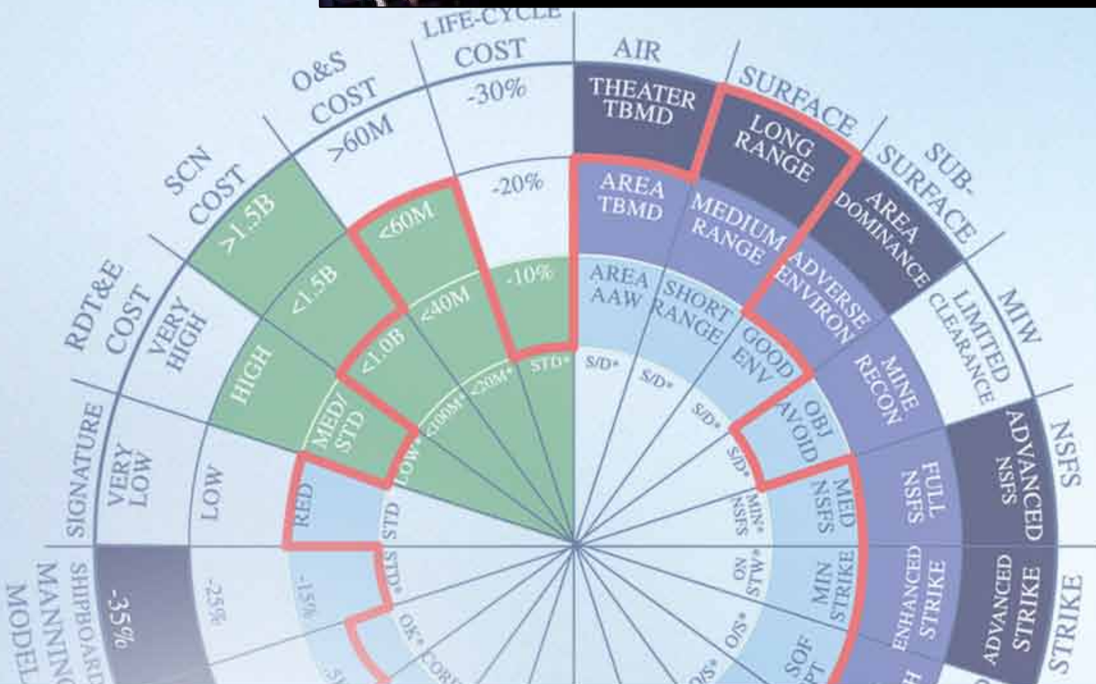




Systems Engineering Planning

by Joel Washington and Gilbert Goddin

The surface Navy adopted an Advanced Capability Build (ACB), technology insertion (TI), combat system modernization approach that implements future warfighting requirements across platforms. As the Navy transitions away from building large end-to-end, platform-unique systems toward cross-platform capabilities, the role of systems engineering (SE) planning has become critical to ensuring systems engineers properly implement newly developed or modified components and capabilities. At the top level, it is important for the government, acting as its own system of systems (SoS) integrator, to fully understand the details of the enterprise-wide SoS architecture and the strategic development planning that accommodates the changes expected over a long SoS evolution. This article addresses the role of SE planning and the processes that enable Program Executive Office (PEO) Integrated Warfare Systems (IWS) to execute the ACB/TI combat system modernization approach and the impact of changes to system requirements, budgets, and schedules on the overall SoS.

Systems Engineering (SE) Planning

Integrated warfare and combat systems are being designed with increasing complexity and with varying interoperability requirements. As a result, these complex systems must operate as an SoS. Consequently, they must be designed as an SoS. A strong SE approach is required to translate operational requirements to a complete set of system requirements. The key to success is flexibility in both TI and business processes to enable the selection, program execution, and delivery of the required capabilities to the warfighter.

SE planning is one of the four pillars of systems engineering. The other three pillars include system integration, system architecture, and requirements engineering. Naval Surface Warfare Center, Dahlgren Division (NSWCDD), engineers have been involved with generating SE plans for numerous programs. The development of SE plans requires a strong understanding of program requirements, knowledge of systems engineering, and the ability to tailor generic systems engineering principles to a specific program. Examples of SE plans that have been developed by engineers at NSWCDD for programs include:

- Systems Engineering Management Plan for Area Air Defense Commander Support System
- Warfare Systems Management Plan, SEMP for the CVN-77 Integrated Warfare System
- SEP, Aegis Advanced Capability Build 2012 (ACB 12)
- ACB/Technology Insertion (TI) Planning Process Users' Guide
- Systems Engineering Concept of Operations (SE CONOPS)

Systems Engineering Plan (SEP)

The SEP is the key guidance document for all technical aspects of a program. Department of Defense (DoD) Instruction 5000.02, Operation of the Defense Acquisition System, states that all acquisition program managers shall develop an SEP for each milestone. It further states, "The SEP shall describe the program's overall technical approach, including key technical risks, processes, resources, metrics, and applicable performance incentives. It shall also detail the timing, conduct, and success criteria of technical reviews."

DoDI 5000.02 is used in conjunction with other acquisition guidance necessary for the preparation of a SEP. Figure 1 shows the relationship between acquisition guidance and systems engineering policy.

The SEP is drafted once initial operational requirements for the ACB are established. The SEP is used to guide all technical activities

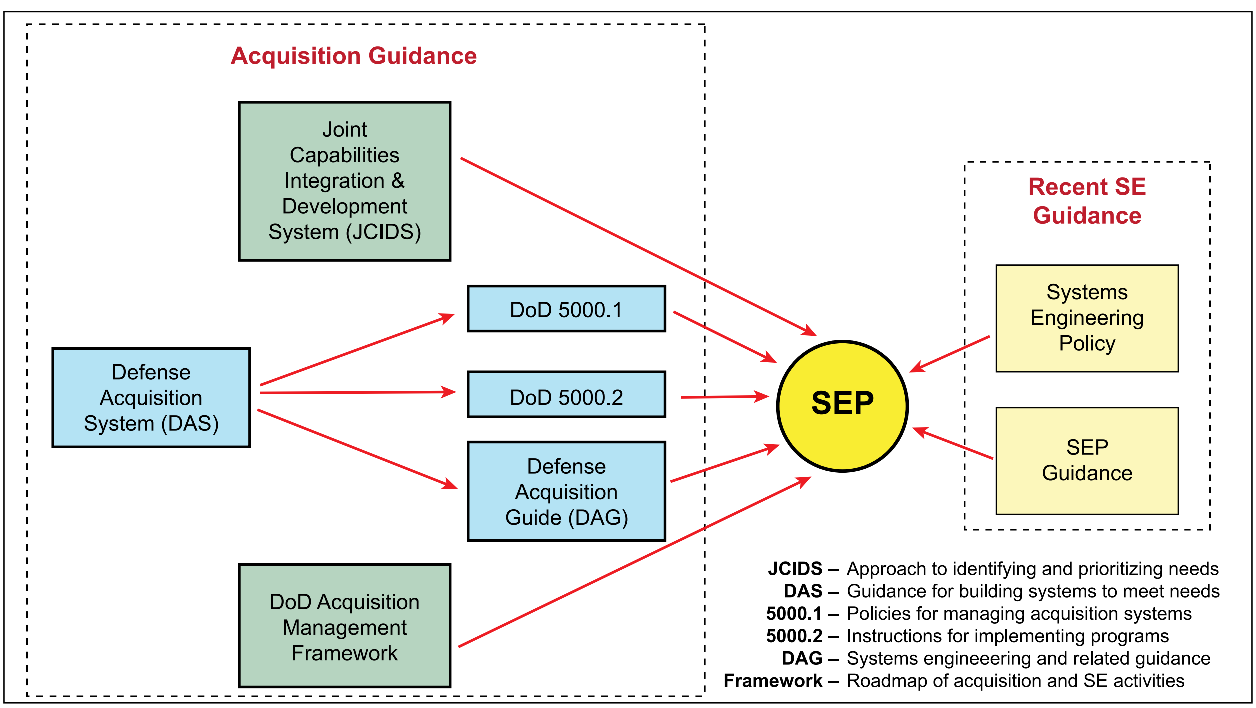
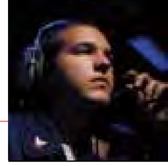


Figure 1. Relationship among SE Guidance Documents



needed for ACB completion. Thus, the SEP is the principal guiding document for all technical aspects of the program. The SEP documents the high-level technical plan, not the details of each process. The SEP describes the organization of the program's Integrated Product Teams (IPTs), including all appropriate technical, certification, and programmatic authority functions.

Systems Engineering Management Process

SE planning is a part of the overall SE technical management process. It is an iterative effort that continues throughout the program until disposal (and sometimes beyond, if the program is restarted). An essential part of SE planning is the determination of the level of technical control the government will exert. Each PEO assigns a lead or chief systems engineer to monitor SE implementation within each program. NSWCDD engineers have supported PEO IWS by documenting the cross-platform systems engineering efforts in the SE CONOPS.

The scope of the technical effort required to develop the ACB is addressed in the SEP. As a minimum, planning identifies which SE tasks must be scheduled, how they will be accomplished, how the overall effort will be scheduled, what resources are needed, how the SE effort will be monitored and controlled, and how the technical effort will be folded into program planning, including the requisite contractual documents. SE management planners must address:

- Program requirements
- Technical planning and control
  - Scheduling
  - Organization structure
  - IPTs
- Technical maturation
- Technical reviews
- Test, evaluation, and certification

Program Requirements

The SE plan should provide a top-level mission description that summarizes user requirements. Identification and refinement of ACB system requirements for each platform's combat system occurs in parallel with the Office of the Chief of Naval Operations (OPNAV) operational requirements definition. Operational requirements for naval surface combatants are drafted and controlled by the OPNAV Surface Warfare Division (OPNAV N86). OPNAV releases an ACB Development Guidance Letter approximately 18 months prior to the System Requirements Review that stipulates the new capabilities expected to be developed, aligned with, and integrated within the combat system. In response, PEO IWS gathers program alignment data (cost, schedule, and technical risk impacts), refines the statements of work and cost estimates from the Program Office Memorandum planning phase, conducts analysis and/or leverages existing studies specific to the requested new capabilities as needed, and assesses the new capabilities against mission-level gaps to generate an ACB evaluation, alignment, and assessment letter (ACB Execution Letter), which details the work that can be accomplished within the available funding and schedule.

Technical Planning and Control

Technical planning and control refers to those elements that are used to plan the technical efforts, the organizational structure used to execute and manage the project, and the definition metrics used to measure progress and to control the technical baseline of the project. The aspects of technical planning and control include scheduling, organizational structure, and integrated product teams.

Scheduling

Scheduling is one of the most important SE planning tools. The schedule serves as the top-level process control document. The schedule identifies the key events and milestones to be accomplished and identifies the critical path for the program. The ACB development schedule depicts development of a two-year delivery cycle and a five-year development, integration, test, and certification timeline. From a cross-platform perspective, a schedule must be maintained of all programs feeding products into the ACB, along with any objective architecture initiatives that will be implemented in the ACB. Figure 2 illustrates how all of these schedules must be linked and managed to ensure that all required products will arrive when needed. For Aegis ACB 14, NSWCDD initiated coordination with the applicable Program Acquisition Resource Managers (PARMs) to obtain and begin management of these various program schedules.

Organizational Structure

The SEP identifies the organizational structure and position roles and responsibilities. It identifies the functional leads, the program management chain of command, and the lead subject-matter experts. From a cross-platform perspective, the organization is matrixed, and the participants

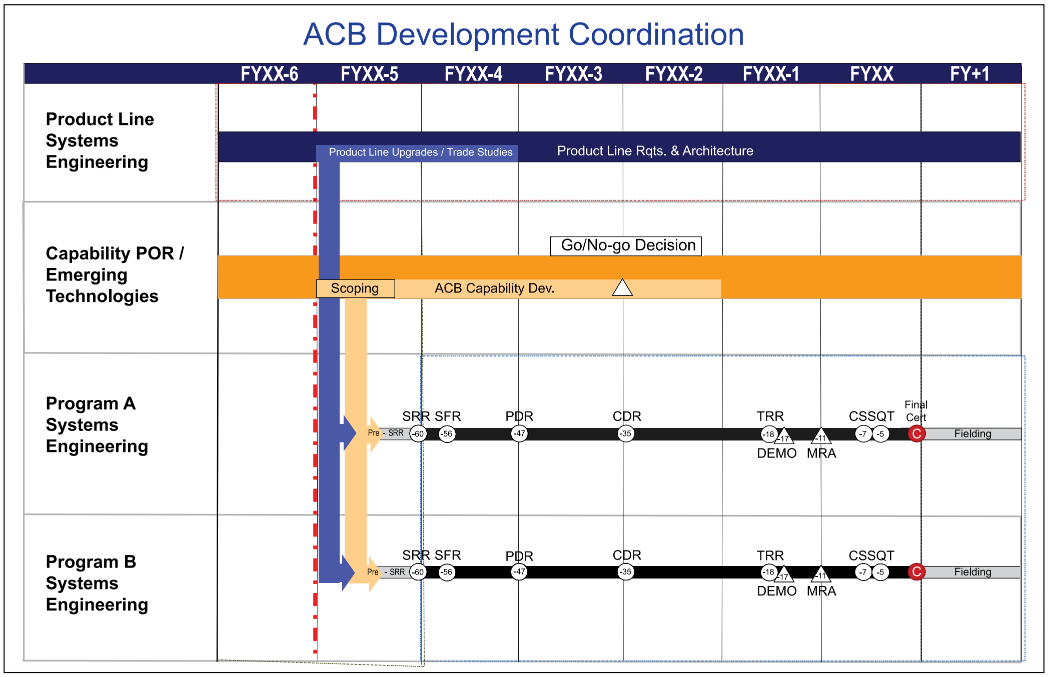


Figure 2. ACB Systems Engineering and Development Notional Timeline

are from several other organizations. NSWCDD engineers performed an SE process definition analysis using a Unified Modeling Language activity diagram format. This analysis resulted in identifying required organizational entities, the functions that these entities must perform, and the interactions and products that must be worked between entities. This information has been captured in the ACB/TI Users' Guide and in the SE CONOPS. Figure 3 depicts a high-level view of the SE functional roles that resulted from the NSWCDD analysis.

The PARMs and element developers work collaboratively with the domain managers and component developers to develop the product based on defined requirements.

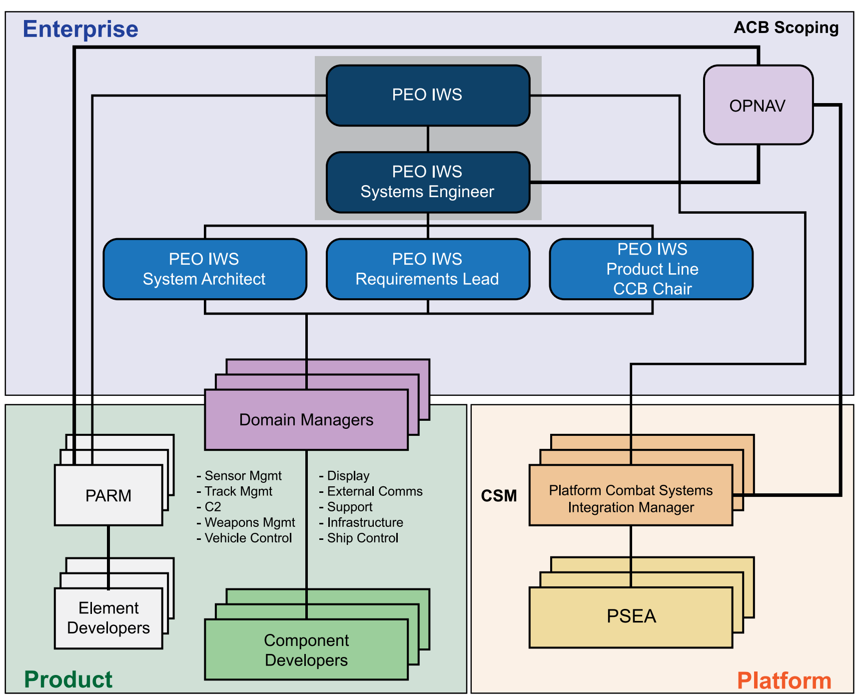
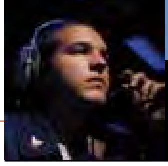


Figure 3. PEO IWS Systems Engineering Functional Roles



Domain leads:
- Identify and upgrade domain candidates
- Coordinate activities with the Platform System Engineering Agent (PSEA)
- Maintain domain and component-level requirements and architecture

Component developers:
- Develop and update component specifications
- Develop new components
- Deliver the components to the domain manager
- Test and integrate the component into the combat system

Combat system integration manager:
- Manages execution and upgrade of surface ship combat systems
- Maintains list of platform integration issues
- Resolves with PARMs and ship design manager platform integration issues
- Maintains long-range upgrade plans for platform
- Maintains hardware and equipment upgrade plans for platform

NSWCDD, as a member of the Naval Sea Systems Command Warfare Center Enterprise, performs the following activities in support of SE planning:
- ACB planning
- Test planning and conduct
- Combat system modernization and upgrades
- Combat system certification
- Systems engineering
- Performance verification assessments to ensure upgrades operate safely, perform ships' missions, and provide stability
- Establishment, maintenance, and control of software and equipment for certified configurations

The PSEA is responsible for integrating government-furnished capability upgrades and other products into each ship class combat system.

Integrated Product Teams (IPTs)

Described in the SE plan is the manner in which the program will organize IPTs to achieve program execution. Different members of a cross-functional team may have primary, secondary, or minor support roles during different phases of ACB development. The goal of the IPT is to get all disciplines involved at the beginning of the development process to ensure that requirements are completely stated and understood for the full life cycle of the ACB.

Technical Maturation

Outlined in the SEP is the approach for managing the overall technical products and how the program will assess and evaluate new technology. Metrics used for the assessment should be closely tied to cost and schedule. In order to plan appropriately, one of the first steps in the ACB development process is to identify and assess new technologies under development by the Navy, other DoD agencies, and industry to determine their tactical importance, maturity, expected performance, and computational resource requirement. There are many techniques that can be used to support sound decision analyses and evaluations of potential new technologies. Alternative concepts should be evaluated in terms of established measures of effectiveness, and the technologies considered should include the interoperability of all components necessary to achieve the capabilities. One of the key outputs of the Analysis of Alternatives (AoA) is an evaluation of technology maturity, as this will be used to define the technology development and demonstration phase, which follows the AoA and must be completed prior to formal acquisition program start.

The Technical Authority (TA) role and responsibility should also be described in the SE plan. The TA provides an independent assessment of engineering processes, products, and risks associated with the ACB. The PEO IWS Technical Director oversees the TA process. TA participants include Technical Warrant Holders (TWHs) and TWH technical team members associated with specific aspects of the project. They are responsible for supporting the PM and the program's systems engineer. The TA pyramid is depicted in Figure 4. The TWH guides the systems engineer in all standards implementations and ensures usability, supportability, and interoperability of the final products. TA participants serve as members of the technical review board.

Technical Reviews

The procedure for the program to conduct technical reviews and how the reviews will be chaired and supported by the technical team, including program-level office representatives, is described in the SEP. The PEO IWS SE process includes technical program reviews as identified by the technical review manual and as Figure 5 illustrates. Technical program reviews are designed to reach decisions regarding technical

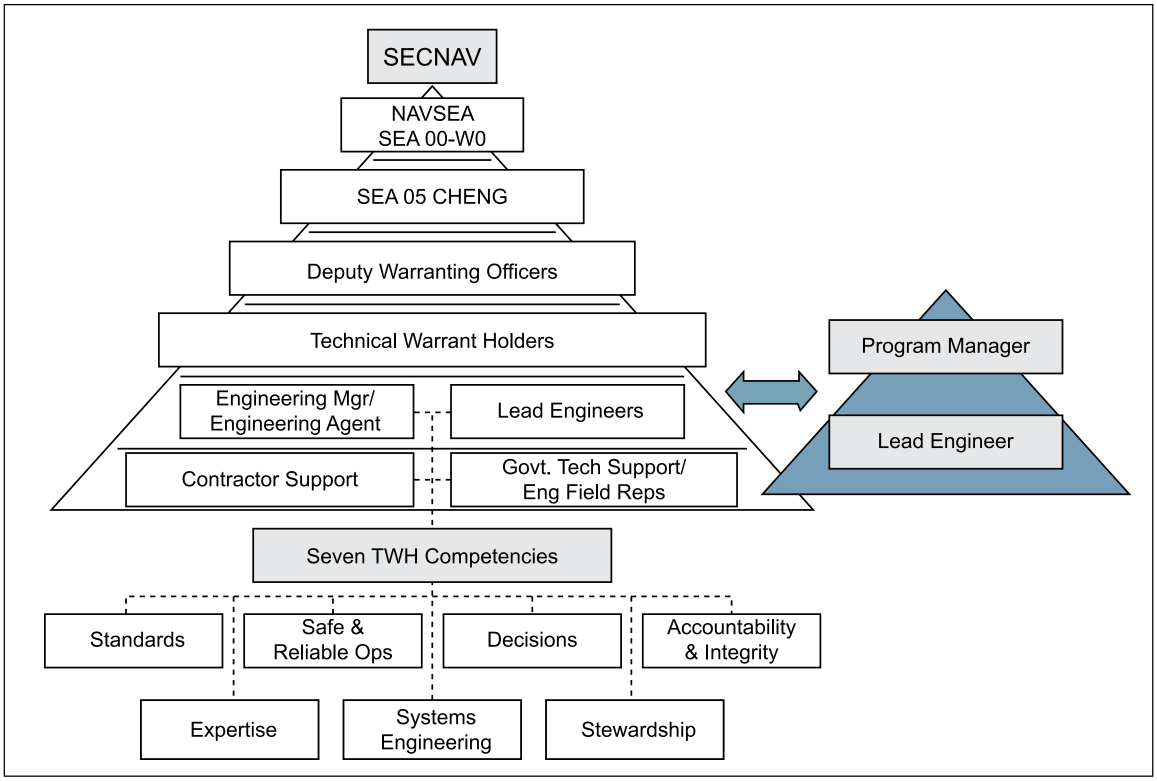


Figure 4. Technical Authority Pyramid

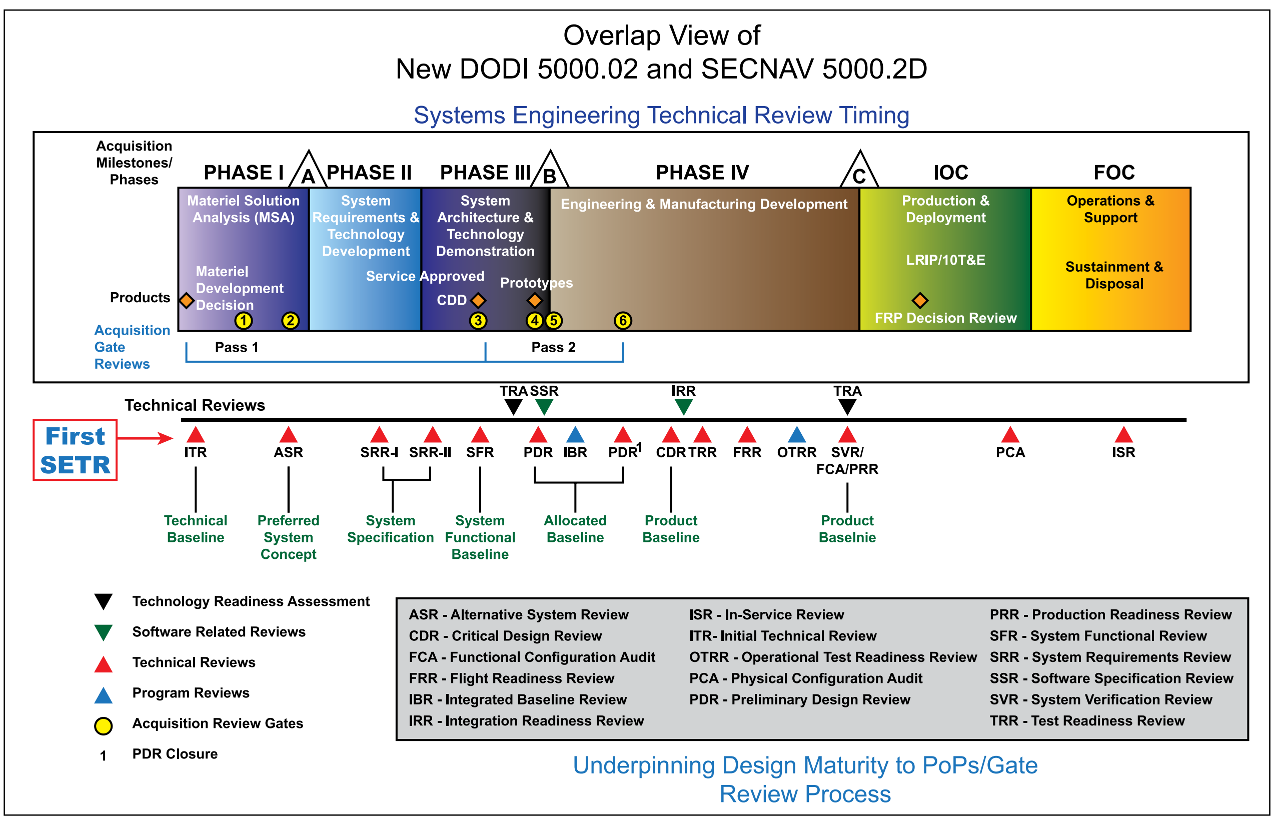
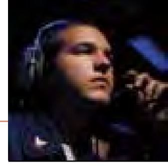


Figure 5. SE Technical Reviews



design approaches, assess technical risk, and measure the maturity of the program or project during the development and maintenance phases. PEO IWS aligns the technical reviews for each program or project with those of the host combat system.

Test, Evaluation, and Certification

Outlined in the SE plan is the technical approach for integration test and evaluation, system certification, and life cycle support. During integration and test, the PSEA is responsible for delivering the ACB required capability. Component developers support the testing and correct problems found in their components during the test period, in accordance with the problem resolution budgets and contracts they have in place.

Figure 6 illustrates that combat system integration and test is a hierarchical process. Level 1 testing starts at the component level to ensure each component meets its requirements. Level 2 testing begins to integrate components to execute chains of functionality. Level 3 testing integrates components to form an element and verifies element-level requirements. Level 4 and Level 5 testing is performed at the weapon- and combat-system levels, respectively, by a collaborative test team composed of PSEA and Navy test engineers. This testing focuses on verifying element- and system-level requirements in the target environment and assesses system performance and stability under stressing and endurance conditions.

	Test Level	Articles Under Test	Contributors	Test Aspect	Approach
Level 5	Combat System I&T	System, Multi-element/subsystems, ACS (includes Requirements & Regression Testing	I&T SEIT	SRV MEIT A-Spec Reqs Testing Regression Testing	Verification system interfaces, functionality, and performance requirements Verify multi-unit interoperability Ensure system stability
Level 4	Weapon System and Subsystem I&T	System, Multi-elements/Subsystems, Including Applicable AWS Elements), AWS Requirements	I&T SEIT Subsystem/Element Engineers	SRV MEIT A-Spec and B1 Testing Regression Testing	Verify subsystem interface, functional, and performance requirements Verify integration of hardware / software components
Level 3	Element Verification	Integrated Components of one product area (ex. WCOA) Subsystem Requirements	Subsystem/Element Engineers	ET&E B5 Testing	Verify element-level functional requirements in subsystem models Leverage desktop test environment
	Software System Integration Test (SSIT)	Subsystem / Elements	Software Developers I&T Subsytem/Element Engineers	Daily Standard Operational Test (DSOT), Functional and Stability Testing	Verify subsystem & component integration Functional thread test procedures through the system Ensure system stability
	Equipment Unit Test	Hardware Components and Component Groups	I&T Hardware Engineers	Environmental / Performance Test B2 Testing Nonfunctional Reqs	Verify equipment (groups) meet design parameters and perform within operating tolerances
Level 2	Software System Integration Test (SSIT)	Component Integrated Components	Software Developers	EI&T	Early functional testing of integrated components Leverage desktop test environment
	Equipment Light-Off	Hardware Components	Hardware Engineers	ILO / Smoke Test	Verify Power-On & OE configuration
Level 1	Component Developmental Class Testing	Classes and Collaborating Classes	Software Developers	Unit	Low-Level class testing and class Integration Leverage desktop test environment
	Equipment Receipt Inspection	Hardware Components and Accessories	Hardware Engineers	Inspection	Verification of physical component and accessories

Figure 6. Integration and Test

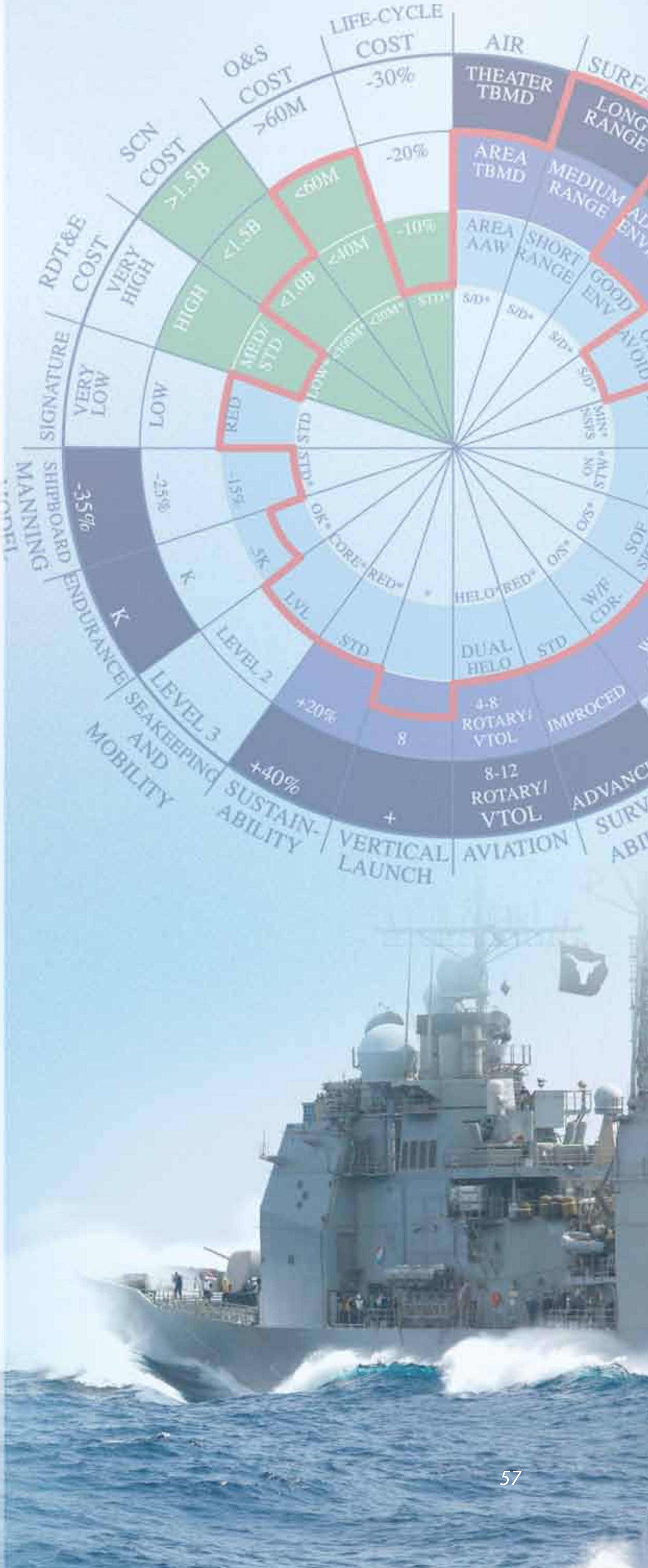
ACB at-sea testing, conducted by the PSEA and Navy test engineers, is the most important phase of testing prior to inclusion of the technology in the combat system. This test provides the opportunity to verify performance and collect calibrated data for future use. The PSEA is also responsible for evaluating and assessing the test results and for the interpreting the component-level and subsystem- or system-level results. These at-sea tests are not intended to serve as the system certification.

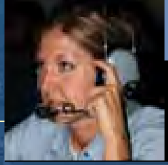
Described in the SEP is the manner in which the program will implement system certification. PEO IWS accomplished system certification via a separate testing effort following full integration of the ACB into the baseline system. However, this step is designed with certification in mind so that the program office can ascertain the level of certification testing required. In addition, Navy Operational Test and Evaluation Force representatives participate in testing as independent observers, facilitating decisions regarding future certification testing. Upon test completion, the system is delivered to the program office for incorporation into the combat system.

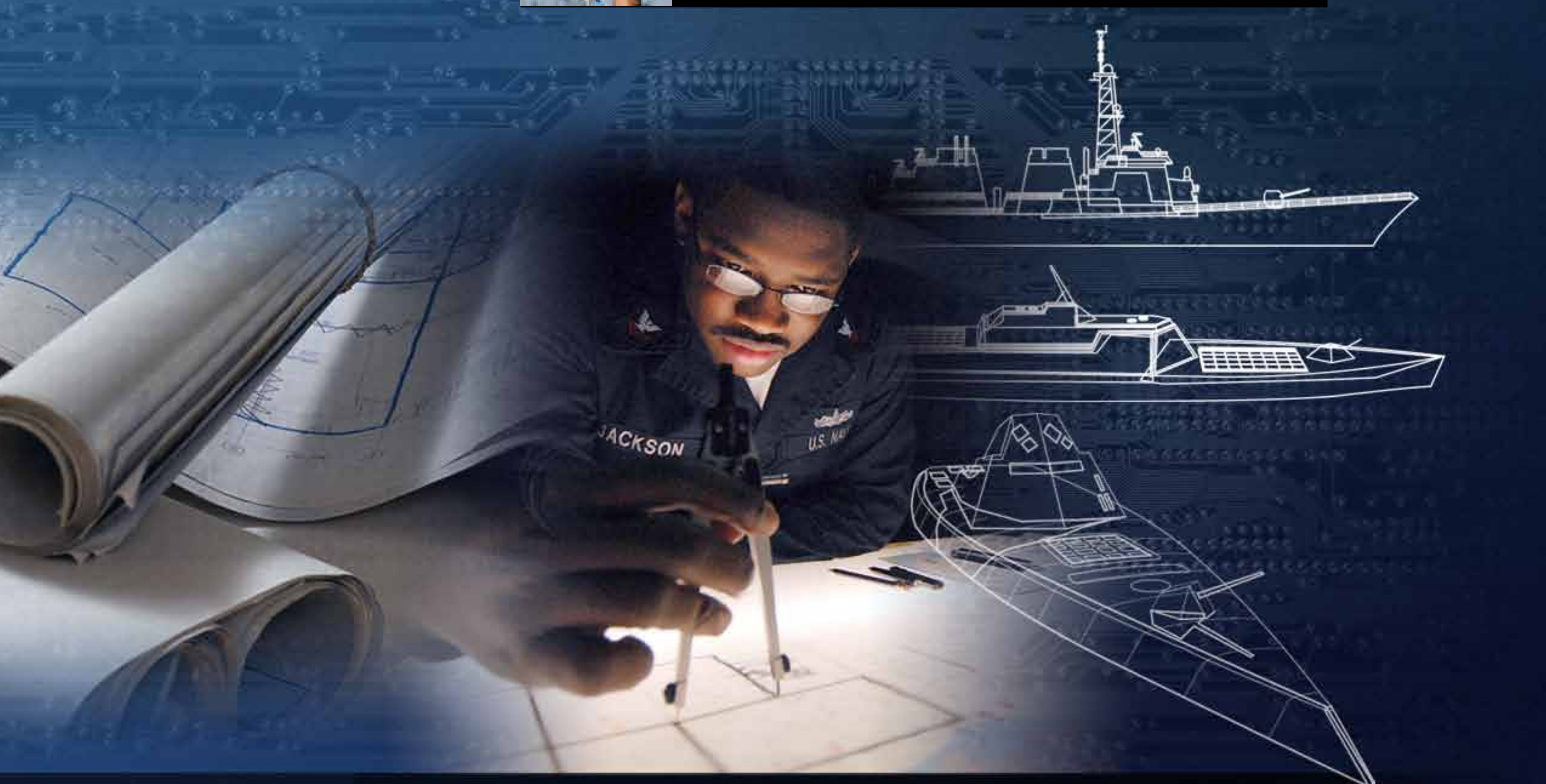
Following the fielding of a combat system, its performance is analyzed based on data collected during deployments in actual operational environments as part of a life cycle support plan. The life cycle support plan is designed to provide data to support future ACB spirals, to establish a new baseline capability to compare to future improvements, and to address real-world Fleet issues in operational environments.

Value Added

The SE plan captures the program's current and evolving SE strategy and its relationship with the overall program management effort. It documents the program office's understanding of how the program will accommodate and balance cost, schedule, performance, sustainment requirements, and constraints, expected products of SE activities, and how these products will contribute to program decision-making. The real value from SE planning, however, is realized when warfighting capabilities and platforms work effectively and seamlessly together to help warfighters fight, win, and come home safely.







Systems Engineering and Design — From the Total Ship Perspective

by Miguel E. Rivera, Mark L. Williams, and Ashby G. Hall

The systems engineering (SE) landscape changed dramatically over the past decade due, in part, to a shift in the design and development of larger, more complex systems that cut across multiple programmatic, contractual, and technical boundaries. Recent acquisition policy changes and surface combatant lessons learned now emphasize the need for an SE process that facilitates coordinated total ship systems engineering (TSSE) through a total systems engineering team (TSET) construct developed in alignment with a structured technical baseline. This article introduces a new approach that blends a combination of top-down and bottom-up SE through the employment of an architectural core utilizing the DoD Architecture Framework (DoDAF) as the foundation.

The key phrase throughout this discussion is "from the total ship perspective." As far as is known, this recommended SE approach provides, for the first time, a process to apply SE from a total ship perspective with a focus on the technical baseline and engineering and design management acquisition phases. This approach has yet to be performed from cradle to grave for a large ship program.

Systems Engineering and Design Process

The Systems Engineering and Design Process (SEDP), shown in Figure 1, merges top-down and bottom-up SE by employing an architecture framework as the foundation to facilitate coordinated TSSE and design processes in alignment with a TSET construct. The approach utilizes the DoDAF as the architectural core

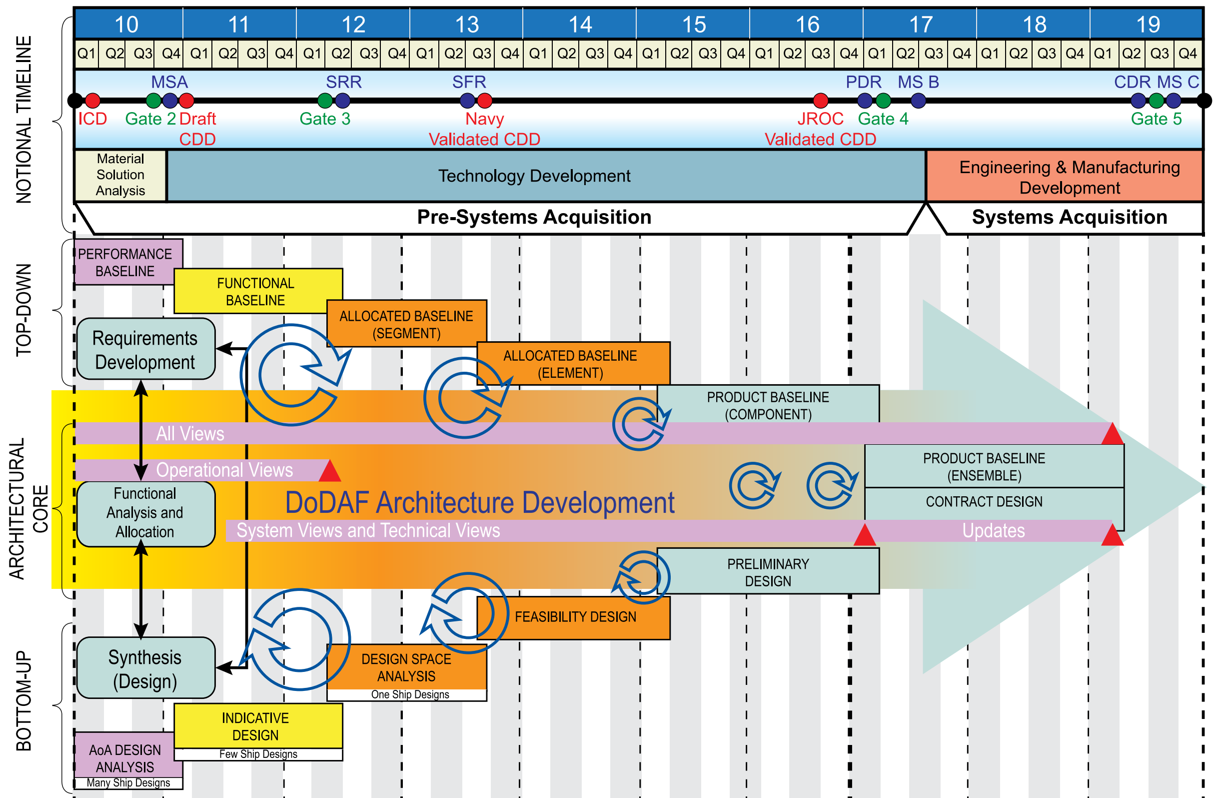


Figure 1. Systems Engineering and Design Process

to facilitate total ship (mission systems, ship systems, and support systems) coordination and evolution throughout the program life cycle. An iterative evolution converges on a traceable, testable, feasible, and cost-permissive design that meets Office of the Chief of Naval Operations requirements as provided through the Joint Capabilities Integration and Development Systems (JCIDS) Process within the Initial Capabilities Document (ICD) and Capability Description Document (CDD).

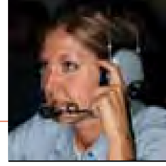
The SEDP is a comprehensive, iterative, and recursive problem-solving process, applied sequentially by integrated teams. It transforms needs and requirements inset of system products and process descriptions, generates information for decision-makers, and provides input for the next level of development. The SEDP is applied sequentially, one level at a time, adding additional detail and definition with each level of decomposition.

The SEDP is derived from lessons learned from recently engineered and designed surface combatants and aligns with acquisition policy updates. The SEDP includes four components: (1) Notional Timeline; (2) Top-Down SE; (3) Architectural Core; and (4) Bottom-Up SE. Each of the components is addressed in further detail below.

Notional Timeline

The notional timeline, depicted in the top of Figure 1, encompasses the material solution analysis, technology development, and engineering and manufacturing development phases of the acquisition life cycle. The timeline identifies milestones, gates, technical reviews, and pertinent decision points in alignment with new and updated SE and acquisition guidance. The timeline provides the driving force for alignment of TSSE. Actual timelines will be program-specific and may require tailoring for program needs.

A key element of the timeline is the operational requirements. For most major defense acquisition programs, this requirement will come in the form of a CDD that has been validated and approved by the Joint Requirements Oversight Council through the JCIDS process. Since the CDD is not formally approved until Milestone B, it is assumed that the acquisition program will be



provided with various draft and Navy-validated releases. The timeline depicts notional CDD releases and assists in ensuring design alignment to end-user needs.

Top-Down Engineering

Top-down engineering, depicted in the upper middle of Figure 1, aligns with requirements development SE activities and commences with the analysis of process inputs. Requirements analysis is used to develop functional and performance requirements; i.e., customer requirements are translated into a set of requirements that define what the system must do and how well it must perform. The systems engineer must ensure that the requirements are understandable, unambiguous, comprehensive, complete, and concise. Requirements analysis must clarify and define functional requirements and design constraints. Functional requirements define quantity (how many), quality (how good), coverage (how far), timelines (when and how long), and availability (how often). Design constraints define those factors that limit design flexibility, such as environmental conditions or limits; defense against internal or external threats; and contract, customer, or regulatory standards.

An initial set of DoDAF operational viewpoints (OVs) is provided as input within the net-ready key performance parameters of the CDD. These OVs provide a mechanism for capturing the organizations, tasks, or activities performed, and information that must be exchanged to accomplish DoD missions. OVs convey the types of information exchanged, frequency of exchange, tasks and activities supported by the information exchanges, and nature of the information exchanges. The DoDAF OVs are used to support and validate the operational and functional requirements.

The iterative requirements loop ensures that both the requirements and architecture are consistent and characterize the complete system. The process then proceeds with the Synthesis Phase. After the completion of one complete SE cycle, a baseline is established and the process begins again for the next baseline.

Architectural Core

In parallel with the top-down and bottom-up engineering, a series of architectural products is developed through functional analysis and allocation SE activities. The architectural core is depicted in the middle of Figure 1. Functions are analyzed by decomposing higher-level functions identified through requirements analysis into lower-level functions. The performance requirements associated with the higher level are allocated to lower functions. The result is a description of the product or item in terms of what it does logically and in terms of the performance required. This description is often called the functional architecture of the product or item.

Functional analysis and allocation allow for a better understanding of what the system has to do, in what ways it can do it, and to some extent, the priorities and conflicts associated with lower-level functions. This provides information essential to optimizing physical solutions. Key tools in functional analysis and allocation are use cases, functional flow block diagrams, requirements allocation sheets, and the DoDAF All Views (AVs), OVs, System Views (SVs), and Technical Views (TVs).

The DoDAF SVs capture information on supporting automated systems, interconnectivity, and other systems' functionality in support of operating activities. The SVs provide a functional alignment to the requirements through OV mappings and alignment and facilitate a framework to capture the physical ship design. The AVs provide an overall description of the complete architecture, the scope, and definitions of the terms used. The TVs define the applicable and emerging technical standards, conventions, and business rules.

Bottom-Up Engineering

The bottom-up engineering aligns with the synthesis (design) SE activities as depicted in the bottom of Figure 1. Design synthesis is the process of defining the ship in terms of the physical and software configuration. The result is often referred to as the physical architecture that includes ship arrangements and layouts. Each part must meet at least one functional requirement, and any part might support many functions. The physical architecture is the basic structure for generating the specifications and baselines.

The design process employs the ship work breakdown structure as a system-oriented coding structure to categorize the various subsystems. Standard design engineering, in accordance with Naval Sea Systems Command (NAVSEA 05) Ship Design Manager Manual, evolves development of the ship design from the analysis of alternatives to the contract design.

Similar to the requirements loop described above, a design loop is employed to revisit the functional architecture to verify that the physical design synthesized can perform the required functions at required levels of performance. The design loop permits reconsideration of how the system will perform its mission and helps ensure consistency with the requirements and architecture. DoDAF SVs are a mechanism to capture the physical design.

Technical Baseline

Baselines signify departure points for government configuration control. Figure 2 depicts a notional technical baseline with technical review overlays. The technical baseline was constructed to resolve the lesson learned for closer coordination between mission and ship design developers. The specification tree aligns TSSE activities to ensure a final design that converges and is traceable back up to the ICD.

The technical baseline includes four independent baselines: (1) performance, (2) functional, (3) allocated, and (4) product. The performance baseline consists of the operational requirements as captured in the ICD as developed in the material solutions analysis phase and the CDD, both of which are under the purview of the Office of the Chief of Naval Operations, Surface Warfare Division for the Surface community.

The functional baseline includes the Specified Performance Document (i.e., the total ship system requirements document), the System/Subsystem Design Description, and the other associated ship architectural products.

The allocated baseline is composed of functional, performance, and interface requirements as flowed down from the Specified Performance Document and allocated to lower level segment and element specification. The product baseline contains an approved design that describes the system configuration during the procurement and production, fielding/deployment, and operational support phases of its life cycle. The product baseline includes the Ship Specification [i.e., Design, Build and Process Specification] and lower-level detailed design artifacts.

At the point in the design when development of the ship specification has begun, all portions of the requirements flow into the ship specification and are broken down by the ship's work breakdown structure. This includes all lower-level requirements, purchase specifications, drawings, and diagrams. Again, the purpose of this construct is to ensure all aspects of the design stay coordinated by the entire team throughout development. As previously mentioned, the key

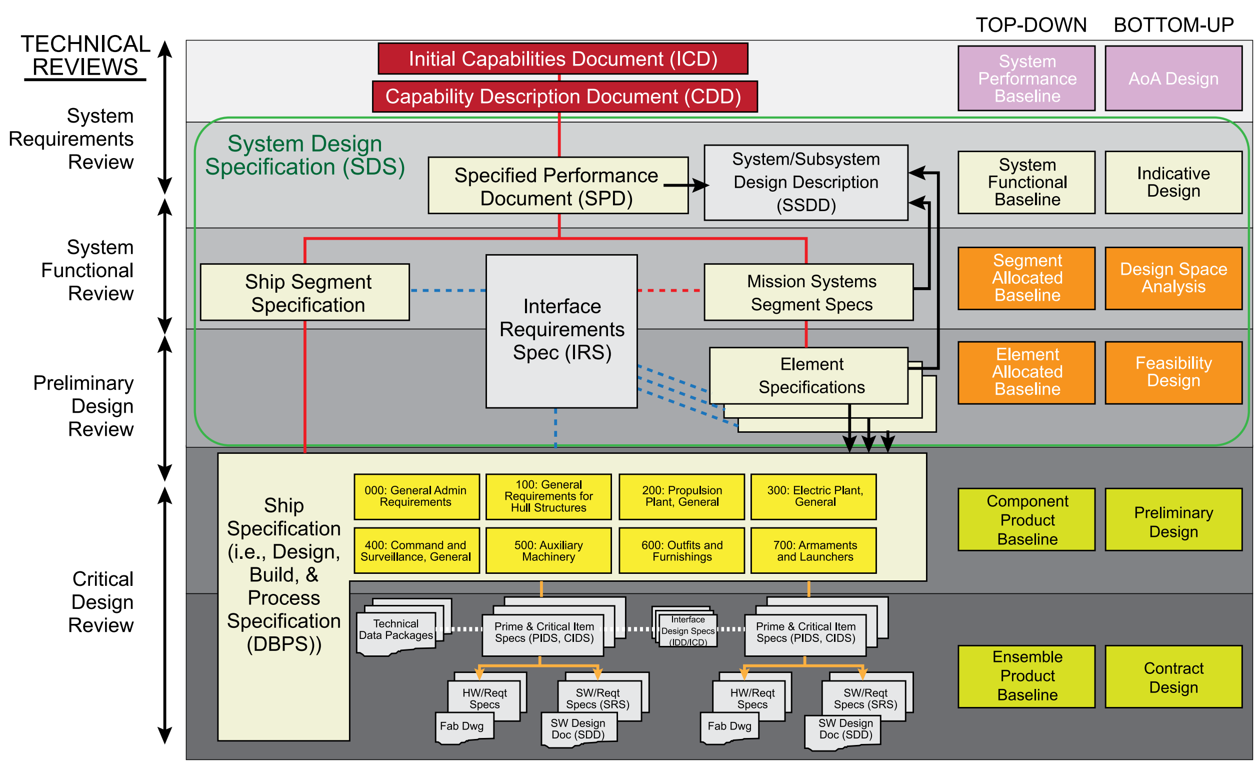


Figure 2. Example Technical Baseline

to the SDEP and development of the Technical Baseline resides with a coordinated TSET.

Teaming

Figure 3 illustrates a notional teaming concept for maximization of SEDP benefits. This teaming structure provides a coordinated approach that aligns the programmatic side, led by the Program Manager, and the technical side, led by the Technical Director and Ship Design Manager, into a seamless organization. Based on a total ship focus, it is assumed that all aspects of the program are included (i.e., risk management, configuration management, cost), although these are not specifically discussed within this article. The notional teaming concept includes three components: (1) the Program Management Team; (2) the Technical Management Team; and (3) the TSET. The TSET manages the Product Teams and Cross-Product Teams. Each of the components is addressed in further detail below.

A key element of the teaming concept is a team with co-leads. Each major team will have two co-leads, typically one from the top-down and one from the bottom-up portion of the process. This co-lead approach is loosely based upon that of the *Virginia*-Class Submarine Program and has been modified to complement the SEDP approach and the associated technical baseline.

Program Management Team

The Program Management Team is the top-level team that manages the program and coordinates with other program, business, and financial managers in partnering organizations. The Program Manager and Senior Ship Design Manager are co-leads.

Technical Management Team

The Technical Management Team is composed of engineering leads from the systems commands and participating PEOs as well as

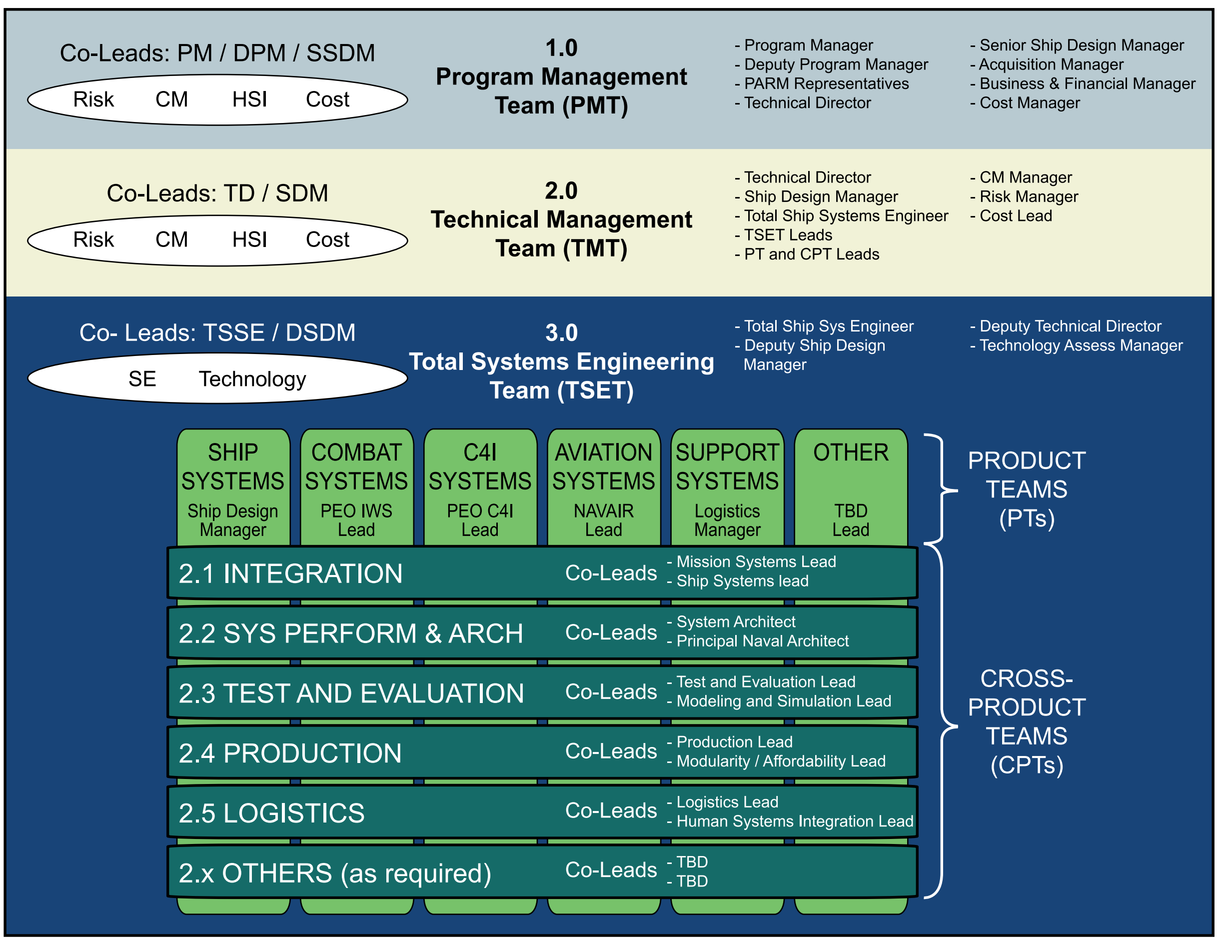


Figure 3. Notional Teaming Construct

leads from the TSET, Cross-Product Teams, and Product Teams. The team provides day-to-day technical management and coordination with emphasis on integrating efforts related to requirements, architecture, interfaces, interoperability, testing, and system verification and validation. The team is the bridge between the technical and programmatic work. The Technical Director and Ship Design Manager are co-leads.

Total Systems Engineering Team

The TSET performs SE management and technology development management functions. The TSET defines and establishes SE processes; coordinates SE activities across Product Teams and Cross-Product Teams; supports the Technical Director in the preparation and execution of technical reviews; oversees technology risk reduction activities; and coordinates technology readiness assessments. The team is key to the success of the SEDP and maintains coordination among all the stakeholders and teams. The TSSE and Deputy Ship Design Manager are co-leads.

Product Teams represent the functional areas such as Combat Systems, led by PEO Integrated Warfare Systems; Command, Control, Communications, Computers, and Intelligence Systems, led by PEO C4I; Aviation Systems, led by Naval Air Systems Command; and Ship Systems, led by NAVSEA 05. The teams work the development and design of their respective functional areas and provide the membership for all the Cross-Product Teams, thereby ensuring that they have input into all aspects of the design. Product Teams do not require co-leads.

Cross-Product Teams perform and coordinate functions that must cross the product boundaries to help facilitate an integrated total ship systems design. Cross-Product Teams form the lowest management level that requires co-leads.

Conclusions

A systems engineering design – from the total ship perspective – is necessary to manage an integrated technical baseline for the total ship as it advances through the Navy surface platform acquisition life cycle. This proposed approach blends a combination of top-down and bottom-up SE. A DoDAF architecture framework serves as the foundation to facilitate coordinated, total ship SE and design processes that are aligned with a total ship engineering team. It is based on lessons learned from multiple platforms. If adopted, this approach will help the Navy better design and build systems-engineered ships more efficiently and more effectively, ultimately benefiting naval warfighters with enhanced capabilities for years to come.

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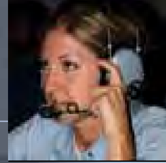


Total Ship and Enterprise Approach to the Navy Platform Technical Team Model

by David S. Richardson, Greg LaCava, and Stephen Haug

For more than a decade, the Navy's surface ship technical community has supported system acquisitions using a model known as "Tech Team." This model focuses the right technical expertise at the right levels from warfare centers, university-affiliated research centers, and support contractors into a virtual enterprise for the Navy to ensure necessary technical oversight in the research and development phases of ship design. With the recent refocus on systems integration, the roles and responsibilities of government and private sector engineering staffs are being reevaluated. The Tech Team model can be sized and structured appropriately for a given program based on the acquisition approach and desired risk level. In addition, the Navy is moving toward a product line systems engineering approach for platform development, where consolidation of components and openness of architectures is embraced. Items addressed in this article are how the model operates, lessons learned over the last decade, critical environments and tools to maintain technical insight over varying levels of design detail, and how it can be utilized by the Navy to support systems integration challenges in a 21st century Fleet.

Introduction

Motivation

The surface Navy requires a centrally managed, technically founded, large-scale system of systems engineering capability at the cross-platform, combat system level to effectively manage combat system enterprise development. The focus needs to be on key technical initiatives to enable this evolution; specifically, architecture, requirements, systems engineering planning, and systems integration. This will be further enabled through an enterprise organizational structure that includes technical teams, maintains continuity of leadership, and revitalizes government technical roles in the warfare centers. The need to transition the surface Navy's combat systems acquisition processes, technical underpinnings, and organization is pressing. The benefits to be derived from implementation of the new business model and enterprise systems engineering principles extend from tangible cost savings to rapidly and effectively integrating warfighter capabilities in response to ever-changing threats. The transition of the surface combat system acquisition enterprise to the new business model is an essential element in the Navy's ability to achieve its goals for its future surface combatant force.

The approach to moving toward an enterprise warfare systems environment for surface combat systems is centered on establishing a product line of reusable components that can be assembled by the platform system integrators into systems that meet all of the requirements of a particular ship class to enhance broad Navy warfighting. Requirements and systems engineering processes are tailored to implement these principles and foster competition and collaboration throughout the acquisition and operations and support phases of a ship and of a system's life.

Failure to adopt an enterprise development model will maintain the existing cost structure, within which multiple efforts to provide the same capabilities must be funded. Legacy architectures will still require a higher level of effort and cost to maintain and modernize. New construction ships will focus significant resources on redesigning and testing capability similar to what is already fielded, and any new capabilities will not be readily backfit on legacy ships. The extra expense of this redundant effort will hinder the Navy's ability to build the future Fleet, and is already unaffordable for the Navy to sustain.

Naval warfare centers have a long heritage of integrating ever more complex systems into the warfighting capability for the nation. For example, this unique capability was recognized by the 2005 Base Realignment and Closure Commission and in international texts on the subject of large-scale systems integration at Naval Surface Warfare Center, Dahlgren Division (NSWCDD). With an enduring technical professional development program, the NSWCDD laboratory has successfully shown the value of engineering rigor up the systems' hierarchy: components, systems, ships, and force. An aggressive reinsertion of the warfare center to lead as the prime integrator for targeted major weapon system acquisitions is a sound strategy, especially in aligning programs at the beginning of their acquisition and development cycles. This action rebalances the risk between the public and private sectors and will help reestablish the military-industrial complex needs while providing stability to combat system platform developments.

Challenge

Decades of increasing requirements driving increasing levels of machine complexity, coupled with socioeconomic business strategies, have led to major ship and submarine cost deviations, an atrophying of the public sector work force of scientists and engineers, and a significant decrease in affordable naval force structure. This has been caused in part by a gradual diminishing of government technical participation and active technical oversight during development, the classical technical team roles. Acquisition strategies for ship development must lean more heavily on the Navy laboratory infrastructure to regain and maintain long-term technical control of the most highly integrated, complex, capable machines ever to go to sea—the naval warship.

The Navy is organized for systems acquisition in a way that reflects its historical planning, funding, and acquisition execution. Requirements are defined around platform programs (the verticals) as opposed to product line capabilities (the horizontals) that can be employed across multiple platforms. The responsibilities for providing these requirements, as well as the structure within which budgets are developed and executed, are similarly aligned to the verticals. Because organizations tend to reflect the environment in which they work, both the acquisition community and the customer side of the Navy are aligned to the vertical perspective. The broader industry (beyond the defense industry) historically was also aligned in verticals but has now recognized the need to integrate horizontally across platforms with common products managed horizontally. While many sectors of industry have been able to transition to the horizontally aligned organization in recent years, the Navy is constrained by the realities of working with Congress and with the complexity of multiple organizations interacting to deliver capabilities. The most effective mitigating action to address this challenge is to organize the requirements and budget infrastructure, including how appropriations are structured, to better reflect the benefits of the horizontally integrated enterprise. Critical to the success of the technical team organizational model is setting up the technical authority and technical structures to enable successful insertion of warfighting capabilities across platforms.

Systems-of-Systems Context

Baron (2007)[1] opines a good summary of the state of play in the military and public sector, which is summarized here. There has been a collapsing of available private sector contractors in the military business base due to corporate acquisition and merger—actions that were driven by short-term financial pressures of share price protection and major contract capture. This state of affairs should be troubling to senior government leaders who rely on this competitive industrial base to economically execute decade-long national programs. Also surprising is that the government's own technical infrastructure is not leaned on more heavily to bridge the inherent gaps in current corporate business ventures. Not only should the government provide critical services, it should also act as the technical risk management arm on behalf of the sponsor to continue program progress through completion. Industry contractors must not be given the full responsibility for our national defense, for accountability rests with our government. The current defense acquisition strategy is overreliant on private sector prime integrators for large-scale, complex system development at the exclusion of government technical institutions.

The private sector prime contractor may also have limited knowledge into the full range of technological possibilities to resolve technical issues. It is not unreasonable to expect that by the simple nature of a depth of knowledge in its own internal technological investments, the prime contractor will tend to overly defend and rely on its internal technology for problem resolution. This may be at the expense of suboptimization of the design. Trust in and protection of proprietary rights and equitable compensation for corporate technology is a coveted governmental characteristic. The government laboratories, through proper disclosure arrangements, can have a much broader insight into the potential range of technological solutions to engineering challenges.

There are several functions that must move back to the government, but care must be taken to not swiftly move too many acquisition roles in that direction. Recent workforce reshaping and reduction activities in the warfare centers will limit the warfare centers' ability to initially respond with significant additional resources. Reengagement of the government lead integration agent roles should take place with targeted programs and then continue to grow (crawl, then walk). This will allow the programs most in extremis to gain the earliest and maximum support while allowing the laboratory structure to rebuild human capital. The relationship between the program offices and laboratory must be shared responsibilities and not simple hands-off risk transfer as was with the industrial prime contractor integrator. Sustainment demands of a national intellectual infrastructure must be balanced and checked through resourcing and workflow mechanisms. A mutually agreeable condition that would allow more governmental technical leadership and execution in large-scale integration efforts can certainly be achieved, and it should be executed through organizational growth and targeted divestitures.

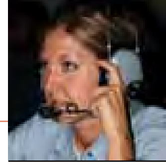
The Navy surface and undersea warfare laboratories that are focused on the research, development, acquisition, and test and evaluation stages of acquisition, such as at NSWCDD and Naval Undersea Warfare Center, Newport, Rhode Island, can play key inherently governmental and critical technical leadership roles in major acquisition programs and in a system-of-systems context. These two organizations lead partnering between the warfare center enterprise and industry on the integration task, giving the program office the best minds, the widest knowledge base, and unbiased technical assessment as to program progress. Engineering across the ship mission domain and across all surface and subsurface platforms uncovers opportunities for efficiencies in engineering to fully realize warfighting and affordability goals. This is usually executed through a Tech Team model, where senior government experts lead various teams consisting of diverse public and private participation under the integrated product and process team structure of the particular acquisition. The Navy must lead certain critical teams while only providing unique subject-matter expertise to others. Determining which teams are led by the government and which teams are just supported is unique to each program, usually due to unique acquisition strategies and contractor-government relationships. Technical participation to gain insight and to be able to report technical progress as well as quick surfacing and participation in the realization of new technical unknowns or challenges that must be resolved for program success is critically important. This would take the form of an integrated warfare center technical team that is capable of working across Navy platform programs. In addition, resource sponsors must be incentivized to allow Navy platform technical teams to work across programs to enable better products for less investment. These changes will enable a better usage of a total ship and enterprise approach to national technical teams led by the warfare centers, and will create better and more reusable products across Navy combat systems.

A secondary advantage of exploiting integration centers at Dahlgren and Newport is the ability to share, implement, and exploit cross-program system solutions, standards, processes, and integration strategies; thus, providing a system of systems integration. Government leaders, senior scientists, and engineers are able to oversee and direct enterprise initiatives within their programs on such important integration topics as open architecture, modular development, and cross-program reuse since these initiatives are not only good business strategies but also enable the force-wide capabilities of naval and Joint systems of systems to be technically realized.

Current Surface Navy Tech Teams

Approach

In recent Navy surface combatant acquisitions, the common practice has been for an industry contractor to be selected as the



Platform System Engineering Agent (PSEA), in charge of integrating the various Program Acquisition Resource Manager-provided products (e.g., sensors, communications, and weapon systems) into a combat system. The PSEA often also provides the Combat Management System software that controls the combat system. A Navy Technical Team is then stood up to oversee the efforts of the contractor. The Technical Team acts in an advisory role, assisting in identifying risks and mitigations and solutions to issues but not making decisions or developing products, which are the responsibility of the PSEA. The Technical Team also provides the Program Manager with an independent technical assessment of progress and risks.

In general, the Technical Teams mirror the work breakdown structure of the PSEA. The work breakdown structure is usually broken down by product, and the Technical Team is then defined as Integrated Product Teams (IPTs) along those product lines. Examples include Command, Control, and Intelligence; Weapons, Communications; and Sensors. In addition to product IPTs, there are usually a few Cross-Product Teams (CPTs) covering areas that touch many of the product IPTs. Examples include test and evaluation, modeling and simulation, and certification. Figure 1 represents a typical technical team structure.

All recent Navy acquisitions also have an overarching, high-level technical team, represented by the Systems Engineering and Integration (SEI) team in Figure 1. The main role of the SEI team is to coordinate the IPTs and CPTs to ensure that the integrated system is capable of meeting its requirements. This includes identifying issues and decisions from lower level teams that may affect other teams and identifying and managing risks across the system. The SEI team also includes internal teams responsible for system requirements architecture development that affect the whole system.

IPTs are composed of members from industry (including the PSEA and system component developers) and Navy. Navy members come from the warfare centers (e.g., NSWCDD and Naval Surface Warfare Center, Port Hueneme Division), Navy contractors (e.g., Johns Hopkins University Applied Physics Laboratory), and the program executive offices (e.g., Program Executive Office [PEO] Integrated Warfare Systems and PEO Command, Control, Communications, Computers, and Intelligence [C4I]). The Navy lead of each IPT is typically from the organization that specializes in the area; for example, the C4I IPT Navy lead is from PEO C4I.

IPT member responsibilities vary from program to program. In some programs, the Navy members participate in development of the products. In others, the Navy members participate in more of an advisory role. In all cases, the Navy members are responsible for understanding the product, reviewing requirements and design, identifying and recommending solutions for potential problems, and reporting progress to the IPTs.

Managing IPTs whose members are all across the country requires the use of good systems engineering tools and collaborative environments. Programs provide collaboration tools like VIEWNet, which is a Navy-owned "virtual war room" that allows teams to access information affecting engineering decisions quickly, utilizing calendar, action item, program review, library, and technical artifact review management. Programs also provide collaborative environments like the Navy Integrated Collaborative Environment, which serve as data repositories and hosts for engineering tools like the Dynamic Object-Oriented Requirements System (DOORS), the de facto standard requirements management tool for Navy surface combatant programs.

Advantages of the Tech Team Approach

One advantage to the traditional approach is it allows for a staggered startup of IPTs and allows them to grow or shrink as needed. For example, in the early stages, the SEI team can be fully staffed while the system requirements are being defined. Once those requirements are defined, the lower component requirements are derived from them, at which point the product IPTs' membership would be increased. Similarly, as acquisition progresses from development to integration, the product-based teams can be decreased while the testing and certification teams are increased.

This allows the teams to be the right size at the right time, helping to minimize cost. Perhaps more important, this also enables laboratories to balance resources across programs by having the outgoing team members move to a new project during the right phase. System requirements members can move to a startup program or product team members can move to another program in early component definition. This helps to ensure that lessons learned are rolled into successive development, experts are fully engaged, and a knowledge base is maintained.

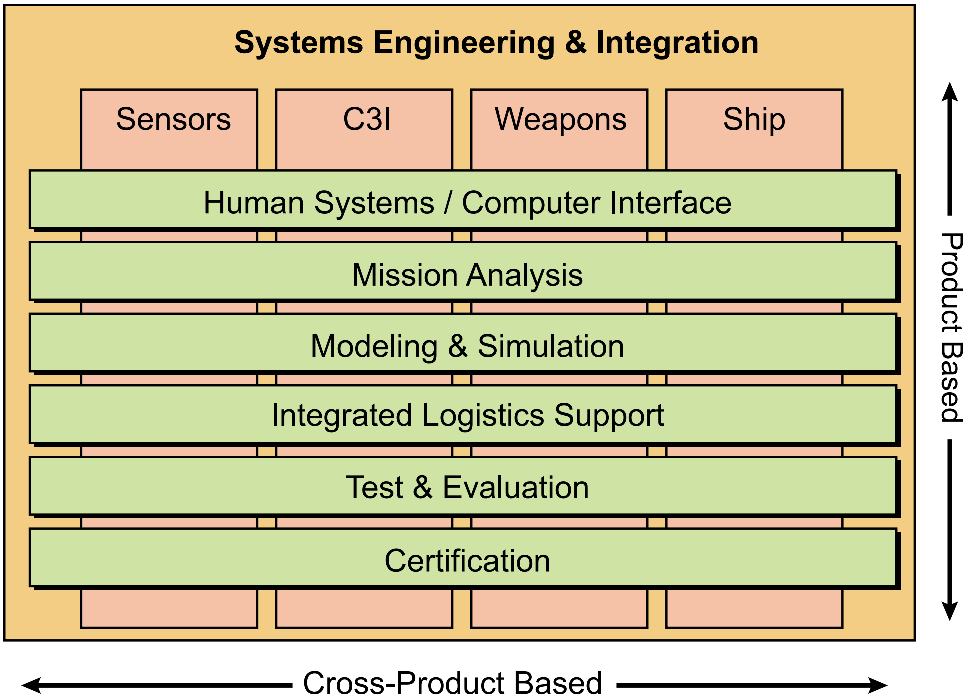


Figure 1. Example of Navy Surface Combatant Technical Team Structure

Another advantage of the current approach is found in the SEI team. The SEI team, as an overarching body of senior engineers, ensures that issues are dealt with at the system level. Product-based IPTs run the risk of becoming stove-piped, unintentionally not considering the effects on others of design decisions, risks, and issues that arise. The SEI team meets regularly with all the IPT leads to ensure all issues were shared, and also keeps a register of risks that includes the impact to all. Similarly, the SEI internal teams ensure that system architecture and requirements reflect all the elements, and that the ways in which changes within one element impact other elements are considered. Frequent communication is instrumental in getting potential risks identified and mitigated early.

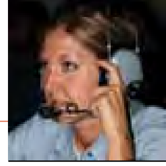
Similarly, the CPTs ensure that, for major design elements, the relevant product teams work together. Within the CPTs, the Subject-Matter Experts (SMEs) not only focus on their elements but work together to ensure that overarching design issues are resolved across the system.

As stated earlier, team membership includes not only the PSEA but many government and support contractors and system component developers. This ensures that, throughout the process, all stakeholders are represented. For example, issues related to operator training would not be found until system delivery if the training community is not involved throughout development. That would result in either operator workarounds or expensive changes that can be avoided by early issue identification.

Disadvantages of the Tech Team Approach

Of course, there are disadvantages to the traditional approach as well. Perhaps the biggest disadvantage is that the bulk of all technical work is done by Navy contractors. This leaves the Navy team members less opportunity to develop the necessary knowledge and skills to become the SMEs needed to oversee the PSEA work. This makes it difficult, if not impossible, to oversee all the PSEA work, resulting in the Navy team targeting oversight to the most risky or significant areas. SMEs are needed to track key issues in their areas and must have the breadth to ensure that issues in otherwise low-risk areas do not develop into critical problems.

While the contractors all work hard to ensure a successful product, there is little incentive or ability to seek out commonality in similar programs for potential reuse. Rather, the contractors are likely to use in-house technologies and solutions to maximize return on their investments. This has led to combat systems with different architectures, interfaces, data models,



and components, even though the systems are implementing very similar requirements. These differences result in increased cost and decreased interoperability.

Another disadvantage is that product IPTs tend to become stove-piped. Although the SEI team and CPTs try to minimize this, for most of the time the IPTs work alone. This can easily result in incompatible designs of the system components, which can cause delays or suboptimal systems.

Similarly, the IPTs can be divided if tech teams are not composed of members representing all stakeholders. The various organizations (e.g., PEO C4I, PEO IWS, and PEO Ships) all have different schedules for their products. Significant coordination is needed to ensure that all the dependencies are maintained. The SEI team has to manage the dependencies closely and ensure that all teams are bringing their products in on schedule, or managing delays such that they don't affect other teams.

Another potential hurdle is enabling collaboration across geographically separated teams. In order to work together, a national Technical Team requires additional infrastructure and tools. Failures in either cause significant problems for the teams. For example, requirements are maintained in a single location, but access is required across the country. Problems at the central servers or the connections to each site can degrade performance, and the likelihood of such issues increases proportionally with the spread of the team. Classified projects require additional security measures that add to the infrastructure cost. Bandwidth issues can hamper team productivity. Similarly, when many team members require simultaneous access (e.g., during a major milestone review), the necessary software licenses may expire.

The tools have their own drawbacks in current acquisitions. All the system and software engineering tools used are very capable, but also very expensive, and have large learning curves. The PSEAs, as contractors, are sometimes free to choose whatever tools will best suit them. Although DOORS is generally the requirements tool of choice, there is little commonality between other tools. In order for Navy Technical Teams to function effectively, the Navy has to purchase sufficient licenses for every tool and invest in training for their teams. When a team member moves to another project, the training must be repeated for a new tool that performs the same functions. In addition, many tools (e.g., modeling and simulation tools) are created by the PSEAs, leaving the Navy dependent on PSEA expertise for any future analysis.

Finally, the advantages gained from the "divide and conquer" product-based team approach can also become a disadvantage. Even though the teams are divided by product, there are dependencies between the teams that cannot be eliminated. Schedules invariably change over time as risks are realized and issues or unforeseen events cause delays. Those delays will in turn cause delays in the dependent programs. As a result, the schedule needs to be flexible enough to handle delays, something difficult to do when ship availabilities require a set date delivery.

Tenets of an Enterprise Technical Team

Although maintaining relevancy through continued education is important, competent cadres of systems engineers and major program chief engineers are not hired out of academia; they are developed through numerous experiential assignments. Domain knowledge and significant acquisition and technical experiences are critical to a successful systems engineering work force and establish the baseline technical competency required to drive higher orders of system complexity integration. These experiences form the basis to understand technical progress and risk via various organizational and acquisition models. These are professionals who have had a varied set of technical experiences, traditionally have not stayed in one product area, and use their experiences to develop an ever-increasing set of technical accomplishments.

How to Develop an Enterprise Technical Team

Mr. Neil T. Baron, in the paper, *Large-Scale Systems Integration, an Engineering Challenge of Modern Warship Design,* NSWCDD, 2007,[1] opined how NSWCDD has modeled the development of warfare systems engineers. This presents a solid model for the time and effort required to "build" the technical competency of systems engineers capable of working across the surface Navy enterprise. The NSWCDD work force is trained to always take a "systems approach" to the problem space, thus optimizing the solution through a larger set of technical options. Mr. Baron states, "A general pedigree of the systems engineering work force at Dahlgren looks something like this based on the years of experience compiled over a career:

Base Discipline (1–8 Years)

Element engineering development. Elements of the combat system include sensors, guns, missiles, launchers, decoys, displays, combat management and/or control, communication links, and aspects of physical and functional ship integration.

Technical foundation. Technical foundations of the combat systems engineer include electrical, electronic, mechanical, computer engineering, physics, computer science, and mathematics disciplines.

Apprentice (5–15 Years)

Control systems (basic), either of a combat system element or between elements within a logical family of elements, such as multiple radars, multiple communication links, and multiple defense weapons.

Combat Systems Engineer (15 Years Minimum)

Assimilation of diverse and disparate weapon system components into an integrated whole. Assimilation of the whole into a mobile platform (ship) for support functions and deployment optimization.

Warfare Systems Engineer (15–20 Years Minimum and Combat Systems Background)

Assimilation of a platform combat system with diverse and disparate mission systems, such as intelligence; air traffic control; metrology; battle group command; and Joint Battle Management Command, Control, Communications, Computers, and Intelligence."

Building a knowledgeable and deep cadre of systems engineers capable of working at these levels of complexity and integration takes numerous experiences and time. Once a deep pool of Enterprise Systems Engineers has been developed, the Surface Navy must look at how it is employing these talents through its organizational construct and approaches to Enterprise technical teams.

Organizational Construct

As previously stated, the Navy is organized for systems acquisition in a way that reflects its historical planning, funding, and acquisition execution. Requirements are defined around platform programs (the verticals) as opposed to product line capabilities (the horizontals) that can be employed across multiple platforms. The responsibilities for providing these requirements, as well as the structure within which budgets are developed and executed, are similarly aligned to the verticals. Because organizations tend to reflect the environment in which they work, both the acquisition community and the customer side of the Navy are aligned to the vertical perspective. The broader industry (beyond the defense industry) historically was also aligned in verticals but has now recognized the need to integrate horizontally across platforms with common products managed horizontally. While many sectors of industry have been able to transition to the horizontally aligned organization in recent years, the Navy is constrained by the realities of working with Congress and with the complexity of multiple organizations interacting to deliver capabilities. The most effective mitigating action to this challenge is to organize the requirements and budget infrastructure, including how appropriations are structured, to better reflect the benefits of the horizontally integrated enterprise. Critical to the success of the technical team organizational model is setting up the technical authority and technical structures to enable successful insertion of warfighting capabilities across platforms. Being able to facilitate this management and budgetary change facilitates Enterprise support from Warfare centers.

Figure 2 depicts an operational construct for technical teams, organized by function vice the traditional platform-centric organization. Being able to facilitate management and budgetary change facilitates Enterprise support from warfare centers.

The surface Navy requires Combat System Integration (CSI) leadership that is accountable in developing product line capabilities and optimizing capabilities across the surface Navy. The CSI leadership would be supported by a cadre of experienced Enterprise systems engineers that works all systems engineering disciplines horizontally across the surface Navy. This group would encompass the "Family of Combat Systems Engineers" in Figure 2. These systems engineers would be supported by "product line" engineers chartered to develop products across surface Navy platforms. Some of these products will serve Enterprise needs while others may be unique, if only required by one surface Navy platform. A small percentage of each product line group, represented by the C's within Figure 2, would be dedicated to Enterprise development and integration, and would likely come from the set of experienced engineers articulated above. Nominally, 10 percent of the warfare center work force would be dedicated to Enterprise needs (horizontals), while 90 percent would serve the individual platform development and integration (verticals) that is required to field ships. Executing

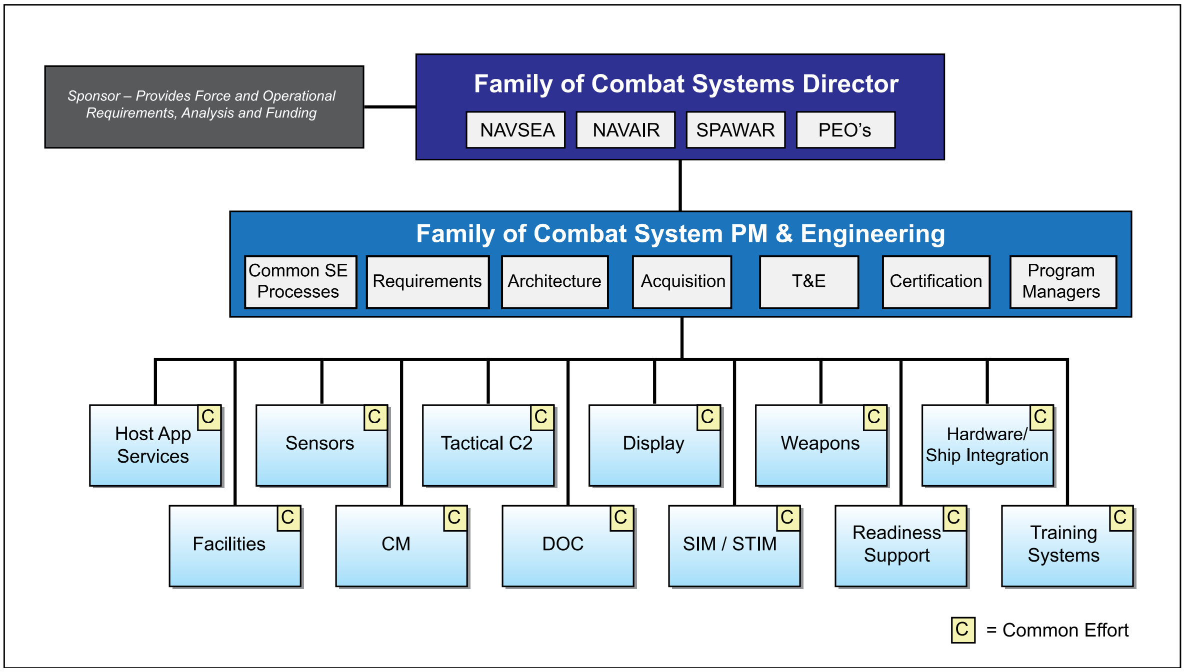


Figure 2. Combat Systems Integration Operational Construct

this construct means Platform Program Managers must accept that 10 percent of their work force will work for the higher good of the Navy and Joint Enterprise. The program managers must also accept that the entire technical team works for the Navy; thus, their best and brightest need to have freedom to work across program bounds without dictating ownership of their technical team to their program solely. Sponsors and program managers would pull from a larger resource pool to meet their individual platform needs. The Navy would be able to integrate product lines into mission capabilities and then into platforms, and technical teams would ensure technical integrity through development of common components and integration into platform Combat Systems. Figure 3 depicts this concept, and illustrates how the Navy Enterprise needs to work through the web of product lines to develop mission capability.

The Navy needs to employ levels of governance to establish systems engineering rigor in the decision-making, definition, and management of Enterprise combat systems.

Enterprise Products Required to Manage Technical Teams

In order for Enterprise technical teams to be effective, the government must own the architecture and requirements for combat systems and their components. The Navy must also put in place a governance structure and program management tools to manage combat system and component development.

Architecture and Requirements

To ensure that common combat system components are compatible across multiple platforms, the Navy must take ownership of combat system architecture, defining what the set of common components will be. In addition, to ensure interoperability of the components, the interfaces and requirements must be well defined and stable, so given a set of inputs, the expected processing occurs and the proper output is generated. Similarly, the performance of each common component must meet the needs of the combat system, or even the proper responses to input will not guarantee threats can be defeated.

On a macro scale, this is not much different from the way combat systems are managed today. For example, the Navy owns the interface between the Cooperative Engagement Capability (CEC) and the rest of the combat system, enabling independent development of both systems while ensuring that the CEC can be integrated into the combat system. The Navy also owns

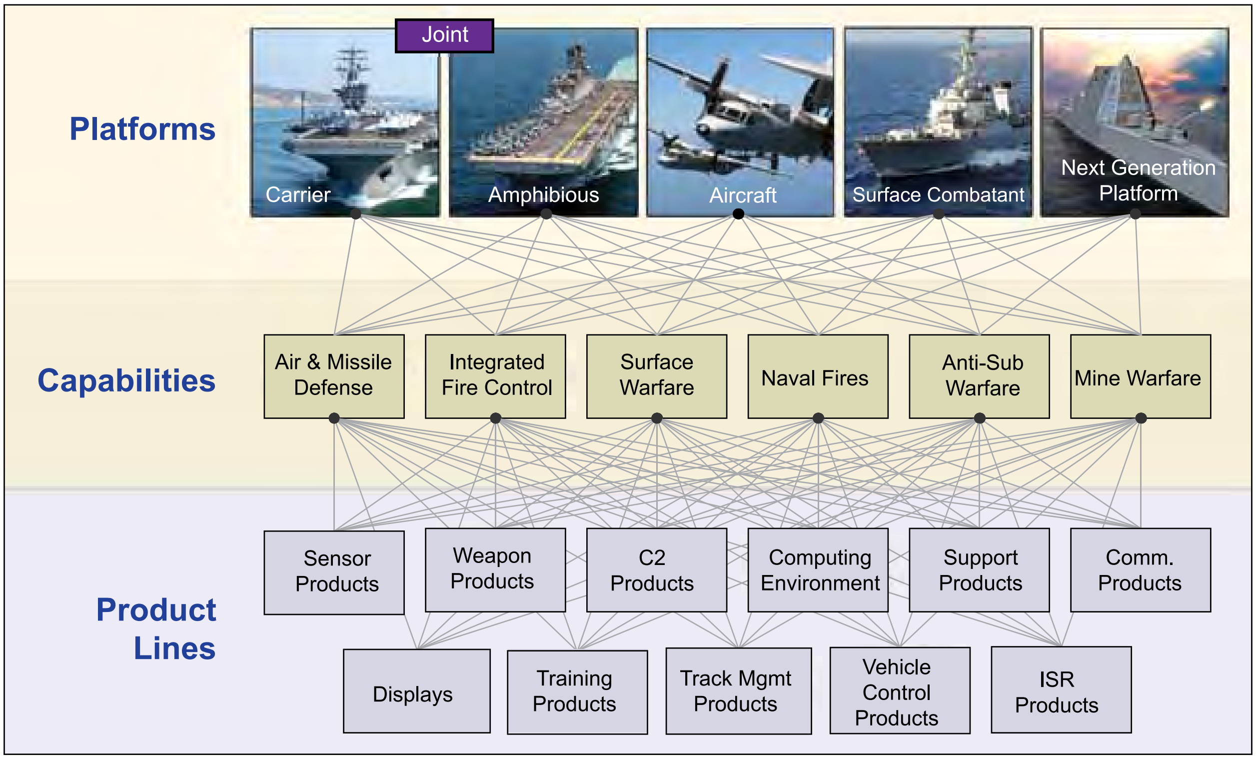


Figure 3. Platform, Capabilities, and Product Line Relationships

the requirements defining CEC functionality, again ensuring that the PSEA can design a combat system that includes CEC, knowing that the CEC will meet the combat system needs. Just as important, Navy ownership of both the architecture and requirements has enabled the CEC to be used on multiple platforms including Aegis and the Ship Self-Defense System.

In order to enable Enterprise technical teams to have the same success throughout the combat system, this model must be expanded to all combat system elements. Traditionally, combat system software has been left to the PSEAs to develop, which has resulted in software components being developed to meet very similar needs multiple times, increasing the cost to the Navy. Navy organizations, such as NSWCDD, are uniquely suited to assess common needs across platforms. Navy ownership of the architecture and requirements allows the Navy to take advantage of that ability to define common components that will still meet PSEA needs and be interoperable.

Although there is significant overlap, the interfaces, functionality, and performance requirements of seemingly common components on different platforms are not identical; it is not possible to simply take components from one platform and put them on another. To truly enable reuse of components across platforms, technical teams must be empowered to define the components such that the overall set will meet platform needs, to define the component interfaces and the standards used, and to define the component requirements. This will enable the teams to oversee component and combat system development by contractors.

Governance

The second element needed to manage combat system and component development is proper governance. As is always the case in development, this includes engineering boards to oversee the teams and make decisions affecting multiple stakeholders where agreement cannot be reached. An Enterprise Systems Engineering Management Plan (SEMP) must be developed to define the governance and define the systems engineering processes. As stated in The Importance of Systems Integration: System-of-Systems Enabler (Richardson 2008),[2]

> "The SEMP should provide (1) technical program planning, implementation, and control; (2) the systems engineering process; and (3) methodology for specialty engineering integration. The first part describes the technical program tasks that must be planned and

> implemented and includes organization, work breakdown structure, scheduling, cost estimating and reporting, technical performance measures, and risk management. It essentially provides an overview of the technical tasks and their relationships and responsibilities to allow the technical manager to evaluate project execution and take corrective action if necessary. The second part provides the systems engineering process steps and tools from requirements development through delivery of the final product. The third part describes the required specialty engineering areas and how these will be integrated into the overall "mainstream" engineering process. Without these elements of the SEMP, the risk of developing an enterprise system at any cost is astronomical. The SEMP provides an efficient way to ensure the final product meets the requirements and measures progress toward the final product."

The Navy must also develop an Integrated Master Schedule of all components and platforms. This schedule must accurately show all the dependencies of all the programs to ensure PSEAs get the components when needed. The schedule must also show the planned evolution of all the components to meet the needs of future platforms. Properly built, the schedule can be closely monitored for progress to identify risks to the programs and can be used to identify impacts of proposed changes.

Conclusions and Recommendations

Establishing an Enterprise naval technical team that works cross-program solutions is at the forefront for developing and integrating naval capabilities. The surface Navy requires CSI leadership that is accountable in developing product line capabilities and optimizing capabilities across the surface Navy. The CSI leadership would be supported by a cadre of experienced Enterprise systems engineers that works all systems engineering disciplines horizontally across the surface Navy. The basis for an Enterprise technical team needs to be actively cultivated through NAVSEA warfare centers. As with any complex change effort, challenges and risks abound. However, the risk of maintaining the status quo is significantly greater than any risk in making this transition. The steps outlined in this article present a very broad overview that must now be translated into more specific actions across the organization to take broad principles and apply them to specific programmatic actions. The way ahead is framed with challenge and opportunity both for the government and industry. Change cannot be instantaneous, and the realization of benefits of the transition will be over a period of years.

References

1. Baron, Neil T., *Large-Scale Systems Integration, an Engineering Challenge of Modern Warship Design*, NSWCDD, 2007.
2. Richardson, David S.; Murphy, Alvin; and Sheehan, Terence, *The Importance of Systems Integration: System-of-Systems Enabler*, NSWCDD, 2008.

Sensors C3I Weapons Ship

Total Ship and Enterprise Approach to Navy Platform Technical Team Model

Human Systems/Computer Interface

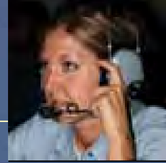
Mission Analysis

Modeling & Simulation

Integrated Logistics Support

Test & Evaluation

Certification



Where the Combat System Meets the Sailor: The Redesign of the Aegis Combat Information Center

by Jon Dachos

The Naval Surface Warfare Center, Dahlgren Division (NSWCDD), has a long history in the systems engineering design, development, testing, certification, and life cycle support of the Aegis Combat and Weapons Systems. Human systems integration (HSI), as an integral part of the systems engineering paradigm, however, is relatively new.

HSI is a multidisciplinary field of study composed of human factors engineering, system safety, health hazards, personnel survivability, manpower, personnel, training, and habitability. HSI emphasizes human considerations as the top priority in systems design and acquisition to reduce life cycle costs and optimize system performance.[1] This article demonstrates how HSI was employed when redesigning the Aegis Combat Information Center (CIC) – the vital link between the combat system and the sailor.

Aegis Combat Information Center

The Aegis Combat System (ACS) was designed as a total weapon system for the Navy to address multimission threats, including antiair, antisurface, and antisubmarine warfare. Onboard an Aegis cruiser, the CIC serves as the warfare center of the ship, facilitating the performance of ten primary and five secondary warfare areas that support required operational capabilities (ROC). The ten primary warfare areas include:

- Air Defense
- Surface Warfare
- Undersea Warfare
- Command, Control, and Communications
- Command and Control Warfare (C2W)
- Strike Warfare
- Electronic Warfare (EW)
- Information Warfare (IW)
- Mobility (MOB)
- Missions of State (MOS)

The five secondary missions include:

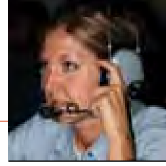
- Fleet Support Operations (FSO)
- Intelligence (INT)
- Logistics (LOG)
- Mine Warfare (MIW)
- Non-Combat Operations (NCO)

Given the vital roles that CICs play, it is necessary that they are designed with HSI in mind to facilitate the needs of warfighters in the most effective and efficient ways. Considering today's new technologies and the fact that the ships are reaching 15 to 25 years of service life, a redesigned CIC was needed to meet the threats of the 21st century. Figure 1 shows a sonar technician working the CIC of USS *Sampson* (DDG 102).

Redesign of the Aegis Combat Information Center

The Naval Sea Systems Command (NAVSEA), Program Executive Office for Integrated Warfare Systems (PEO IWS), tasked NSWCDD, in July 2008 to construct mockups of potential CIC arrangements, incorporating feedback from Fleet surveys and HSI evaluations. NSWCDD engineers, in partnership with PEO-IWS and the Ship Integration & Test and Ship Physical Systems groups at Lockheed Martin, performed HSI analysis to construct CIC mockups for Aegis CIC design consideration. The engineering team leveraged Dahlgren's Human Performance Laboratory (HPL) to bring relevant Fleet operators, system designers, and stakeholders together to build a number of CIC layout options, refine the designs, and formulate a final recommendation.

Figure 1. Sonar Technician (Surface) 1st Class Steven Duncan stands watch in the Combat Information Center during the Fleet Synthetic Training – Joint Exercise (FST-J) aboard the *Arleigh Burke*-class guided-missile destroyer USS *Sampson* (DDG 102). (090617-N-3570S-070 SAN DIEGO; June 17, 2009; U.S. Navy Photo by Mass Communications Specialist 2nd Class Jeremy M. Starr/Released)



HSI Process

The initial HSI process started by developing evaluation criteria with inputs from the Fleet and Navy training community stakeholders on what makes a good CIC design from an operator's perspective. A team of CIC working group members, consisting of PEO-IWS-1 (Integrated Combat Systems), NSWCDD, and Lockheed Martin traveled to San Diego, California, and Norfolk, Virginia, to survey, interview and collect CIC layout feedback from Navy cruiser (CG) and destroyer (DDG) crews with experience in CIC operations.

Partial and full-scale CIC mockups were then developed in the HPL to facilitate evaluations of candidate layouts and to solicit feedback from stakeholders and representative U.S. Navy Fleet CIC operators and maintainers. Mockups of consoles and other equipment were created from plywood and foam core, combined with reconfigurable platforms, large screen displays, bulkheads, and overhead fixtures, which permitted rapid reconfiguration to evaluate additional layout options. Formal Fleet feedback was solicited on potential designs and over 4800 comments were received and evaluated based on interviews with 17 Aegis CG/DDG crews, 5 destroyer squadron/class squadron (DESRON/CLASSRON) staff visits, COMNAVSURFOR staff, and all CSCS Aegis Waterfront Training Detachments.

Mockup evaluations were conducted in three phases: 1) Common Display System (CDS) console-to-console arrangements, 2) CIC layouts of all CDS in space, and 3) peripheral equipment placements. CDS console mockups were used to evaluate the degree to which basic console-to-console placement options impacted operator interaction, display visibility, and maintenance access. Mockups of the overall CIC space were subsequently developed to provide a realistic environment for evaluations with stakeholders, expert evaluators, and representative users. DDG and CG mockup versions were implemented sequentially, and separate evaluation events were held to focus on specific issues and mission areas. After overall console placement was solidified, detailed evaluations of the placement of peripheral equipment around individual consoles were initiated.

Partial mockups were used to quickly evaluate specific features of proposed layouts, including console groupings, raised platforms, and visibility of bulkhead-mounted displays. A full-scale mockup of the proposed layout was created to support stakeholder walkthroughs and to assess various levels of usability from representative users. Different CIC layouts were created by arranging mockups of the CDS and peripherals (e.g., large screen displays (LSDs), telephones, loudspeakers, and status boards). Operationally relevant scenarios also were included in some of the layout walkthroughs with the Fleet. A software tool called Spatial Analysis Link Tool (SALT) was used to analyze console proximity and visual locations of watch-stander positions. From analyses performed, potential console arrangements were down-selected as some arrangements promoted collaboration and supervision, while other arrangements inhibited collaboration, wasted space, or could not accommodate shipbuilding constraints. Key evaluation criteria used by the evaluators are shown in Table 1.

A number of candidate layout options for the CIC were developed and narrowed down to six potential layouts for evaluation. Watch-station adjacency ratings (i.e., individual watch-stander pairs were rated with respect to the

Table 1. Key Evaluation Criteria for Combat Information Center (CIC) Mockups

Console-to-Console Arrangements	Platform Height and Large-Screen Display (LSD) Viewability
Operator-operator interaction	Viewable height of LSDs
Ability to observe displays on adjacent consoles	Viewable width of LSDs for individual watchstander
Ability to observe shared visual displays (LSDs, Auto Status Boards)	Viewable width of common LSD space
Accessibility of console components	Legibility of display content
Space for physical peripherals and storage	Space for physical peripherals and storage
Console ingress/egress, accessibility, and clearance	Suitability of ID Fusion concept
Efficiency of use of floor space and overall volume	Above-console displays
	CEM exhaust and noise

need for physical proximity and visual sightline) were collected from Fleet subject matter experts to support placement decisions for individual console positions. A quantitative, more objective comparison of alternative layouts was then performed using a link analysis approach. Link analysis established a relative rating or score for each element-to-element relationship or "link." The physical and visual links were rated with respect to criticality, or importance of the link, and the frequency in which benefit was realized from the adjacency. Once scores or priorities for individual links or watch-stander pairings were defined, those scores were used individually to prioritize placements or collectively to score and compare overall layouts.

The link ratings were entered into SALT to calculate overall scores for each of the layouts under consideration at the time of the analysis. SALT was used to model and analyze the impacts to human performance associated with placement of human and machine resources within the workspace. It enabled human and machine resources to be positioned and connected using links that represent auditory, visual, and other types of relationships. These links were used as input into analysis algorithms that ultimately provided feedback as to the overall quality of a particular layout. A screen capture from SALT is shown in Figure 2.

Partial CIC Mockups

The partial mockups were used as the first set of CDS console mockups constructed to evaluate specific features of the numerous CIC layouts. The candidate layouts were reviewed to identify unique or central features that had a direct bearing on the suitability and effectiveness of the layout. Figure 3 shows a sampling of CIC layouts considered, with the features evaluated in the partial mockups highlighted. Over two dozen console arrangements or other unique features were identified for evaluation through the partial mockups.

Evaluations were organized by NSWCDD's Human Systems Integration Branch. Evaluation participants included personnel from the Center for Surface Combat Systems (CSCS), Dahlgren, Virginia, and from the Human Systems Integration, Ship Integration & Test, and Ship Physical Systems groups at Lockheed Martin. The first of the two partial mockup evaluations focused on console-to-console arrangements. A total of 20 different console arrangements or variations, employing up to six consoles at a time, were evaluated sequentially. The second evaluation focused on evaluating the impact of the distance from a second row console to a bulkhead-mounted display, and of the height of the second row above the first row. Two different console distances and two different platform heights were evaluated for a total of four configurations. In each event, the evaluators assessed each configuration in order using the list of evaluation criteria. Evaluators then held a group discussion to identify the highest priority issues. Example layouts are shown in Figures 4 and 5.

Full CIC Mockups

Overall, the development of the full mockup supported four types of evaluations: 1) stakeholder tours, 2) role-playing usability assessments, 3) scenario-based usability evaluations, and 4) expert walkthroughs. A pair of mission usability evaluations were held to focus on identification of issues with the "ID Fusion" layout concept in general and the positioning of ID-related and coordinator positions in particular. The DDG layout was used for these two events. The first event embedded expert users, primarily instructors and staff from CSCS, in an ID-centric scenario. The scenario was presented using static tactical situation (TACSIT) screenshots on representative large-screen displays and on paper printouts at each console. Information was provided via the TACSITs and through communications to each role player, permitting the watch team to conduct representative evaluation activities for air and surface contacts. The positions of Tactical Action Officer (TAO), Combat System Coordinator (CSC), Radar System Controller (RSC), Anti-Air Warfare Coordinator (AAWC), Anti-Surface Warfare Coordinator (ASUWC), Surface Warfare Supervisor (SWS), Tactical Information Coordinator (TIC), and Electronic Warfare Supervisor (EWS) were included in the event. Each role player had an evaluator specifically assigned to monitor the player's activities and identify any problematic issues. A second event was conducted using the same scenario, but with an intact watch team from USS *San Jacinto* (CG 56) as the CIC watch standers. A photo of an underway ID fusion usability assessment is shown in Figure 6.

Approximately 20 evaluators participated in a walkthrough evaluation to address areas difficult to assess through a watch-standing scenario. The major focus areas included safety, maintenance, and off-watch operational support.

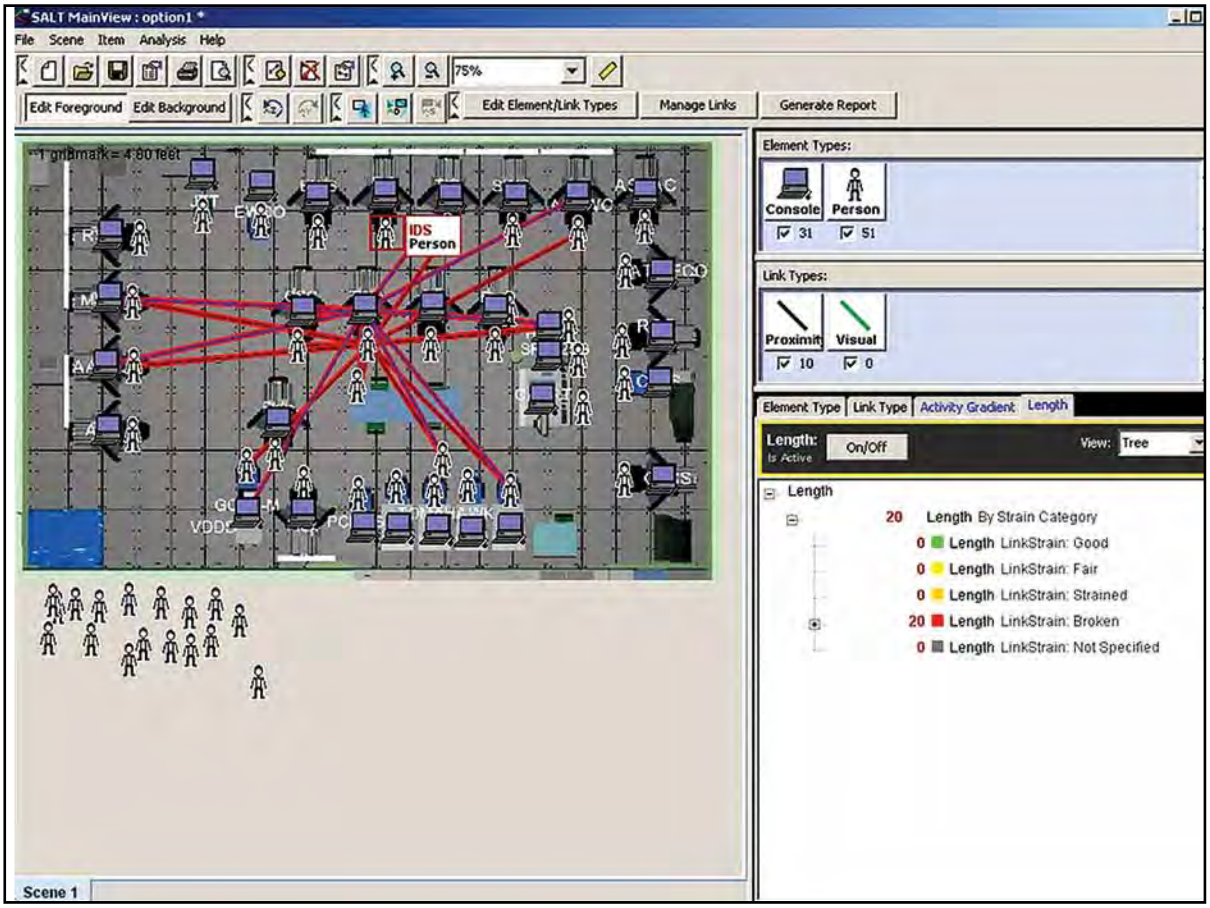


Figure 2. SALT Screen Capture

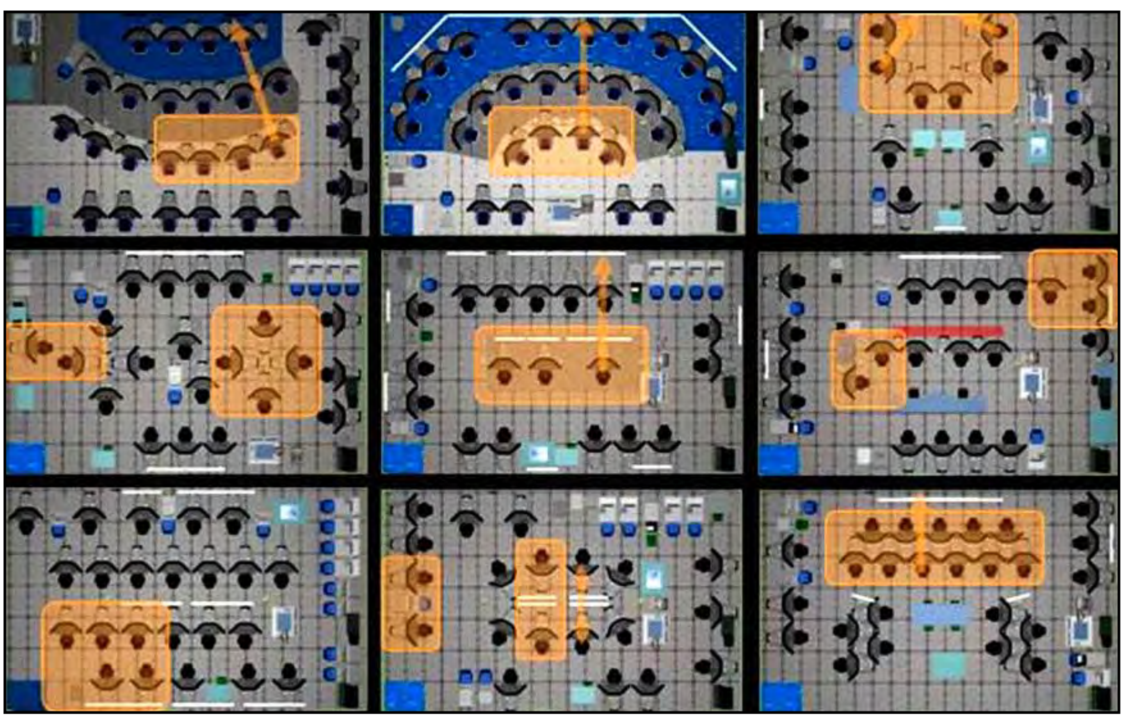
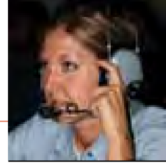


Figure 3. Sampling of CIC Candidate Layouts

Figure 4. Sample Partial Mockup Console Arrangements

Figure 5. Platform Height and Display Visibility Evaluations Using Partial Mockups



The evaluators were briefed on the work to date, assumptions for the CIC layout, and specific areas of interest for evaluation. Each evaluator examined the mockup independently and then met in focus groups to discuss their findings and determine priority issues. In addition to the role-playing usability evaluations, a series of scenario-based usability assessments were also incorporated to address a multi-day tactical scenario. For each stage of the scenario, specific evaluation questions were presented, and the strengths and weaknesses of the layout to support relevant activities were discussed.

Console Workspace and Peripheral Evaluations

Once the overall CIC layout was stabilized and planned positions of individual watch standers were confirmed, a detailed evaluation of the placement of equipment associated with each watch stander was initiated. Foam core mockups of the equipment items associated with each position were constructed, allowing current operators and subject matter experts to provide recommended positions for each item and rationale in terms of function, criticality, and frequency of use. The evaluations included a focus on discerning the placement principles for each participant in order to understand the priorities behind individual recommendations, support deconfliction of competing recommendations, and allow development of overall principles applicable across the CIC. The goal of this series of evaluations was to provide recommended locations for critical positions within the CIC and to identify general recommendations that could be extended to peripherals for many other locations. The aim was to create a consistent layout that considered grouping peripherals by function and positioning them within operator reach based on importance and frequency of use. By focusing on a consistent design, shipbuilders and on-board operators alike can avoid creating or dealing with complicated mounting systems. Existing space also can be maximized to allow for the potential growth of new peripherals on board.

The Aegis CIC modernization concept redesign analysis team examined all CIC layout options and considered all of the direct feedback from CIC operators, maintainers, coordinators, and decision-makers. Based on total system feedback, HSI evaluators were able to provide an optimized CIC layout recommendation with detailed rationale for each positioning, which was approved by Chief of Naval Operations, Surface Warfare Directorate (OPNAV N86). The final, approved, layout design is shown in Figure 7.

Conclusion

Aegis Weapon System (AWS) and Aegis Combat System (ACS) modernization efforts increase capabilities against current and future threats, extend service life, and increase interoperability. If CIC's were designed without considering HSI, the Navy could produce CICs that do not enable operators and decision-makers to effectively or efficiently perform the ten primary and five secondary warfare areas that support required operational capabilities (ROC). Fortunately, as a result of the Aegis CIC modernization concept redesign effort, the analysis team was able to recommend an optimal CIC design and identify and document key impact areas to include cost avoidance, safety, human performance, situational awareness, and enhancement of warfighting mission capabilities. The impacted time frame (2012 to 2047) covers the operational lifetimes of Aegis CGs and DDGs – approximately 80 ships with a combined 2000 years of naval service remaining for the Navy. An enhanced Aegis CIC design, therefore, not only provides warfighters with modernized capabilities but with capabilities designed with human systems factors integrated to enhance CIC warfighting effectiveness.

Reference

1. Naval Postgraduate School, http://www.nps.edu/or/hsi/, accessed 4 November 2010.

Figure 6. ID Fusion Usability Assessment

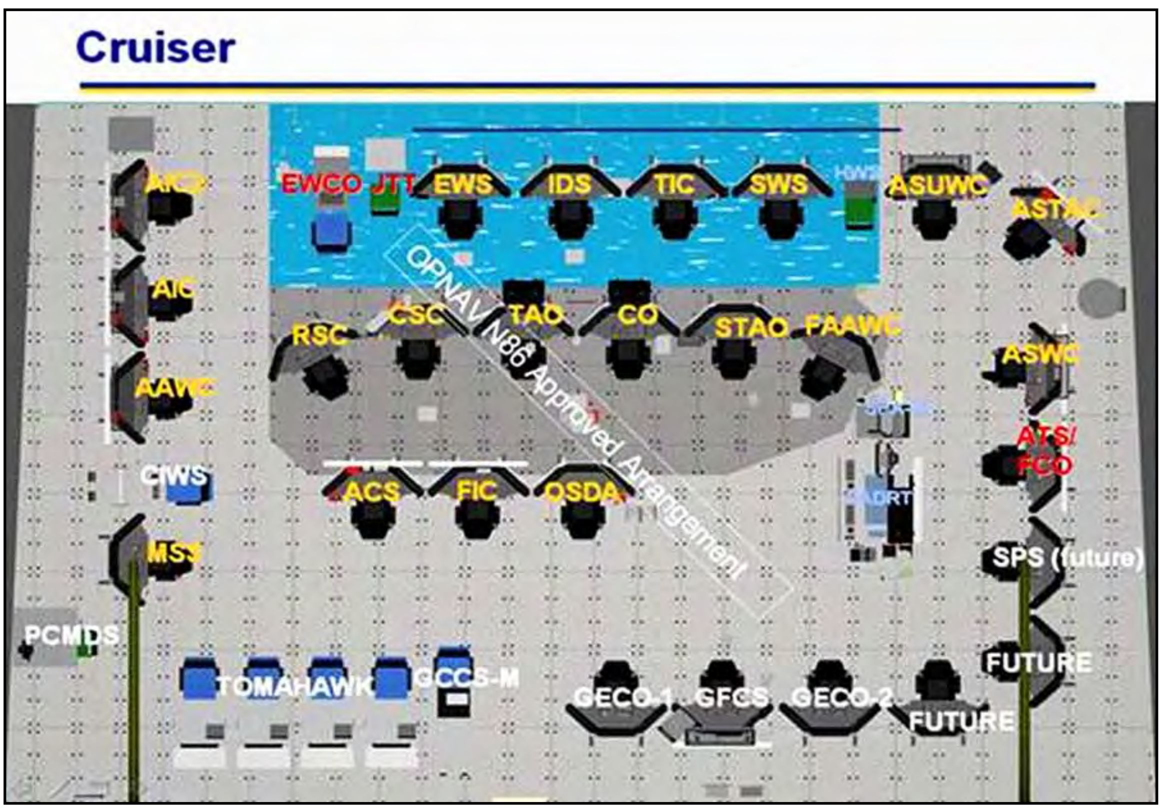
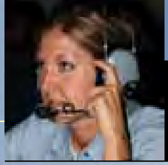


Figure 7. The Final, Approved, Aegis CIC Layout Design



Advanced Capability Build Concept in Product Line Systems Engineering

by Joel Washington and Gilbert Goddin

Introduction

The surface Navy has adopted a new acquisition model for the design, development, integration, and delivery of combat system upgrades. This new model was adopted for three primary reasons: (1) to institute a regular, repeatable delivery of capabilities to the Fleet; (2) to provide synchronization points for integration and test of combat system upgrades to achieve cost efficiencies; and (3) to increase the flexibility of introducing new capabilities later in the process to enable "rapid" introduction into the Fleet. This model is referred to as the Advanced Capability Build (ACB) process.

In addition to ACBs, product line systems engineering processes are being adapted both within a family of combat systems as well as across combat system families to develop reusable combat system capabilities outside of a major baseline development and then integrate them into ongoing ACBs. This provides the ability to develop new capabilities off the critical path of a baseline or ship deployment schedule and cut the new capability into a baseline when it is sufficiently mature. The ability to reuse the software in multiple baselines increases the number of ships that can receive the capability and reduces the overall cost of providing that capability.

ACBs define the capabilities that are to be delivered to a specific ship in an integrated combat system package that satisfies its operational requirements. The delivered package includes interface software for all baseline-specific elements, the Combat Management System, and other software and systems integral to the overall core functions of the combat system. The ACB process consists of a single cross-combat system planning phase (ACB Planning) and multiple individual combat system execution phases (ACB Execution). The planning phase is a government-led activity that commences with initial scoping of multiple ACBs and concludes with the definition of system-level requirements and architecture products for specific ACBs, including the successful conduct of the System Requirements Review (SRR) for each of the combat system baselines. The execution phase focuses on the design, development, certification, and fielding of an ACB, and is carried out by industry with government oversight. The ACB concept allows for revisiting the capability scope at major milestones to allow additional specific functionality to be added in order to meet emerging operational needs or to defer originally planned capabilities that are not able to meet the overall ACB schedule.

The surface Navy is implementing a combat system development approach that places emphasis on commonality of software components across surface Navy combat systems by moving the portfolio of surface combat system programs toward a common architecture over time. The engineering approach to support this cross-baseline/cross-program focus is referred to as product line systems engineering (PLSE). The cross-program nature of PLSE dictates that the government must perform the systems engineering associated with the requirements and architecture definition and development, since it spans multiple program office prime contractors. The product line focus introduces specific attributes to the ACB process. This article will describe the PLSE process and how it supports the ACB concept, and how the government role is changing with respect to early requirements and architecture definition.

Surface Warfare Tactical Requirements Group/Capability Phasing Plan

The OPNAV Surface Warfare Tactical Requirements Group (SWTRG) provides guidance and governance for ACB content definition. It is the decision-making body for aligning requirements, priorities, and budgets for a given ACB. The SWTRG, with inputs from program executive offices, provides coordination and collaboration across resource sponsors, program offices, and the Fleet to provide integrated surface warfare capability requirements to the acquisition community. The SWTRG's goal is to maximize resources and increase the efficiency with which the surface Navy delivers and modernizes integrated combat system capabilities.

The Program Executive Office (PEO) Integrated Warfare Systems (IWS) ACB planning process includes a Capability Phasing Plan (CPP) process that evaluates combat system candidate upgrades for inclusion into future ACBs. The CPP process results in a proposed roadmap for aligning existing programs, integrating new technologies, and implementing new capabilities to achieve the Office of the Chief of Naval Operations' (OPNAV) requested capability requirements. The CPP is an input to the SWTRG ACB definition process. Figure 1

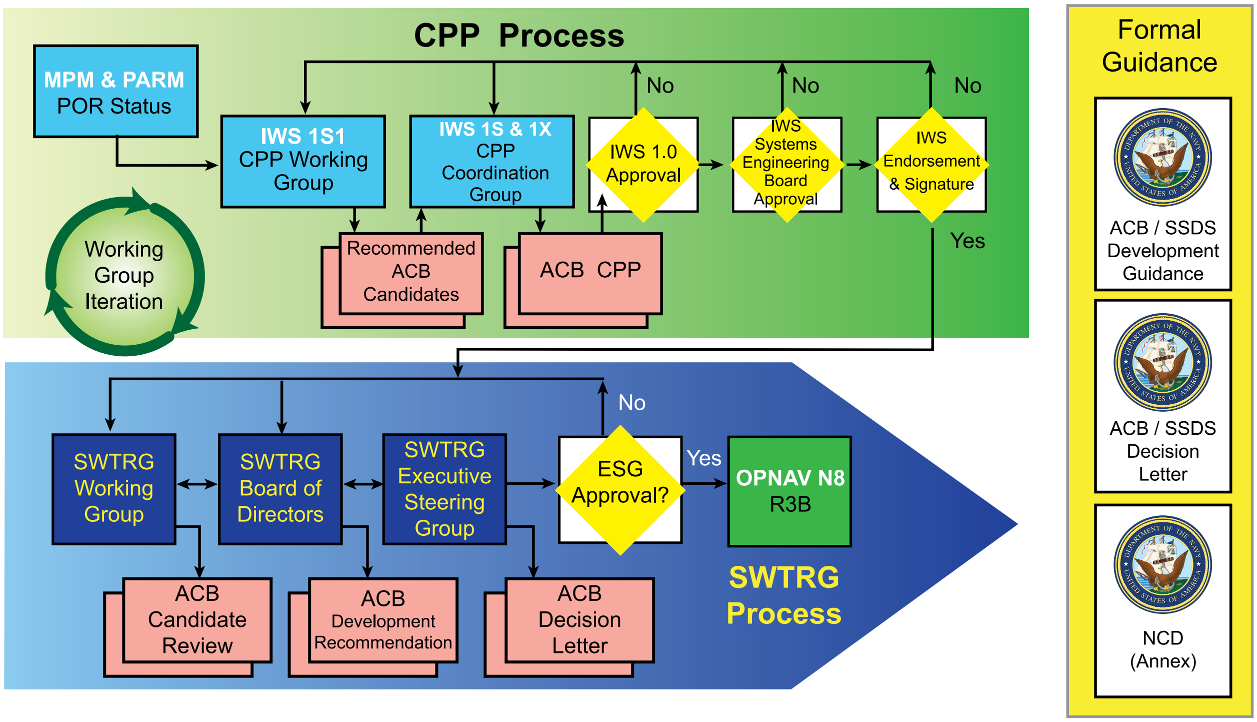


Figure 1. ACB Content Definition Process

illustrates the SWTRG/Capability Phasing Plan (CPP) process.

ACB Planning and Execution

The ACB planning process results in two primary products. The first is the CPP. The second is a set of combat system-level requirements and a combat system-level architecture that represent the scope and constraints of the capabilities to be implemented in a particular ACB. The ACB planning phase concludes with a successful SRR for each baseline. Aegis ACB 16 is currently in the planning phase.

ACB execution commences with an approved set of system-level requirements and a system-level architecture resulting from the SRR and concludes with the fielding of a complete, tested, certified capability. Nominally, the ACB execution timeline will be four years from SRR to first shipboard delivery and five years from SRR to final combat system certification. Since ACBs for multiple ship classes will be under parallel development, close coordination between product line integrated product teams (IPTs), cross-product teams, system integration program managers, major program managers, and combat system engineering agents will be required throughout the engineering lifecycle. PEO IWS-led coordination of cross-product line impacts and interdependencies will be critical.

Naval Surface Warfare Center, Dahlgren Division (NSWCDD) has had significant roles in both ACB planning and execution. NSWCDD led the effort to develop combat system-level requirements and architecture for Aegis ACB 14 capability upgrades. NSWCDD engineers also led execution of the SRR. Currently, NSWCDD is working closely with PEO IWS and OPNAV to develop the CPP and to define the specific capability upgrades for Aegis and SSDS ACB 16.

Likewise, NSWCDD has had a significant leadership role in the execution phase of Aegis ACB 12. NSWCDD generated the Systems Engineering Management Plan that guides all ACB 12 systems engineering activities. NSWCDD, working with OPNAV, led the development of the Naval Capabilities Document (NCD), which identifies the operational capabilities document for this ACB. Lastly, NSWCDD is the lead Navy technical organization working with PEO IWS to manage and oversee all ACB 12 design, development, and integration activities.

Systems Engineering Efforts

As systems become larger and more complex, the design, development, and production of such systems, or system of systems (SoS), require greater levels of integration of numerous activities and processes. Systems engineering seeks to coordinate and integrate all acquisition life-cycle activities. It integrates diverse technical management processes and develops technical information to support the program management decision-making process to achieve integrated system design.

Presently, each acquisition program defines its own systems engineering plan and executes it relatively independently from other acquisition programs. The concept of PLSE expands the focus from a single program or system to identifying common requirements, interfaces, and implementations across a wider set of surface Navy combat systems. As each surface combat system moves towards a predictable, repeatable ACB development cycle, it becomes increasingly possible to coordinate capability development schedules across ship classes and find opportunities for common product line solutions to shared operational needs. PLSE makes use of the same systems engineering techniques and strategies that have become familiar in complex software-intensive combat systems engineering projects. What makes PLSE unique is that it widens the aperture of what is considered a system to include an entire product line rather than just a single ship class. While each program follows the systems engineering "V" in order to develop its unique products, PLSE applies across all programs to identify commonality in system-level requirements and define common architectural approaches, common interfaces, and component-level requirements for common solutions to those system-level requirements. During each individual combat system ACB execution phase, close coordination between the program-specific and cross-program systems engineering efforts must be maintained to ensure that all components are being developed based on the common architecture framework and that all components will come together as a system.

Product Line Systems Engineering

In order to better enable component reuse across ship class combat systems, PEO IWS has defined a combat system product line software architecture that consists of software components, their interfaces and allocated functionality, and the underlying data models that define the data they manage and exchange. A conceptual description of this product line architecture is defined in an Architecture Description Document (ADD). The ADD defines the software architecture to the level that describes the components and component interfaces the Navy will control to achieve product line commonality. A description of major functional responsibilities of each domain is provided in Figure 2.

To support product line engineering efforts, an overarching Combat System Architecture IPT is led by the PEO IWS Combat System Architect. The Combat Systems Architecture IPT maintains the product line architecture, as defined in the ADD, develops and maintains the prescriptive architecture models and common data models that support common component development, and sponsors and oversees IPTs and working groups focused on defining requirements and interfaces for common components within the product line architecture.

The Combat Systems Architecture IPT approves changes to the objective architecture and participates in configuration management boards for products being developed in accordance with the product line architecture. The ADD guides the efforts of Navy-led IPTs that, over time, further define the data models and component descriptions to a level that can be used for contractual requirements and work products. The common data model and component requirement specifications form the prescriptive definition of the components and their interfaces.

The PLSE concept expands the focus from a single program or system to identifying common requirements, interfaces, and implementations across a wider set of surface Navy combat systems. As each surface combat system moves toward a predictable, repeatable ACB development cycle, it becomes increasingly possible to coordinate capability development schedules across ship classes and find opportunities for common product line solutions to shared operational needs. PLSE makes use of the same systems engineering techniques and strategies that have become familiar in complex software-intensive combat systems engineering projects.

Summary

The ACB process is a fundamental change in the way that the Navy designs, develops, integrates, and fields combat system upgrades. The ACB approach allows more flexibility in defining combat system upgrades and provides an avenue to field emerging capabilities more quickly than before. It is the foundation of a cross-program, system-of-systems approach to systems engineering for driving commonality into combat system designs across ship classes. The ACB concept assists in migrating combat systems toward the end goal of the product line software architecture. Detailed advanced planning is required for this to occur, including common combat system requirements and common architectural designs.

NSWCDD is leading the development of ACB and PLSE systems engineering processes and the generation of key products such as the Combat System Requirements Document and System Subsystem Description Document, Software Requirements Specifications (SRSs), common data model UML data definitions, autogenerated software code, Interface Definition Language (IDL), and Interface Design Description (IDD) documentation. The updated ACB process will include government-led milestone events. NSWCDD has a significant role in the preparation and conduct of these government-led milestones, pioneered through the Aegis ACB 12 program.

EXTERNAL COMMUNICATIONS DOMAIN
- Provide Secure and Non-secure Voice / Data Communications
- Perform Link Management and Data Forwarding
- Control / Monitor Comms Devices and Route Data Among Them
- Report Comms Status and Effective Throughput

SENSOR MGMT DOMAIN
- Manage and Control Sensors
- Search / Detect Objects in Background Environment
- Transition to Track Targets
- Report Target Measurement, Track, and Attribute Data
- Assess and Correct Measurement Errors / Biases
- Report Sensor Status and Capabilities

NAVIGATION DOMAIN
- Provide Fused Navigation Data
- Coordinate Ship Movement Requests with the Bridge Control Systems
- Monitor Navigation and Time Data
- Provide Digital Nautical Charts and Geospatial Data

DISPLAY / USER INTERFACE DOMAIN
- Display Data (e.g., Tracks, Tactical Situation, Operational Readiness)
- Provide Set of Common Display Services and Frameworks for Applications
- Support Variety of Display Services
- Display Alerts and Status
- Process Operator Actions
- Provide Common / Consistent GUIs Across Platforms
- Provide Visualization Tools

TRACK MGMT DOMAIN
- Create Composite / Tactical Track File
- Contribute to Operational Picture
- Determine Track ID
- Resolve ID Conflicts
- Integrate Multiple Track Data Sources
- Perform Geodic Registration
- Distribute Track Data According to Need

COMBAT CONTROL DOMAIN
- Control Tactical Doctrine
- Evaluate Threats
- Evaluate Tactical Options
- Determine COA
- Plan Missions
- Assess Mission Effectiveness
- Synchronize Cross-domain Execution
- Provide Decision Aids for Operators

INFRASTRUCTURE DOMAIN
- Provide Computing, Security, and Network Services for Applications
- Monitor and Control Computing Environment Resources and Report Status

VEHICLE CONTROL DOMAIN
- Launch, Recover, and Control Manned Air Vehicles (Fixed Wing and Helo)
- Deconflict Maneuver Space / Maintain Safety
- Control Manned Small Boats
- Control Unmanned Vehicles (Air, Surface, and Undersea)
- Manage Links to Controlled Vehicles

WEAPON MGMT DOMAIN
- Process Engagement Orders
- Compute Threat Engageability
- Confirm Weapon Availability
- Select Weapons and Schedule Engagements
- Initialize / Control Weapons
- Monitor Engagement Status
- Monitor / Control Missiles in Flight
- Assess Engagement Effectiveness / Kill
- Report Weapon and Engagement Status

SUPPORT DOMAIN
- Evaluate Overall Ship Readiness
- Provide Data to Fleet Logistics Systems and Distance Support

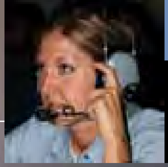
TRAINING DOMAIN
- Provide Simulated Training Environment
- Script and Execute Training Scenarios
- Simulate System Inputs IAW Scenario
- Control Training Configuration and Events
- Capture Training Assessment Data
- Playback Training Results and Debrief Crew
- Provide Simulated Ship Position / Movement
- Maintain Training Record

Figure 2. Product Line Architecture Partitioning

ACB

Advanced Capability Build Concept

Product Line Systems Engineering



ZUMWALT (DDG 1000) Combat System Integration Aboard the Self Defense Test Ship (SDTS)

by Eric Sarabia and Alfredo Gabertan

The first large-scale integration of the *Zumwalt*-class destroyer (DDG 1000) combat system into a sea-based test environment will culminate in multiple firings of live ordnance against threat-representative targets. The live-firings of Evolved Sea Sparrow Missiles (ESSM) will require the integration of the *Zumwalt*-class destroyer's combat system with the U.S. Navy's unique test asset, the unmanned, remote-controlled Self Defense Test Ship (SDTS). The SDTS is shown in Figure 1. The integration effort will enable the SDTS to demonstrate the effectiveness of the U.S. Navy's next generation, multimission destroyer combat system.

The Program Executive Office for Integrated Warfare Systems, Program Executive Office Ships, and the Naval Sea Systems Command (NAVSEA) are teaming with industry to demonstrate the capability of the *Zumwalt*-class combat system to defeat stressing Anti-Ship Cruise Missile (ASCM) threats in an at-sea environment through Integrated Testing (formerly referred to as a combined Developmental Test (DT)/ Operational Test (OT) Air Warfare (AW) Ship Self-Defense (SSD) event) conducted on the SDTS. The Integrated Test is a requirement of both the Capstone Enterprise AW SSD Test and Evaluation Master Plan (TEMP) 1714, and DDG 1000 TEMP 1560 analysis of data collected from ESSM live firings against an ASCM threat will provide validation data for the Probability of Raid Annihilation (Pra) Test Bed federation of models. Validation of these models is a necessary step in determining if the *Zumwalt*-class destroyer combat systems performance meets the TEMP Key Performance Parameter (KPP) for ASCM engagement.

Figure 1. SDTS, the Decommissioned *Spruance*-Class Destroyer Ex-USS *Paul F. Foster* (EDD 964) Under Way In Support of the AN/SPY-3 Engineering Development Model (EDM) At-Sea Testing, 2006

SDTS Platform

The SDTS has evolved from four generations of various decommissioned Navy ships. The at-sea configuration supports remote control operations. The current platform is based on the decommissioned *Spruance*-class destroyer Ex-USS *Paul F. Foster* (EDD 964).

During typical operations, test targets simulating ASCMs are launched against the SDTS and the combat or weapon system being tested responds in defense of the ship. The predetermined attack is actually aimed at a decoy barge pulled behind the SDTS to protect the ship and its assets while still providing a threat-representative flight profile and engagement timeline. Manned live-fire test operations typically require a minimum Closest Point of Approach (CPA), which is dictated by range safety, at a much greater CPA than that able to be used during an unmanned SDTS test event. This larger manned test CPA offset results in unrealistic crossing target profiles and reduced engagement windows for ship self-defense tests. Figure 2 provides a visual comparison of flight profiles offered by the CPA of the SDTS versus that of a manned test engagement.

SDTS Integration

The effort to integrate a part of the *Zumwalt*-class destroyer's combat system onto the SDTS started in 2007 with a definition of the subset of equipment required to test DDG 1000 air defense capabilities in a realistic threat environment by detecting the threat, processing targeting data, and executing an engagement. The AN/SPY-3 radar installed on SDTS will detect the target and provide target illumination and ESSM midcourse guidance to support engagement. Target data will be processed by the Cooperative Engagement Processor (CEP). The SDTS CEP will be a *Zumwalt*-class production asset connected to the Total Ship Computing Environment (TSCE) through a Distributed Adaptation Processor (DAP). Using tactical software, the TSCE will control the engagement. The targets will be engaged with ESSMs launched from a Mk 41 Vertical Launch System (VLS) outfitted with DDG 1000 unique Mk 57 electronics. Unique integration challenges facing the team included incorporating the *Zumwalt*-class combat system along with both legacy and current combat systems onboard the SDTS that support other Department of Defense programs.

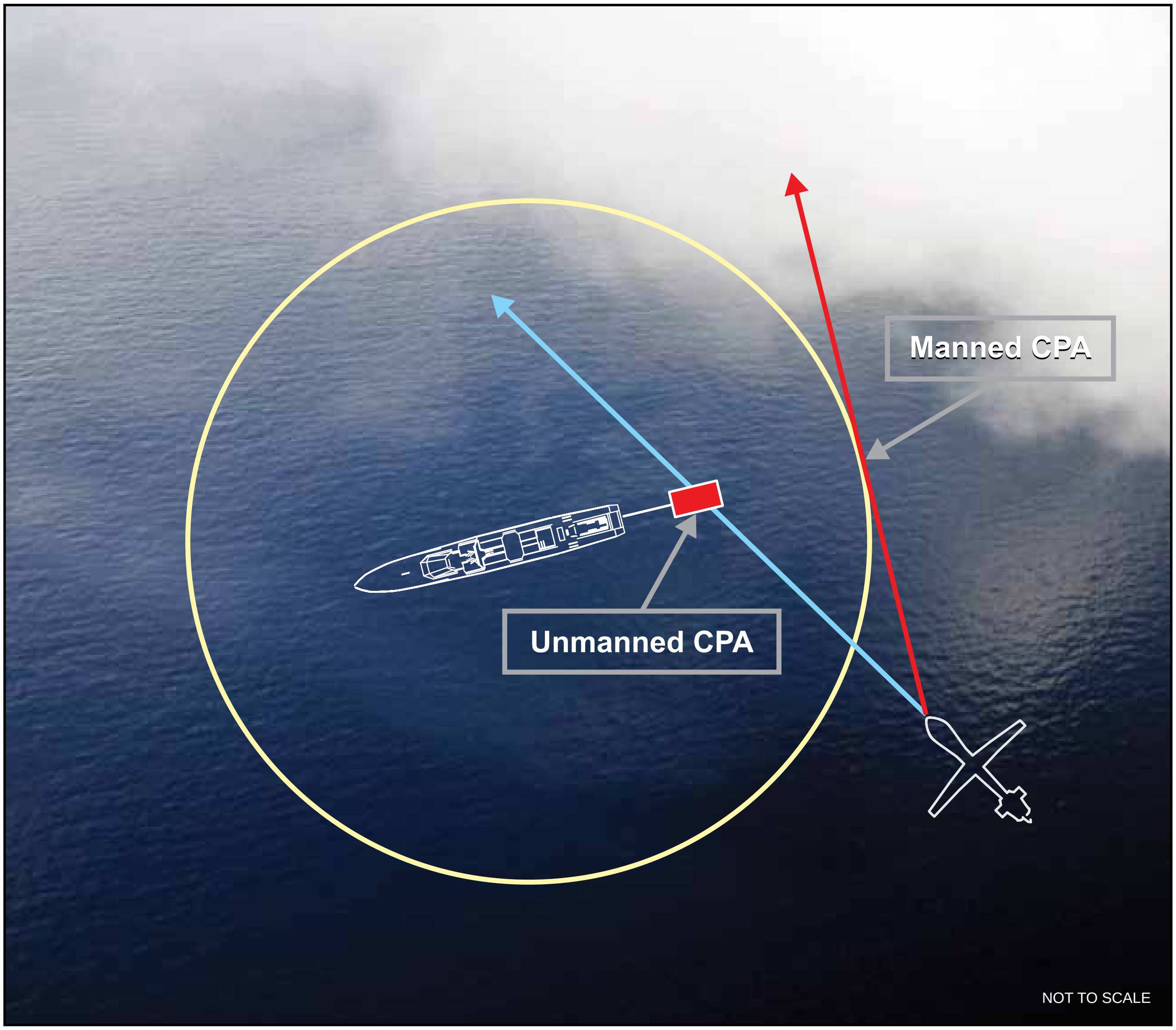


Figure 2. Visual Comparison of Unmanned SDTS CPA vs. Manned Test CPA

An installation study recommended that the SDTS could be modified by installing an enlarged hangar extension that would support the majority of the *Zumwalt*-class equipment housed in Electronic Module Enclosures (EMEs) as depicted in Figure 3.

AN/SPY-3

A complete SPY-3 radar set is composed of three array faces providing 360-degree coverage aboard DDG 1000. These arrays are supported by two X-Band Receiver Exciters (REXs), four IBM P6 computers, the Common Array Cooling System (CACS), and the Common Array Power System (CAPS). The IBM P6 computers are housed in the EMEs along with Distributed Adaptation Processors (DAPS). To support testing on the SDTS, only a single array face, a single REX, CAPS CACS, and two of the four IBM P6 Computers for the SPY-3 radar were required to be installed and integrated to meet the TEMP 1714 and TEMP 1560 test requirements.

The ship power from the SDTS is 440 volts alternating current (VAC), 3-phase, vice the *Zumwalt*-class destroyer's 4160 VAC, 12-phase. Integration of the SPY-3 CAPS required the analysis of several power conversion design alternatives. The most cost effective alternative was to bypass and eliminate the CAPS's Power Distribution Unit while supplying 440 VAC, 12-phase, directly to the CAPS's Aperture Power Raft via a COTS transformer. This transformer converts the ship's 3-phase to the required 440 VAC 12-phase.

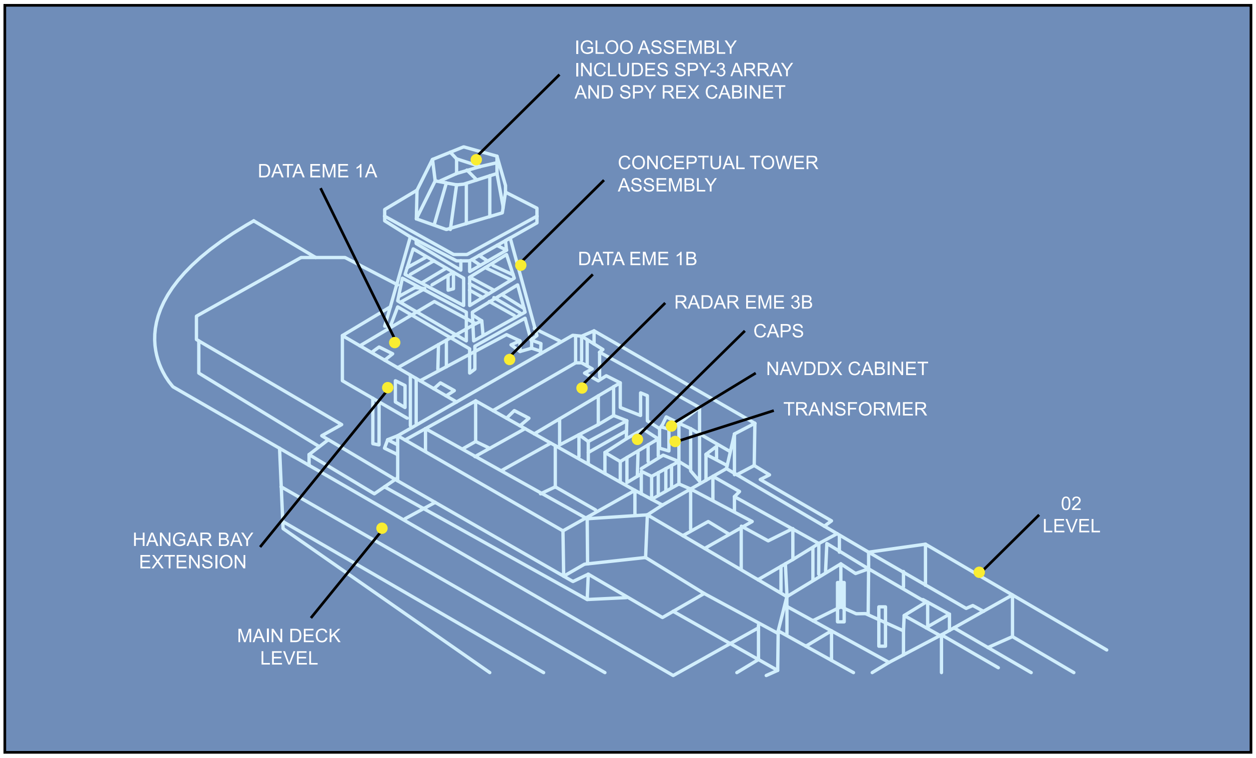


Figure 3. SDTS *Zumwalt*-Class Equipment Placement

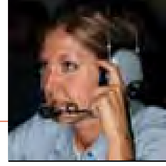
Navigation Data Distribution Extension (NAVDDX)

The *Zumwalt*-class TSCE relies on the navigation data provided by NAVDDX and an interconnected navigation suite of sensors, (e.g., Inertial Navigation System (INS) and Global Positioning System (GPS)). However, the SDTS utilizes the Navigation Sensor System Interface (NAVSSI) AN/SSN-6(V) for satisfying combat system navigation data requirements. NAVSSI provides processing and distribution of highly accurate positioning, navigation, and timing (PNT) data to combat system users. PNT data is based on external system interfacing with shipboard sensors, INS units, and GPS antennas/receivers.

It was determined to be both impractical and expensive to port the entire *Zumwalt*-class navigation suite onto the SDTS platform. Overall, NAVDDX employs the same type of functionality as NAVSSI, but both systems have very different equipment interface architectures and different message output formats to combat system users. The engineering challenge was to design a hardware/software solution for NAVDDX that leveraged NAVSSI and the existing sensor suite, INS units, and GPS antennas, while retaining the tactical functionality of both the *Zumwalt*-class and the existing SDTS combat systems. Raytheon and government engineers collaborated and engineered a viable solution that allowed NAVSSI to relay the existing navigation suite data to NAVDDX by utilizing a compatible network interface (i.e., reflective memory) between the two systems. The AN/WSN-7 remains connected to NAVSSI as it normally is on the SDTS without modification. This solution for integrating NAVDDX on the SDTS was approved through a Critical Design Review. The solution helped to eliminate functional duplication and reduce overall program costs.

Vertical Launching System (VLS)

A commissioned *Zumwalt*-class destroyer will include the new Mk 57 Vertical Launching System (VLS) in its design. The SDTS has the current generation Mk 41 VLS installed. Both, the Mk 57 and the Mk 41 are capable of launching ESSMs. The government/industry team determined that it would be more cost effective for the SDTS to employ a hybrid Mk 41/Mk 57 utilizing the Mk 41 mechanical structure for gas management and the *Zumwalt*-class unique Mk 57 electronics to control the launcher



and provide a Mk 57 representative end-to-end launch. The selected Mk 57 components consisted of Mk 57 VLS Module Controller Units, Mk 57 Hatch Controller Units, Mk 57 Canister Electronic Units, and modified Mk 57 Hatch Actuator Units (HAU), referred to as Hybrid Hatch Actuator Units. Using these Mk 57 components during the test events enables the launcher to communicate with the Weapon Control Element (WCE) software within TSCE. The hybrid system provides the functionality to select the launch ESSM against ASCM threats.

Another integration challenge involved determining the optimal placement of the VLS with respect to the single SPY-3 radar array on the SDTS. Because of the limitations of having only a single MFR array face, the Mk 41 VLS was relocated to the aft end of the ship to place it in close proximity to the radar field of view to support ESSM engagements requirements.

Test Ship Remote Control Network (TSRCN)

The SDTS version of the *Zumwalt*-class combat system will be integrated with the existing TSRCN. The TSRCN will enable remote control of the *Zumwalt*-class combat system on the SDTS through an encrypted radio link which will connect the Local Area Network (LAN) on the SDTS with the LAN at the Remote Control Center (RCC), located in the Surface Warfare Engineering Facility (SWEF) at Naval Surface Warfare Center, Port Hueneme Division (NSWC PHD).

The test team will control the combat system through Common Display System (CDS) stations. Two CDS stations will be onboard the SDTS to support in-port verification tests and tracking exercises. The CDS interface will be accessed remotely by consoles on shore at SWEF. This will be done by transferring the CDS Graphical User Interface (GUI) on the SDTS to a commercial off-the-shelf (COTS)-based client station at the SWEF. The CDS's dual display, touch pads, trackball, and keyboard will be emulated on the client station, giving the test team control of the combat system, VLS, CEC, and SPY-3.

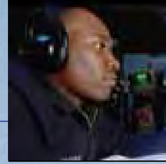
In order to safely integrate the *Zumwalt*-class combat system into the TSRCN, the test team will define system behavior in the unlikely event of a loss of remote control. Remote control safety features will be provided, such as a loss of RF link fail safe, to disable the radar and weapon systems in case of communications failure and Arm Lock to keep the combat system armed and able to fire for a set period of time in the event of a loss of link once the target is committed. The fail-safe will be built into the system by integrating an Arm Lock function into the Remote Control Interface Unit (RCIU). Under normal conditions, the RCIU supports remote control of the system. Arm Lock will represent a user entered state that will keep the system armed for a set period of time. Once the time expires, the systems will automatically go to safe mode. At this point, the user will be able to cancel or extend Arm Lock. Provisions for onboard security and data collection/recording also will be addressed.

SDTS Testing Way Ahead

The *Zumwalt* hardware installation plans and methods aboard the SDTS are considered as permanent installations. However, the flexibility to integrate with future combat systems such as the CVN 78 *Gerald R. Ford*-class aircraft carrier combat system for planned Enterprise testing was retained.

The effort to integrate the advanced mission capabilities that give the *Zumwalt*-class destroyer unprecedented versatility in a variety of operational environments on the SDTS will culminate with numerous ESSM firings against an array of threat-representative targets and flight profiles. Successful integration of the next generation of surface ship combat systems and the ability to test in as realistic an environment as possible will result in lower risk, characterization of system performance, and the mitigation of significant issues before being introduced to the Fleet. Through collaboration, a NAVSEA and industry team is meeting the challenge to ensure that sailors onboard the DDG 1000 *Zumwalt*-class destroyer will be armed with safe, effective combat systems.

Spruance-Class Destroyer,
Ex-USS *Paul F. Foster* (EDD 964)



Architecture Development for Shipboard Combat Systems

by Diana Kolodgie, Alvin Murphy, and Terence Sheehan

The Naval Surface Warfare Center, Dahlgren Division (NSWCDD), leads the Navy's development and use of architectures for engineering surface shipboard combat systems. Architectures are used to define the integrated roles, responsibilities, and functions of systems for large-scale, complex battle forces. The Institute of Electrical and Electronics Engineers (IEEE) Standard 1471-2000 defines architecture as: "The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution."

The Navy employs the Department of Defense (DoD) Architecture Framework (DoDAF) for developing and representing architecture descriptions that ensure a common denominator for understanding, comparing, and integrating architectures across organizational, joint, and multinational boundaries. DoDAF establishes data element definitions, rules, relationships, and a baseline set of products for consistent development of integrated or federated systems architectures. These architecture descriptions may include families of systems (FoSs), systems of systems (SoSs), and net-centric capabilities for interoperating and interacting in the net-centric environment (NCE).[1] DoDAF supports the development of interoperating and interacting architectures by defining three related views of architecture:

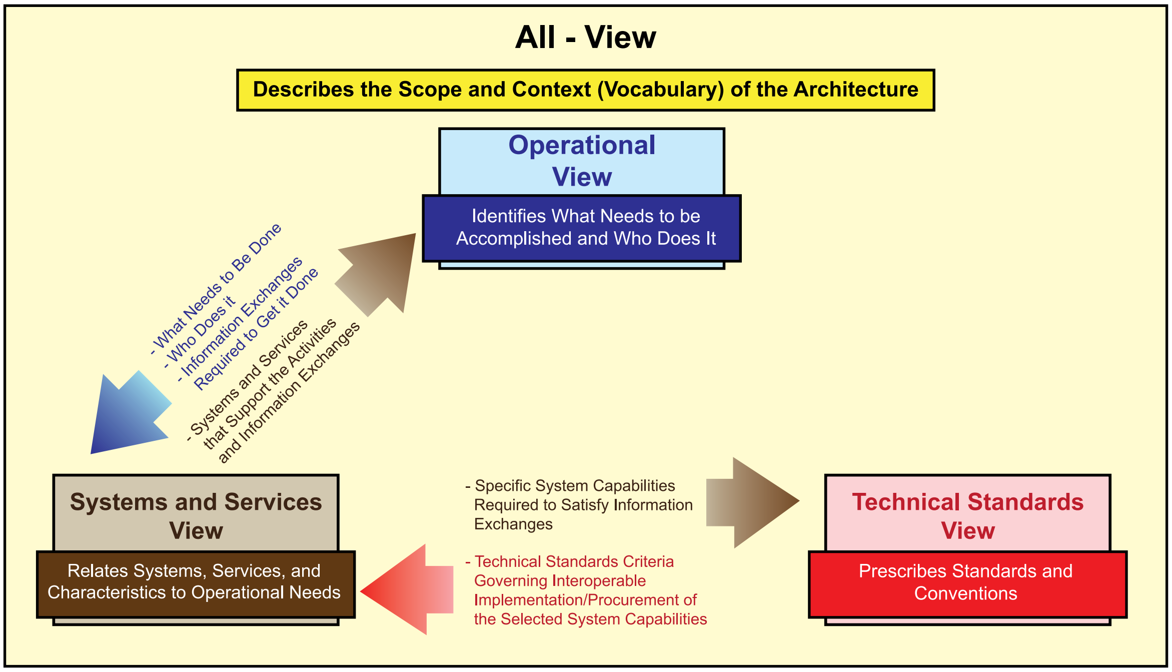


Figure 1. Information Linkages Among Architectural Views

Operational View (OV), Systems and Services View (SV), and Technical Standards View (TV). Each view is composed of sets of architecture data elements that are depicted via graphic, tabular, or textual products. Information linkages among architectural views are shown in Figure 1.[2]

NSWCDD Architecture Experience

NSWCDD systems engineers use DoDAF architectural standards for communication between the operational and acquisition community, as well as for supporting system development. Architecture development is an iterative process and continuous evaluation of the views must occur throughout development. Upon completion of DoDAF views, an evaluation, to include traceability to requirements and stakeholder review, must be performed to ensure consistency among all views.

DoDAF defines a six-step process to ensure the developed architecture is fit-to-purpose:[3]

1. Determine intended use of architecture
2. Determine scope of architecture
3. Determine data required to support architecture development
4. Collect, organize, correlate, and store architectural data
5. Conduct analyses in support of architecture objectives
6. Present results in accordance with decision-maker needs

The architectures for surface platforms and their subsystems are first documented within a system Capability Development Document (CDD). A CDD captures the information necessary to develop a proposed program, normally using an evolutionary acquisition strategy. The CDD outlines an affordable increment of militarily useful, logistically supportable, and technically mature capability.[4]

To function most effectively, the realized systems architecture must maintain a connection to the CDD architecture, requiring that the system architects and CDD architects have clear and consistent process associations and relationships. In recent years, the surface platform community has built relationships with CDD architects who have facilitated the maturing of architecture products through the systems engineering process, rather than replacing those products with unique systems engineering products.

While the CDD provides high-level system architecture within the context of other DoD acquisitions, a System/Subsystem Design Description (SSDD) provides system-level architecture details. The SSDD describes the system- or subsystem-wide design and the architectural design of a system or subsystem.[5] As depicted in Figure 2, which was adapted

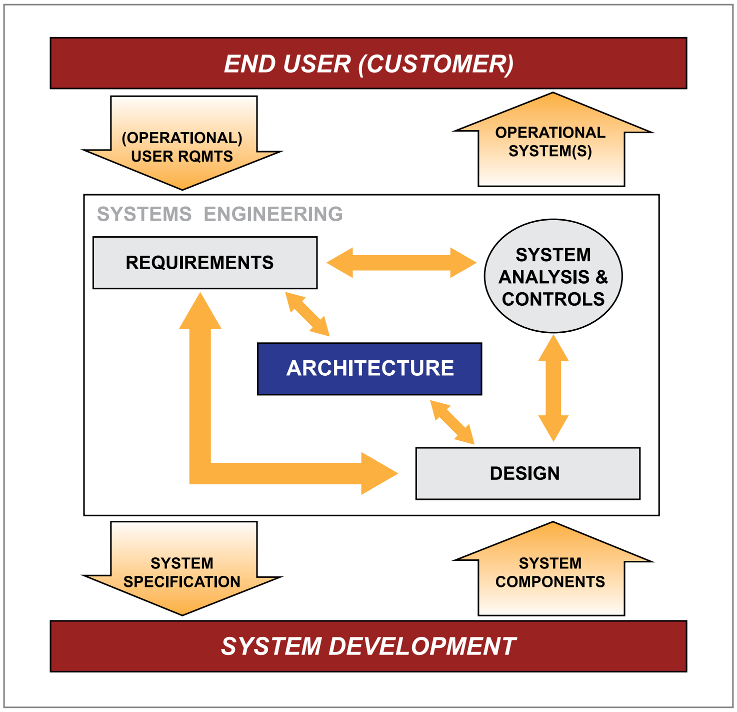


Figure 2. Systems Engineering Process

from Defense Acquisition University (DAU) Systems Engineering Handbook 2001, the SSDD documents the results of a systems engineering analysis of operational requirements and the force-level architectures from the CDD.[6] The SSDD provides the allocation of top-level requirements, functions, and interfaces to system elements, components, and software. A surface platform may have multiple SSDD documents for each major system element. Historically, prime contractors have developed SSDD documentation; however, the surface community is moving toward government-developed, top-level architectures to facilitate product line alignment of enterprise systems. This approach supports delivery of common product line components across combat systems with common functions.

NSWCDD Example Use of DODAF for a Notional System

NSWCDD engineers are at the forefront of systems engineering and architecture development. Their experience spans decades. Based on lessons learned from previous surface platform architecture development efforts, systems engineers have learned that it is best to simplify the design for both usability and readability to effectively evaluate and analyze the effectiveness and completeness of the architecture. What follows is an example use of DoDAF for a notional system, USS *Dahlgren*, to illustrate the content of various architecture views and products. The example begins with mission threads.

Mission Threads

Mission threads provide specific scenarios, environmental conditions, and event sequences for a set of missions. It provides the context for operational activities and operational event-trace description diagrams. An example of a surface warfare thread for the notional USS *Dahlgren* example is provided below:

> USS *Dahlgren* receives notification from Combined Task Force (CTF) 151 Counter-Piracy Operations that pirate activity within the USS *Dahlgren* Area of Responsibility (AOR) has recently escalated, and attacks on commercial shipping are imminent. USS *Dahlgren* processes recent AOR piracy intelligence and undertakes planning to search for and neutralize the pirate threats. Planning is coordinated with USS *Dahlgren* Air and Ship Control Operations to establish voyage and search plans for the mission. Plans are reported to CTF 151 and

USS *Dahlgren* coordinates with the Joint Force Maritime Component Commander for authorization to proceed. Prior to mission commencement, USS *Dahlgren* coordinates with Naval Support Operations for required resource and supplies. Once pirates have been localized, USS *Dahlgren* assesses potential threats for hostile intent. If deemed hostile, USS *Dahlgren* determines which weapons to employ—nonlethal, guns, missiles, and/or unmanned air system—based on threat characteristics. Once engaged, USS *Dahlgren* will assess effectiveness and reengage as necessary to neutralize the pirate threat.

Overview and Summary Information (AV-1)

Overview and summary information (AV-1) provides a planning guide to define the who, what, when, why, and how for the project. An example is shown in Table 1. Additionally, AV-1 provides the context in which the architecture exists, i.e., assumptions and constraints, publication and development status, schedule, and milestones.

Integrated Dictionary (AV-2)

The integrated dictionary (AV-2) creates a common vocabulary for integrated architecture development. The goal is to ensure data elements are uniquely defined and commonly linked across all operational and system views. This approach provides a common denominator for understanding and comparing views across mission areas to aid stakeholders in the decision-making process.

Operational View (OV) Products

The next step in architecture development is to define the operational architecture using operational views (OVs). The OVs are directly related to the operational requirements and concept of operations provided by the OPNAV. OVs, as described in Table 2, depict the nodes, tasks, and activities performed by USS *Dahlgren* and the internal and external resource flows to accomplish the mission. Additional operational views, not depicted, are included in DoDAF to assist in the architectural description.

As illustrated in Figure 3, the OV development begins with a High-Level Operational Concept Graphic OV-1, which provides a graphical representation of USS *Dahlgren*'s missions, environment, and interactions with external nodes.

System View (SV) Products

Development of system views typically occurs as part of the systems engineer's functional analysis and allocation activity. SysML, which

Table 1. Initial AV-1 (Notional System)

Architecture Description Identification: Name: USS *Dahlgren* Organization developing the architecture: NSWCDD Approval authority: Office of the Chief of Naval Operations (OPNAV)
Scope: Architecture View(s) and Product Identification: • AV-1, AV-2 • OV-1, OV-2, OV-4, OV-5, OV6c • SV-2, SV-4, SV-5, SV-6, TV-1
Purpose and Perspective: Provide a sample architecture based on lessons learned
Context: USS *Dahlgren* is a surface combatant to be designed and built specifically to search for and deter pirate ship activity. The platform is equipped with an AN/SPY-3 radar for surveillance. A Non-Line of Sight Launching System (NLOS-LS) provides the capability to engage pirate threats. A Vertical Takeoff Unmanned Vehicle provides surveillance, reconnaissance, and targeting capability. When transiting in and out of port, USS *Dahlgren* uses a Shipboard Protection System to protect the ship's force.
Tools: System Architect, MagicDraw

Table 2. Minimum Required Operational Views

Operational View	Description
OV-1 High-Level Operational Concept Graphic	Graphical representation of missions, environment, and interactions with external nodes
OV-2 Operational Resource Flow Description	Illustrates the need to exchange information between nodes and/or resources
OV-4 Organizational Relationships Chart	Depicts key players, their command structure, and their relationships
OV-5a / OV-5b Operational Activity Decomposition Tree / Operational Activity Model	Integrated summary of all operational activities and their input and output flows
OV-6c Event-Trace Description	Illustrates the dynamic behavior of operational activities by depicting the timing and sequence of events

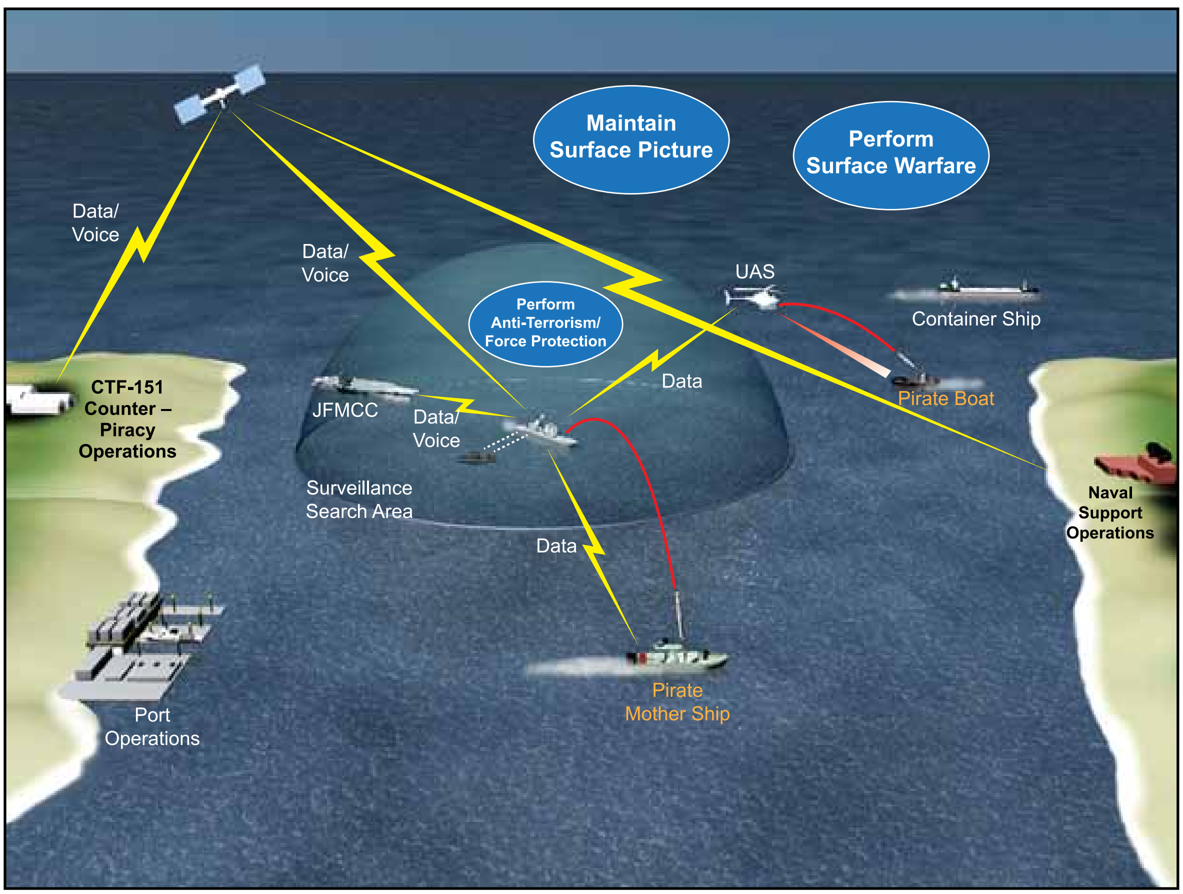


Figure 3. USS *Dahlgren* High-Level Operational Concept Graphic—OV-1

Table 3. System View Descriptions

System View	Description	SysML Approach
SV-2 Systems Resource Flow Description	A description of resource flows exchanged between systems	SysML Internal Block Diagrams (IBD)
SV-4 Systems Functionality Description	The functions performed by systems and the system data flows among system functions	SysML Activity Diagrams or modeled activity hierarchy tree using a Block Definition Diagram (BDD)
SV-5 Operational Activity to Systems Function Traceability Matrix	A mapping of system functions back to operational activities	A table of activity diagram actions mapped to OV-5/6c activities. May require modifications to SysML tool database schema to automate generation.
SV-6 Systems Resource Flow Matrix	Provides details of system resource flow elements being exchanged between systems and the attributes of that exchange	A table of item flows depicted on the SysML IBDs. Items may be modeled as blocks in a BDD.

represents Object Management Group (OMG) Systems Modeling Language (SysML) standards, provides a framework for the required systems engineering activities, while providing views that satisfy DoDAF SV requirements. Table 3 summarizes the relationship between system views and SysML products.

The initial definition of a system functional architecture traces operational activities to system functions. These functions are documented in a DoDAF Systems Functionality Description (SV-4a). Each operational activity in the OV-5/6c products may yield one to many mappings to functions in the SV-4a in order to realize the required system capability. This mapping is depicted in an Operational Activity to Systems Function Traceability Matrix (SV-5a). For example, the "Fire Missile" activity in an OV-5/6c may require "Initialize Missile" and "Launch Missile" functions in an SV-4a. This relationship is usually depicted in a matrix with the initial functional hierarchy depicted in a tree. Figure 4 provides a sampling of operational and system views developed for USS *Dahlgren*.

Application of the Architecture

Once the USS *Dahlgren* architecture is defined, engineers need to address how the architectural products will be used in the combat systems engineering and acquisition effort. Operational architecture products are part of the "contract" between the operational fleet forces and the combat system engineers describing how the system will be used in various real-world scenarios. System architecture products define the physical and functional instantiation of the combat system required to provide the operational capabilities at the required performance levels. The system architecture can be used to determine the development cost to migrate from existing program of record combat systems to the objective design.

Moreover, the surface Navy has been actively transforming from the acquisition of independent platforms to a product line approach to provide maximum mission capability across multiple platforms within budgetary constraints. The combat systems engineers, therefore, need to identify opportunities for implementing existing product line components within the system architecture. For new components, system architecture should be defined in terms of concordance to the product line architecture to the extent possible to provide the best return on investment to the Navy Enterprise. Operational architecture mission threads should be very similar regardless of which ship classes are fielding the systems and conducting the missions.

In fact, it is desirable to fight missions similarly and consistently across classes to improve interoperability, mission coordination, and training. A common repository of system views and tools with standardized

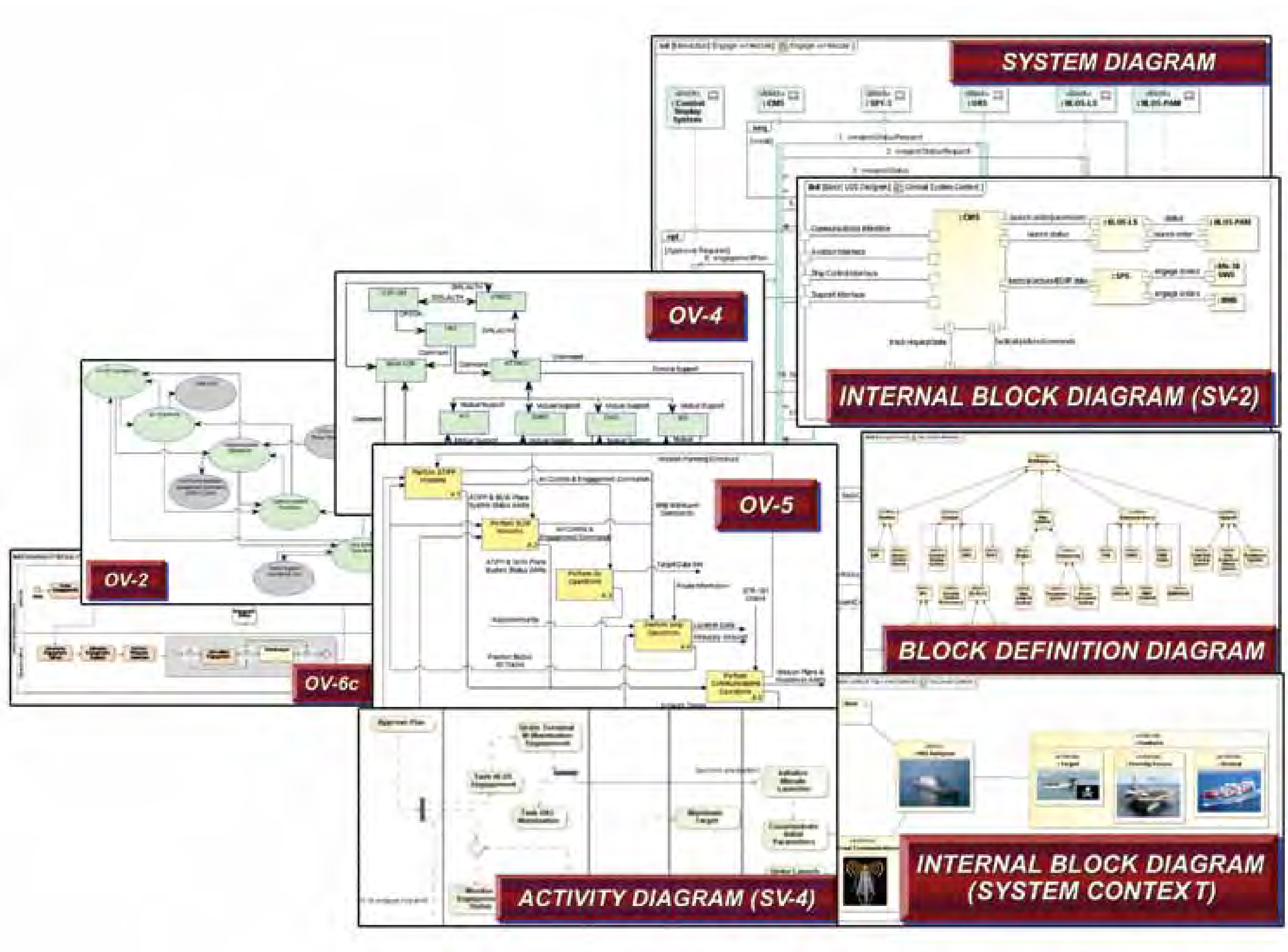


Figure 4. USS *Dahlgren* Systems Engineering Products

system functions, functional definitions, and standardized messages and message exchange implementations best serves this purpose.

Conclusion

The USS *Dahlgren* example illustrates how NSWCDD systems engineers employed DoDAF to create useful products for defining a shipboard combat system that operates within complex battle forces and satisfies stakeholder requirements. Architecture provides the foundation for defining combat systems implementation, as documented in the SSDD, which can be traced back to the user's requirements invoked in the operational views. By designing and developing architecture using the DoDAF construct, surface Navy warfighters will benefit considerably from NSWCDD's systems engineered shipboard combat systems necessary for 21st century naval missions and operations.

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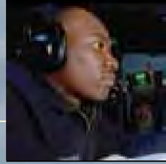
6. DAU, *Systems Engineering Fundamentals,* 2001.

Operational View

Systems and Services View

Technical Standards View



Technology Integration and Assessment Capability

by Darren C. Barnes, Neil T. Baron, and Jerry W. Oesterheld

Radar Lab(s)

C2 Labs
Command & Control

UXV Integration Facility

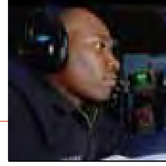
Marine Corps Lab

The integrated Naval Strike Force, made up of tens of combat systems, hundreds of weapon elements, and thousands of components desiring commercial-like computing with Internet-like access and yet the unwavering discipline required for the use of deadly force, puts great demands on the engineering and integration realm. Speed of evaluation, consistency of the evaluation framework, and the mere ability to test components within a highly integrated system-of-systems (SoS) environment were challenges that had to be overcome to consistently evaluate and field force-level warfighting capabilities. The core of a Technology Integration and Assessment Capability (TIAC) was established at Naval Surface Warfare Center, Dahlgren Division (NSWCDD), to begin serving these functions.

With the advent of the Navy's open architecture technical and business strategy for the development of combat systems, the need for an independent evaluation facility for third-party product development was recognized. In response to this need, NSWCDD christened its Open Architecture Test Facility (OATF) in July 2003 to provide an independent site for evaluation and certification of products to open architecture standards. Subsequently, to be more responsive to the pace of the Navy's Advanced Capability Build (ACB) upgrade process administered through its Program Executive Office for Integrated Warfare Systems (PEO-IWS), it was further recognized that the OATF concept had to evolve and expand into an integrated laboratory environment where science and technology (S&T) products under development could interact more easily and regularly within existing combat systems architectures. This was needed to verify and validate proposed capabilities prior to a program decision to advance products under development into a program of record (POR). Additionally, the regular nature of a two-year development cycle, coupled with a more flexible research and development evaluation facility, was envisioned as a way to quicken the delivery of capability to the Fleet. Accordingly, NSWCDD established the TIAC as a mechanism to address specific SoS technology and architectural engineering challenges and time-to-market fielding demands by the Fleet.

TIAC Overview

TIAC provides an instrumented, dispersed, command and control (C2) laboratory environment that interconnects individual warfare development laboratories into SoS constructs able to represent entire ships or groups of ships prosecuting a warfighting scenario. With the explosion of information technology into every aspect of the C2 functions of combat systems and



warfighting SoS architectures, it became apparent to laboratory leadership that a focused effort to integrate disparate facilities would provide critical capabilities to the laboratory's mission to perform integration engineering functions at all levels of the systems engineering hierarchy. TIAC started as a single laboratory within NSWCDD's Integrated Warfare Systems Laboratory (IWSL) complex, and is now expanding to include other C2 and computer laboratories for distributed experimentation and testing (on site and off site). The overall intent of the TIAC is to gain early (prior to a fielding decision) insight into technology integration into SoS environments, support value engineering activities, and reduce total ownership costs. (Value engineering analyzes the functions of a program, project, system, product, item of equipment, building, facility, service, or supply of an executive agency, performed by qualified agency or contractor personnel, to improve performance, reliability, quality, safety, and life cycle costs.)

TIAC's Mission

The mission of TIAC is to:

- Provide an independent evaluation environment with hardware-in-the-loop (HWIL) and simulation/stimulation to support warfighting system developments up to the Strike Force level.
- Exploit the facilities and subject-matter expertise at the laboratory to enable architectural alignment of engineering developments and synchronize science and technology capability development into main stream program developments.

TIAC's Three Main Objectives

1. Provide an innovation center for industry, small business, academia, and naval and joint government laboratories enabling affordable and efficient C2 technology integration and unbiased technological assessments into combat systems, ships, and naval forces within realistic operational warfighting scenarios.
2. Provide local federated facilities and connectivity (multiple networks and venues) in an unbiased, government facility to connect innovative solutions with laboratory simulations, stimulations, and HWIL representations of combat systems of today's Navy, the next Navy, and the Navy after next.
3. Effectively manage ever-changing security requirements for information assurance (IA) that burden control system laboratories by enabling prioritization of resources aligned to planned laboratory needs and strategic proposals for experimentation, evaluation, and assessment.

TIAC Components

Core TIAC components consist of local connectivity, a robust modeling and simulation (M&S) environment, both operational view (OV) and system view (SV) architectures, local and global connectivity, and a robust IA environment. These TIAC components are represented in Figure 1.

Local connectivity enables different systems housed in local, unique, tactical laboratories at NSWCDD to be brought together into one virtual laboratory environment, thereby increasing the ability to represent a complex SoS environment. A representative list of laboratory facilities and capabilities includes the following:

- Tomahawk Weapon System
- Surface Electronic Warfare Improvement Program
- AN/SLQ-32 Electronic Warfare System
- Aegis Weapon Control
- Aegis Command and Decision, Cooperative Engagement Capability laboratories
- Marine Corps' Common Aviation Command and Control System (CAC2S)
- Systems Integration Laboratory (SIL)
- Radar and Sensor laboratories, including AN-SPY-1 and Ground/Air Tasking Oriented – Radar (G/ATOR)
- Human Systems Integration (HSI) laboratories

Well-planned and properly configured local connectivity enables TIAC to represent an integrated test bed immediately for either S&T integration and assessment or early system integration assessments. The integrated test bed better represents the final operational environment of integrated elements operating synergistically in a combat system or an SoS framework. Local connectivity requires close cooperation, not only in technical areas, but also in coordination of M&S environments to reflect desired system environments. HWIL and threat and environmental simulations must work seamlessly within SoS mission threads (plan-detect-control-engage-assess) to maximize the SoS realism and the effective capture of relevant engineering artifacts from the elements. Local

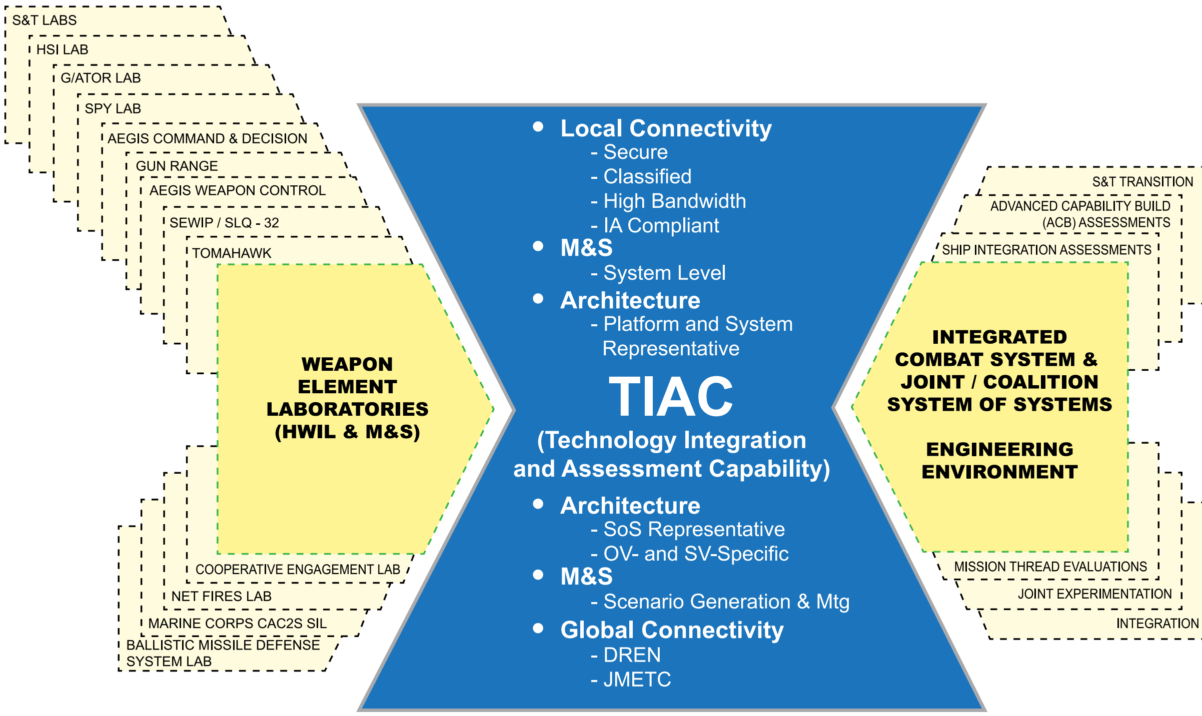


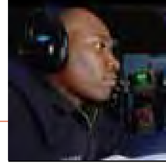
Figure 1. TIAC Components

connectivity also supports the integration of IA and security aspects, an area that continues to expand as the commercial computer information security domain continues its Moore's law rate of development. Connecting existing capabilities further facilitates the transition of S&T from inception to integration to warfighting systems. It also facilitates a more timely assessment of technologies into predefined architectural descriptions of ACBs, bringing new and improved warfighting capabilities and the exploration of naval and Joint system architectures into play while minimizing any disruption from the insertion.

The TIAC concept, however, is not limited to the interconnection of locally housed systems within the confines of a local warfare/systems center laboratory. Today's global environment requires the TIAC to create global connections to known (and yet to be known) systems beyond the local confines of NSWCDD. A representation of global connectivity is represented in Figure 2, showing connectivity from the Dahlgren, Virginia, site to other Dahlgren Division laboratories at Dam Neck, Virginia, and at the Surface Combat Systems Center (SCSC) at Wallops Island, Virginia. This triad of surface combat system facilities can then connect to other service, national, and international collaborators.

Global connectivity must account for the same kinds of technical element-to-element and system-to-system interactions, but at a more complex level due to politics and programmatics spanning different organizational claimants. Instead of dealing with local organizations and networks, global connectivity requires cooperation and coordination among disparate organizations, networks, and interpretations of IA and security guidelines. A single commercially accepted Internet-based "plug-and-play" environment (such as you have at home with your personal computer) does not exist for a fully secure, high bandwidth, low latency national (international) network for military testing and evaluation. The global connectivity for the TIAC must accommodate many different and currently independent networks and protocols, such as:

- The Secure Defense Research and Engineering Network (SDREN), a 100-Mbps network connection used to access various Department of Defense sites using InterTEC tools.
- Missile Defense Agency (MDA) CNET, a 100-Mbps connection using the Defense Research and Engineering Network (DREN) supporting missile defense systems for testing.
- The Joint Mission Environment Test Capability (JMETC), an enterprise-level Live Virtual Constructive-distributed test capability.



The orchestration of these global connections allows the TIAC to reach well beyond the surface Navy environment to include MDA facilities and address the Navy's role in national defense needs. Facilities can be joined to perform complex system assessments of either the whole architecture (including all services and coalition partner contributions) or the integration of new parts into existing complex environments. Likewise, connectivity enables integration with U.S. Marine Corps facilities, such as the Marine Corps Tactical Systems Support Activity (MCTSSA), Camp Pendleton, and Marine Corps Systems Command. Similarly, facilities for the integration of command, control, communications, computers, and intelligence (C4I) are located at Space and Naval Warfare Systems Command (SPAWAR) Atlantic (Charleston, South Carolina) and SPAWAR Pacific (San Diego, California) and at MDA.

Key to connectivity, both local and global, is to bridge together disparate laboratories to try to achieve a system-wide capability, which TIAC has demonstrated successfully in support of a Marine Corps command and control acquisition effort.

TIAC Employment

As part of a proof of concept that turned into a successful program support tool, the TIAC recently supported a Marine Corps acquisition effort specific to complex C2 integration capabilities. For this application of the TIAC, the program office initially solicited industry solutions via a Request for Information, which resulted in responses in the form of proposed technology solutions to be characterized as part of a "String" or mission thread against a set of high-level performance requirements. NSWCDD provided the TIAC to include associated environments: Simulation and Stimulation, Host Combat System,

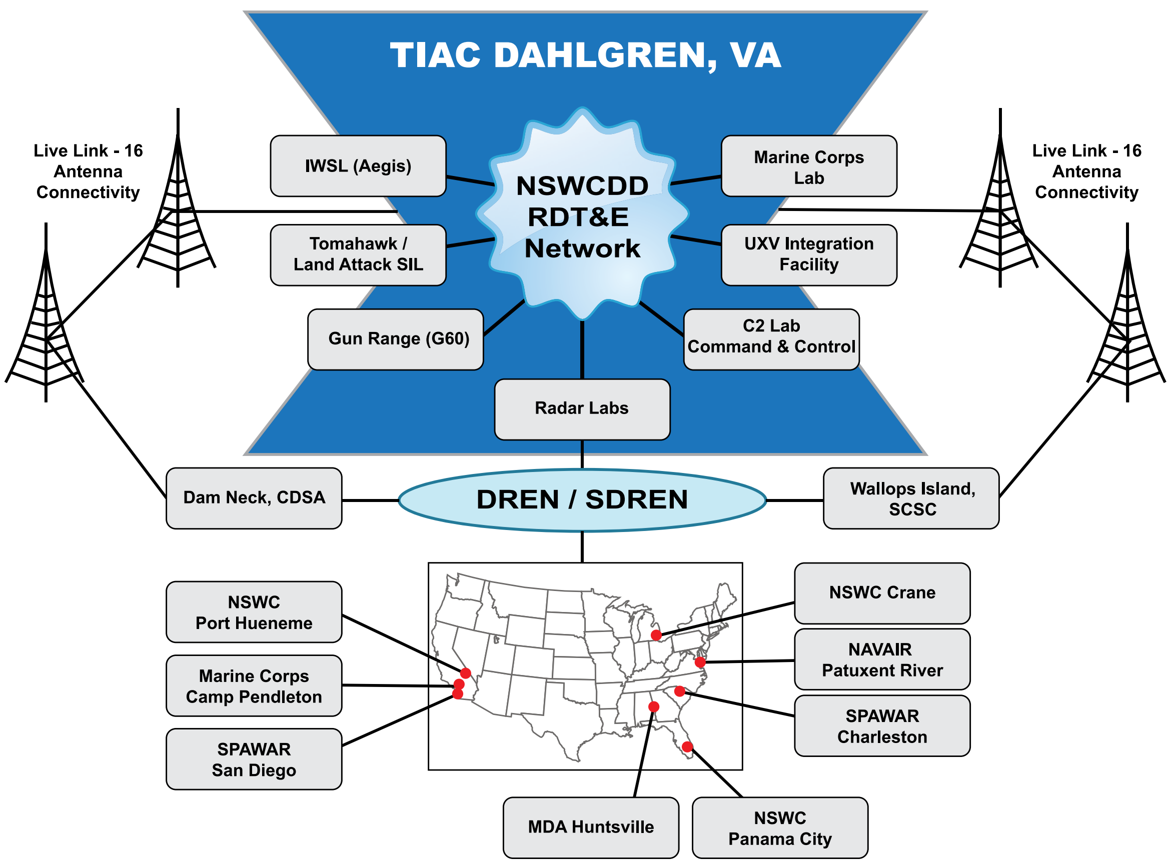
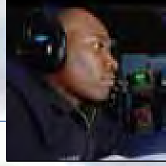


Figure 2. TIAC Connectivity

Component Under Test, Instrumentation Tools, and Post-Test Analysis Tools. Over the span of a few months, numerous vendors brought their solutions (in some cases, a fully integrated system; in other cases, only a small component solution) into the TIAC. NSWCDD and NSWC Corona performed assessments of each technology's performance, its instrumented contribution to the overall mission string success, and the level of integration maturity into the SoS architecture. The TIAC approach facilitated a more streamlined and consistent acquisition approach and allowed the program office to select a best-of-breed solution that met warfighter needs. This proved invaluable to program office decision-makers as TIAC provided the sponsor with unbiased, government assessments of industry-proposed solutions in a fully instrumented operationally equivalent warfighting environment.

The Way Ahead

TIAC will grow to encompass additional C2 laboratories across NSWCDD and by extension through experimentation and networking across the Navy warfare/systems centers and other Joint and coalition laboratories. Reiterating, TIAC's goal is to network independent laboratories in order to realize a "virtual" laboratory capable of accurately representing the entire combat system (regardless of where elements are located) and the distributed nature of warfare at the Naval Strike Force level integrating and assessing current and future naval C2 environments. Different laboratories (local, national, international) can contribute to the TIAC mission based on warfighter and program needs. TIAC serves as a critical tool that enables the government to perform its technical integration and assessment role on highly integrated yet widely distributed systems via interconnected laboratories. Consequently, TIAC will expand to other warfare centers, systems centers, and other government installations to address large-scale, distributed, naval system and SoS development and fielding challenges. Ultimately, a fully realized TIAC will provide the environment, tools, and methodologies necessary to perform early evaluation and characterization of proposed technologies into a Naval Strike Force. TIAC will speed the integration of desired technologies into ship and Fleet architectures, putting critical capabilities into the hands of our warfighters.



Estimating Software Development Effort for Future Naval Capabilities

by Terence Sheehan, Eric Rocholl, and Alvin Murphy

To keep pace with emerging threats, the Office of the Chief of Naval Operations (OPNAV) must ensure that warfighting capabilities are consistent with Navy needs. OPNAV is charged with balancing costs, schedules, and risks associated with efforts to meet new mission requirements, while at the same time striving to close existing capability gaps. In support of OPNAV decision-makers, Warfare Systems Department engineers at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), perform an integral role in the development of combat system cost estimates; this entails establishing architecture options, generating technical data, and quantifying software development effort.

Over the years, NSWCDD engineers have leveraged multiple techniques for estimating software development costs. NAVSEA standard methods include analogy, parametric, and engineering buildup. Each method requires an estimate of the software development scope. This article provides an overview of a Source Lines of Code (SLOC)-based methodology for determining the software scope. SLOC is commonly used as an estimating metric since it has historically been the product or final output of the larger software development process that programs have used to report progress. Industry reports SLOC counts to the government via required contract deliverables. Also, the majority of Department of the Navy (DoN) software cost estimating models are driven by SLOC as their primary technical input. This article highlights ongoing NSWCDD research aimed at investigating relationships between other technical artifacts (e.g., system interfaces) and software development level of effort (LOE), in hopes of adding an alternative software cost-estimating technique to the toolset.

Developing quality software estimates enables OPNAV and Navy leadership to make informed decisions about future capability investments and required resources. Software development effort ultimately drives software development cost and schedule estimates, which are needed to properly plan, program, and successfully execute major defense acquisition programs. Modern combat systems derive an increasing portion of their overall functionality from software, therefore making it imperative for the Navy to accurately estimate software cost to support sound acquisition decision-making.

Surface Navy Software Cost Estimation in Practice

To demonstrate NSWCDD's SLOC-based technique for combat system software development cost estimation for new ship concepts in the early design stage, the following simplistic, fictitious scenario will be used (example and associated SLOC estimates are strictly to demonstrate the estimating technique and should not be misconstrued as representative values for any real acquisition program):

> Combatant Commanders identify a capability gap in the Navy's fire support arsenal. There is a need to support rapid, protected insertion of Marines, Army, and Navy forces ashore that can quickly maneuver to tactical objectives. Naval engineers are charged with designing a new ship with advanced warfighting capability to outpace ever-evolving enemy threats to friendly forces. The Navy needs increased, long-range firepower to counter land and surface targets, but at a much lower cost per engagement than exists in current platforms and weapons systems. The rising cost of fuel, weapon system procurement and maintenance demands that the Navy field more innovative, cost-effective warfighting systems.

Using this scenario and the notional operational concept depicted in Figure 1, NSWCDD combat systems engineers define weapon system alternatives for long-range threat engagements using three gun and munitions designs and two launching systems that support land attack missles. Gun and munitions design alternatives include:

- 5-inch/62 caliber conventional gun with extended-range guided munitions
- Advanced gun system with long-range land attack projectile
- Electromagnetic launcher with hypersonic projectiles

Launching system alternatives that support land attack missiles include:

- Mk 41 Vertical Launching System (VLS)
- Mk 57 Advanced VLS

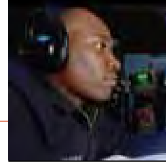
Weapon system alternatives are integrated with combat control systems to generate combat system alternatives, which are used for costing purposes. Combat system engineers, together with Naval Sea Systems Command (NAVSEA) naval architects, explore ship concepts for fielding these capabilities. Several notional ship design concepts are developed and coupled with combat systems alternatives to define total ship design concepts. The combat system part of the total ship design concept is further analyzed for performance and cost. In the example, three notional ship combat system concepts are analyzed:

1. Concept I: New destroyer-sized hull, Advanced Gun System, Mk 57 launcher
2. Concept II: New frigate-sized hull, 5-inch/62 Gun, Mk 41 launcher
3. Concept III: New destroyer-sized hull, electromagnetic launcher, Mk 41 launcher

Figure 2 provides an example of each notional ship combat system concept.

Naval engineers must develop software integration architecture for each combat system alternative. Software architecture impacts projected for the integration of the electromagnetic launcher weapon system in Ship Concept III are shown in Figure 3. (The small red squares connote interfaces between software components that will be impacted by the capability integration. Conversely, the small white squares connote interfaces between software components that will not be impacted.) Several software components within the combat control system require modifications to support the new capability:

- A new electromagnetic launcher manager is required to control the electromagnetic launcher. The electromagnetic launcher manager must receive track data to support aiming the gun. Also, the electromagnetic launcher manager must provide display data and coordinate engagements with the engagement manager. The effort is a new software development.
- The engagement manager requires modified gun engagement logic and a new interface to the electromagnetic launcher manager. Additionally, new display data must be provided. This effort requires modification to existing software as well as creation of new code.
- The doctrine manager requires modifications to support selection of the electromagnetic launcher for engagement recommendations. Additionally, new display data must be provided. This effort also requires modification to existing software and new code.
- Graphical user interfaces (GUIs) must be developed to support new operator displays and interactions with doctrine, weapons selection, and electromagnetic launcher control.



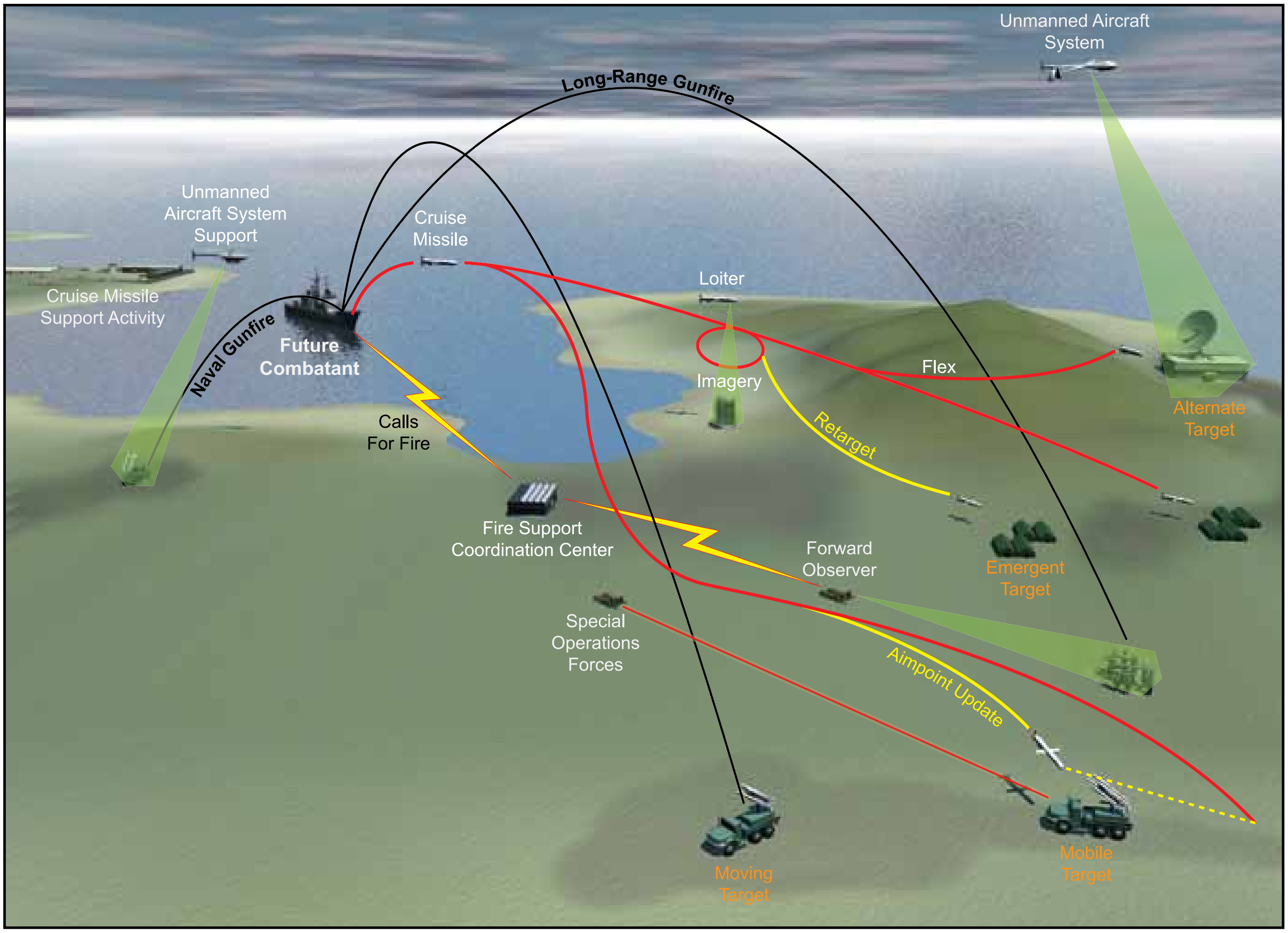


Figure 1. Operational Concept

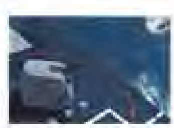
Ship Concept	I	II	III
Hull Design	 New Destroyer	 New Frigate	 New Destroyer
Weapon System Alternatives	 Advanced Gun System	 5-inch / 62 Gun	 Electromagnetic Launcher
	 Mk 57 VLS	 Mk 41 VLS	 Mk 41 VLS

Figure 2. Notional Ship Concepts

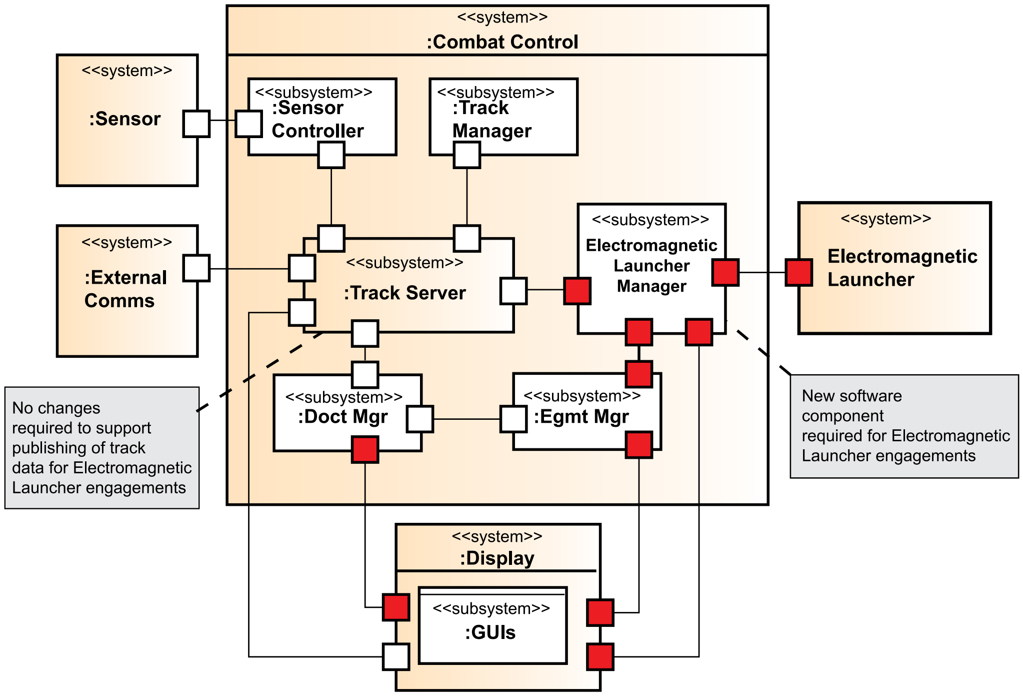


Figure 3. Notional Electromagnetic Launcher Software Integration

Systems engineers consider functional capability and information exchange requirements for each software component. They generate modified and reused code estimates for each component as a percentage of the existing total SLOC. For a new component (electromagnetic launcher manager), or new functionality within an existing component (doctrine manager), SLOC estimates are developed based upon comparison to existing combat system components with comparable functionality. Table 1 provides a summary of SLOC impacts to software components for integration of a notional electromagnetic launcher into the combat control system for Ship Concept III.

Table 2 shows a notional SLOC estimate for the electromagnetic launcher integration in Concept III. The software data above are synthesized into a total estimate of new, modified and reused SLOC. Cost analysts then assess the effort associated with modifying and reusing code (i.e., 0.5 and 0.1), relative to the effort associated with developing new code (i.e., 1.0), to normalize the SLOC counts.

This normalized SLOC estimate is converted into cost using cost estimating relationships (CERs) derived from historical software development efforts. During this conversion process, the effects of technological advances in software development processes and tools are evaluated. The CERs must address the full spectrum of software development activities (e.g., requirements, architecture, integration, system test) not just the design, code, and unit test (DCT) activities.

NSWCDD Research into Alternative Cost Estimation Approaches

The above example provides a simplified representation of the broader scope associated with a full combat system capability upgrade, which may encompass as many as a hundred evaluated software components. It describes one technique used by NSWCDD engineers to quantify software development efforts for new capabilities; this technique scales the size (measured in SLOC) of a known or projected software component that has functionality similar to the software component or new functionality being estimated. SLOC is only one artifact of the overall software development effort. Figure 4 provides an overview of activities and artifacts required for large-scale system-of-systems engineering. As system complexity varies, it is expected that the details, complexity and volume of related artifacts will also vary; however, this

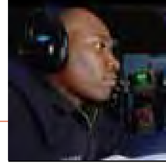


Table 1. Notional Electromagnetic Launcher Weapon System Integration for Concept III

Software Component	Base SW Component Size (SLOC)	Description of Change	% New SLOC	% Modified	% Reuse SLOC
Electromagnetic Launcher Manager	145,000	Develop new software to add electromagnetic launcher manager to existing architecture.	100	0	0
Engage Manager	58,000	Modify software to include electromagnetic launcher in engagement logic.	20	5	95
Doctrine Manager	21,000	Update to include electromagnetic launcher in doctrine statements.	10	5	95
GUIs	15,000	Develop new display software.	100	0	0

Table 2. Notional Estimate of Software Impact for Electromagnetic Launcher Integration

Capability	New SLOC	Modified SLOC	Reused SLOC	Total SLOC
SLOC	173,700	3950	75,050	252,700
Effort Factor to Normalize SLOC	1.0	0.5	0.1	
Normalized SLOC	173,700	1975	7505	183,180

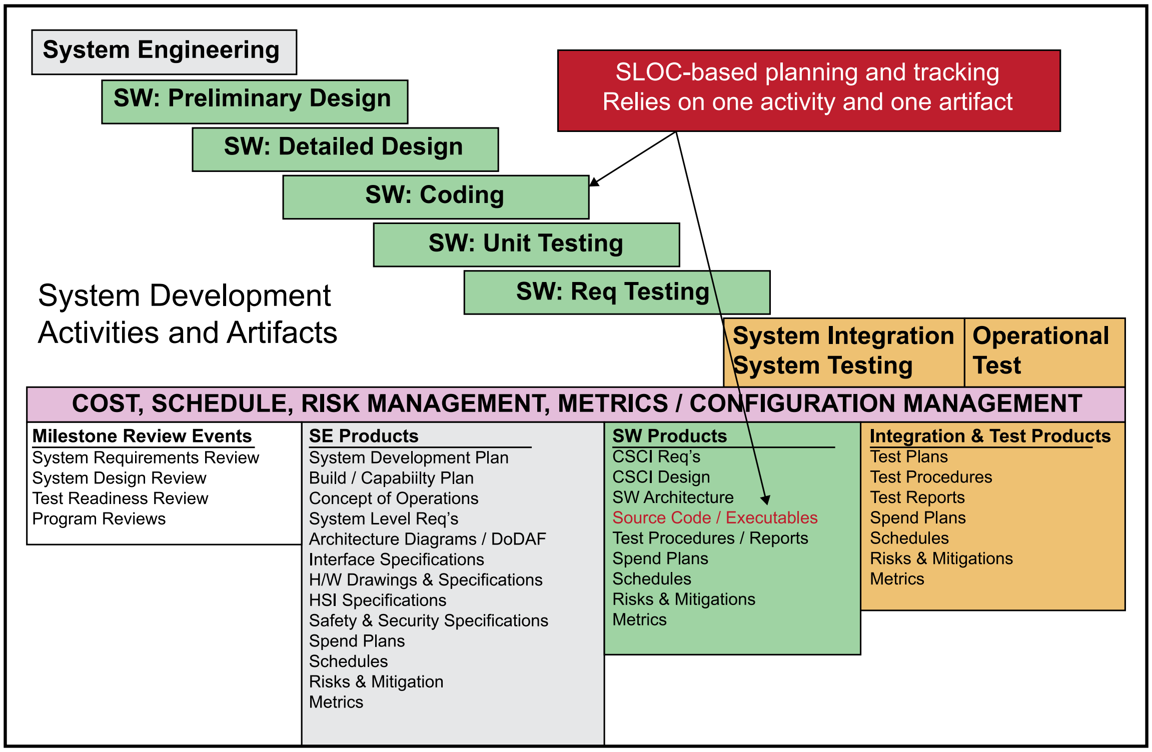


Figure 4. System Development Activities and Artifacts

effect is not clearly ascertained with a sharp, singular focus on SLOC.

NSWCDD is leading the charge to develop alternatives to the traditional SLOC-based software-estimating approach and to expand the software-estimating toolset. Over the past year, NSWCDD engineers have been reviewing artifacts from existing systems to uncover other correlations that may provide reliable estimates. Initial analysis has shown that the number of interface messages and message sizes have direct relationships to integration complexity. Interface descriptions are developed early in the system engineering process and could offer early insight into integration costs. If new correlations prove robust enough to adopt in practice, then non-SLOC-based estimating approaches would ultimately have to be integrated with costing models that use the technical artifacts as input. By implementing modifications to existing contracts via software data reporting requirements, the government's historical software dataset would evolve over time to include cost performance reporting at a level of detail commensurate with technical data reporting.

Value Added

Delivering unmatched warfighting capabilities to U.S. Navy surface combatant warriors requires that Navy research, development, and acquisition organizations maximize the return on every taxpayer dollar. In the 21st century, systems that provide combat advantage will increasingly rely on the functionality of embedded software. Software acquisition programs will live or die based on their ability to deliver required functionality within allocated cost constraints. NSWCDD systems engineers are conducting leading edge research that will help the surface Navy leadership make cost-effective decisions when acquiring capabilities for the warfighter.

Integrated Training for Combat Systems: Past, Present, and Future

by Lori Skowronski

Embedded shipboard training systems are crucial to ensure our Fleet maintains combat readiness. Integrated combat systems team training is not a new concept for the Fleet; today, the Total Ship Training Capability (TSTC) is a training continuum philosophy consisting of both shore- and shipboard-based training, ensuring Fleet readiness. Shore-based team trainers and Navy schoolhouses have long been a standard by which many sailors have been trained to hone their skills and perform in a battle situation as a seamless consolidated unit. However, shipboard team training is an essential component of the Navy training continuum, creating a synergized effort of personnel, which allows the sailors and the Fleet to be onboard and to "Train the Way We Fight!"

Shore-based trainers do an excellent job of training sailors to understand their role and to operate their assigned equipment; however, the aesthetics of the facility does not necessarily allow for the reality of being onboard and under way, as stated in an excerpt from the Chief of Naval Operations (CNO) MESSAGE 051905Z DEC 91.

> "...the concept that the ship, when properly supported presents the most effective training site for appropriate operational and functional training. This allows ships to train using their own equipment, system configurations and operational/casualty procedures. Enhanced training efficiency will result as training redundancy is identified and eliminated, a necessary reality in terms of future downsizing of the Navy."

Creating a congruent Combat Systems Team Training system that could be utilized within the workspace, onboard ship, was theorized to be far more effective than creating and participating in a series of disjointed events and scenarios. As the initial shipboard training requirements matured, the Operational Requirements Document (ORD) to support the effort was developed to accommodate the mission needs of the Fleet. In March 1994, the Battle Force Tactical Trainer (BFTT) Operational Requirements Document (ORD) Rev 1 was implemented and states,

"[BFTT] is an in-port shipboard combat system team training capability to provide:

- Realistic unit level team training in all warfare areas.
- A means to link ships together which are in different homeports for coordinated training using distributed interactive simulation (DIS) protocols.
- Stimulation to shipboard sensors via onboard trainers provided by tactical equipment program managers.
- Simulation of nonshipboard forces such as friendly, neutral, and enemy aircraft and submarines.
- An interface to the at-sea [Joint] Tactical Combat Training System ([J]TCTS)."

Basically, the BFTT was conceived and designed to electronically move real ships and crews located in separated ports, to a common synthetic theater of war (STOW). This provides a realistic, interactive environment that supports positive team training from the level of the battle group commander to the operator at the unit level across all warfare areas. However, to accomplish this training for a complex systems of systems (SoS), three phases of training are required.

The **Basic Training Phase** is accomplished right after an upkeep period for maintenance or system upgrades. During this period, an Afloat Training Group puts the ship's combat system operators through a series of single-ship training events—the Command Assessment of Readiness and Training, Total Ship Training Availabilities, and a final evaluation period.

In the **Intermediate Phase**, ships are brought together for multiship training to include Fleet Synthetic Training (FST) events. These events proceed by multiple steps through their mission areas such as antiair warfare and strike warfare.

Finally, in the **Advanced Phase**, the scenarios are more complex culminating in at-sea Fleet exercises (FLEETEX) or Joint Tactical Force exercises (JTFEX) just prior to deployment.

Through this sequence, training becomes more progressively controlled by the ship's own Combat System Training Team and Battle Group Commander and less controlled by the shore establishment. Throughout all events, Combat Systems Operational Sequencing System (CSOSS) (the set of procedures for equipment/system light-off, casualty reconfiguration, and shutdown) is used and proficiency is evaluated.

The BFTT system has matured since its inception; it has grown from supporting all in-port training situations and single-ship at-sea training events to now supporting the multiship at-sea training or FST events.

The BFTT of today has evolved due to changes in technology and lessons learned. However, the basic concept has not changed; we still need to "Train the Way We Fight." The conceptual framework of today's BFTT is architected to accept controlled changes and solutions with minimal impact to hardware, software, and people, thus lowering operation and support costs.

Central to this notional architecture are core BFTT training capabilities that support planning, conduct, assessment, and management of training and readiness information. These core BFTT capabilities are to be implemented with common services that aid in integrating the system components used by several training domains, functionally distinct trainer components for the training domains, and stand-alone training tools and aids that support both the trainer and trainee. Figure 1 portrays the components that make up BFTT and how they are related.

All external connectivity to BFTT is provided by the Navy Continuous Training Environment (NCTE) as part of the Global Information Grid (GIG). The NCTE, from the BFTT perspective, may operate in two modes. First, NCTE enables the training environment where tools and/or applications provide the scenario and stimulus for the overall Live, Virtual, and Constructive (LVC) Environment (LVE), and BFTT is the host platform for Simulation/Stimulation (SIM/STIM). Second, BFTT can use NCTE connectivity to deliver a multiship or Battle Group (BG) scenario.

Currently, the BFTT program fields seven different builds encompassing 127 ships and shore sites. The builds are derived from a common source library supporting all of the required configurations. As ships are decommissioned and BFTT obsolescence upgrades continue, the number of BFTT baselines will be reduced. The breakdown of the BFTT family of systems' (FoS) specific systems is listed in Table 1.

The next phase of the BFTT FoS, **BFTT FoS Modernization,** ensures that the development of BFTT baselines are accomplished as required by the Advanced Capability Build (ACB) operational and system requirements process to interact successfully and plan for cross-program and platform-specific ACB activities through delivery.

The goal of future builds will be to provide a more realistic and robust training environment, enhancing training processes and capabilities to ensure that the training provided effectively

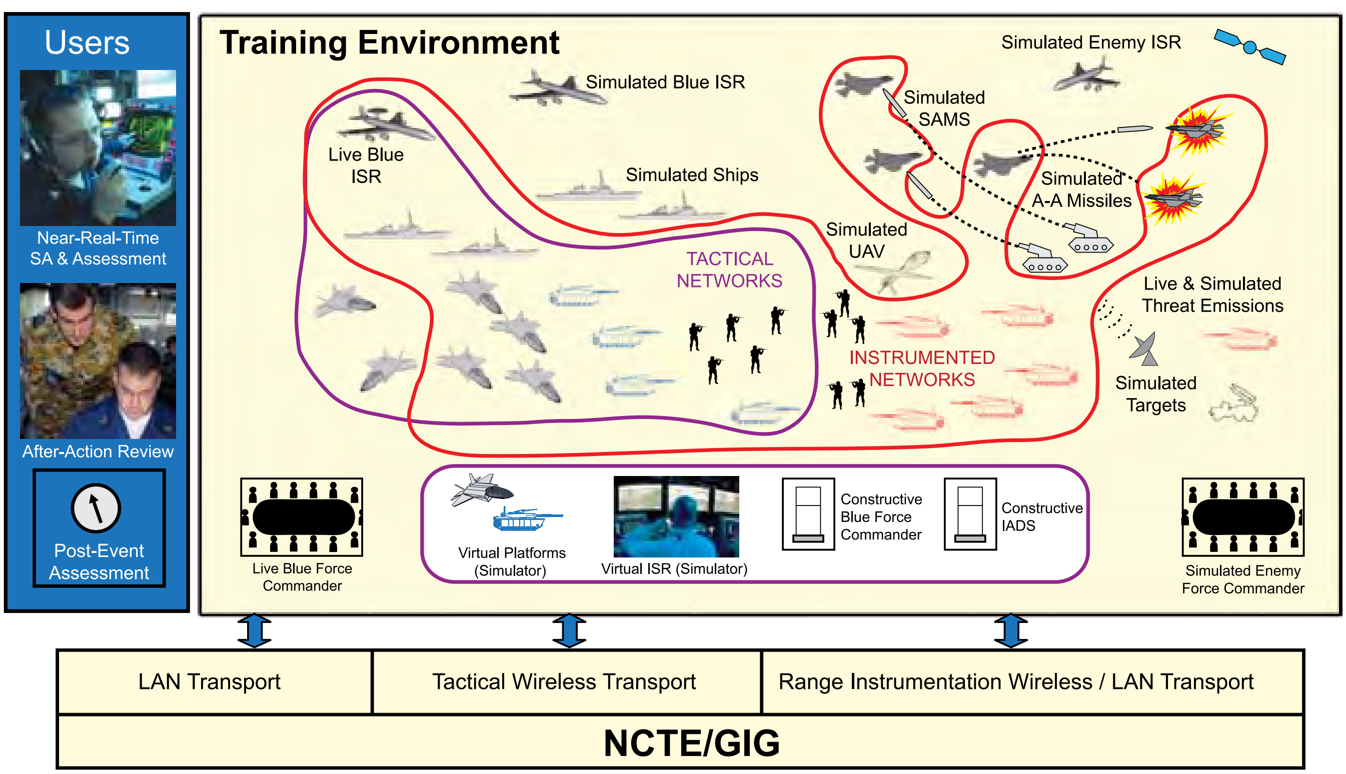


Figure 1. Training Environment

Table 1. BFTT Fielded Software Builds

Software	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19
3.1X	13	13	11	9	7	5	3	1	0
3.2X	44	30	15	6	5	3	1	0	0
3.3X	41	21	8	3	1	0	0	0	0
3.4	15	8	1	0	0	0	0	0	0
3.5	12	50	79	79	61	44	38	31	30
3.5.1	0	3	12	20	28	29	29	29	29
3.5.1A	0	0	0	9	17	18	18	18	18
5.0	0	0	0	3	13	35	46	59	62
Total	**125**	**125**	**126**	**129**	**132**	**134**	**135**	**138**	**139**

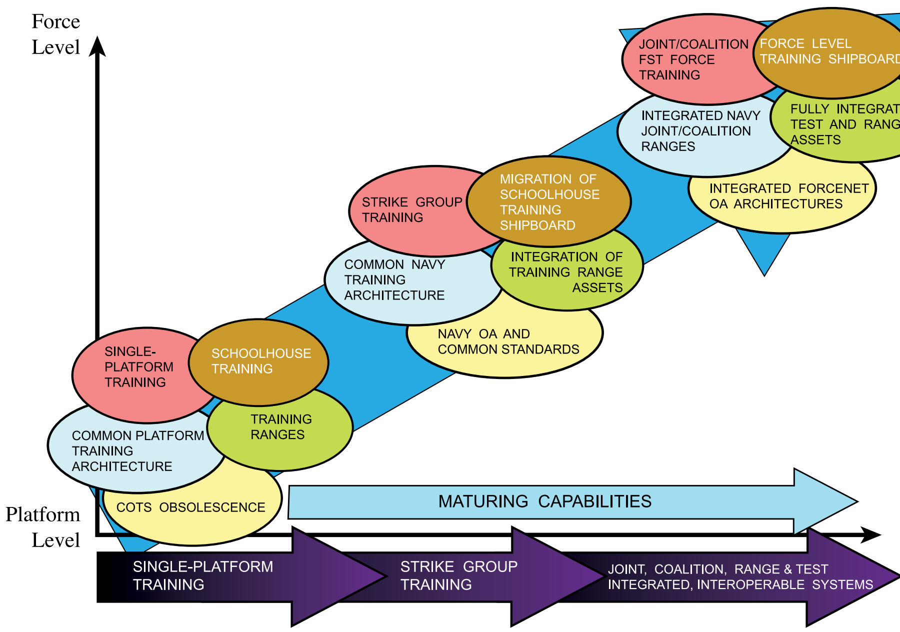


Figure 2. Joint Vision 2020, Sea Power 21 Training Transformation

and measurably improves the performance of the individual/team/ship/task force. The BFTT will require technical insertion of training capabilities or traits into recently introduced and future ship systems such as combat systems, sensor systems, ship engineering, Link communications, navigation, etc. The enhancement of the BFTT architecture will enable economical, efficient, and scalable network management, database management, system resource management, and information assurance. Figure 2 depicts the Joint Vision 2020, Sea Power 21 Training Transformation as capabilities mature.

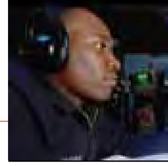
The future plans for the BFTT FoS modernization are depicted in the proposed build roadmap in Figure 3. Some of the competencies for each build are as follows:

Aircraft Simulation: An aircraft can be a simulated entity in a training scenario or the aircraft crew stations can be mocked up enabling a real-time pilot-in-the-loop synthetic training event.

Capabilities include basic flight maneuvers, combat maneuvers, evasive maneuvers, and emergency procedures, including both radio communications and simulated Link within synthetic mission scenarios.

Vehicle Management: The Vehicle Domain Manager controls off-board vehicles, their sensors, weapons, and communication systems. These vehicles include rotary-wing aircraft, fixed-wing aircraft, small boats, unmanned air vehicles (UAVs), unmanned surface vehicles (USVs) and unmanned underwater vehicles (UUVs). These vehicles complement the combat system by extending weapon, sensor, and/or communications footprints.

Scenario Generation and Control: Competency-based training, which requires a cognitive



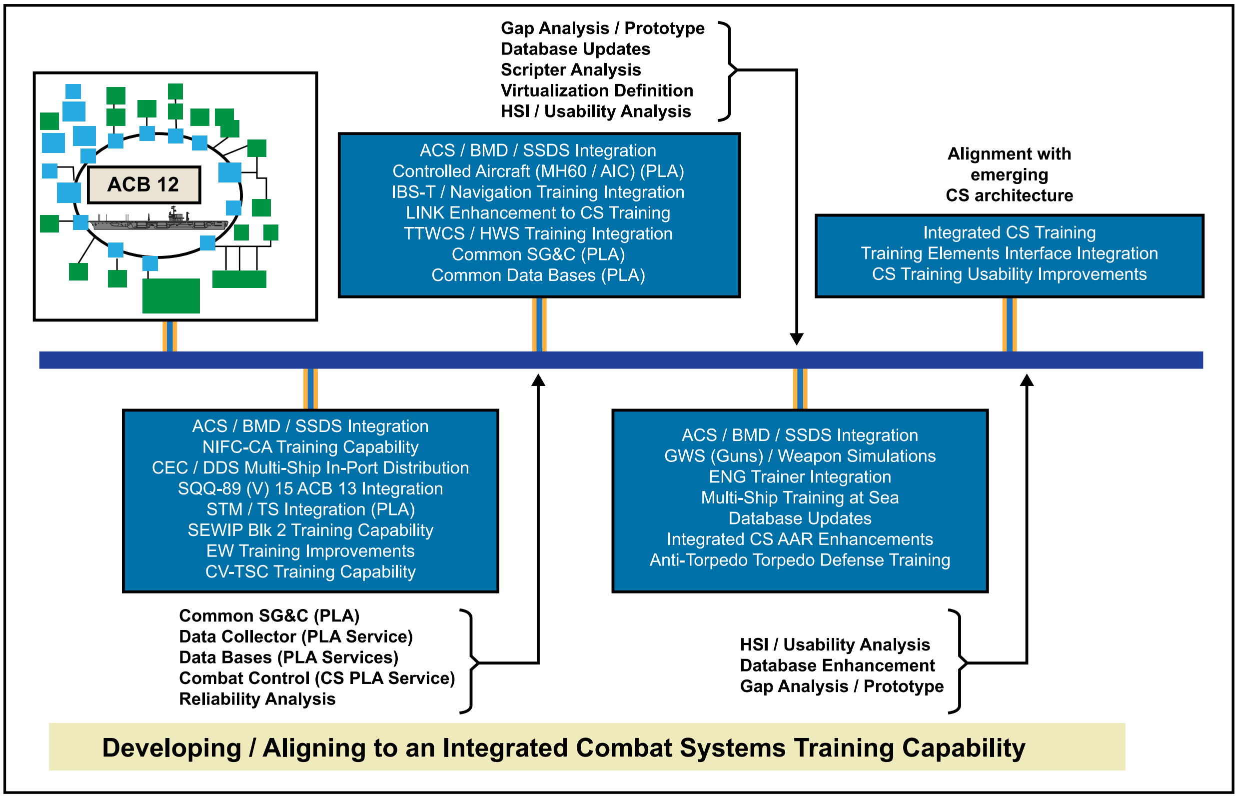


Figure 3. BFTT Roadmap

theory-based Scenario Generation & Control (SGC) module, builds scenarios based on competencies. The scenario generator is used to create scenarios for stimulated/simulated realistic circumstances.

Common Database Schemas: Common database development would include all the training data. First, requirements must be developed and then the database schemas are implemented. Types of data may include Cognitive Theory Analysis, Competency-Based Training Metrics, Competency-Based Metrics Automated Analysis, and Internal and External Capability Requirements for training organizations, such as individuals, teams, units, ships, and strike forces.

After-Action Reporting: An After-Action Review (AAR) is a means of providing feedback to the principals on performance metrics captured during a training event. This feedback compares the actual performance of the individual/team/ship/strike force with the expected performance.

These **competencies** and the **metrics** gathered, based on automated measurements and analysis, will provide details on specific training objects and their effectiveness. Differences between the actual and expected performance will be identified and then remedied via more exercises and drills or by the development and implementation of targeted training.

Fortunately, our leadership over 20 years ago realized that to have an efficient and effective battle force, an integrated training system was crucial to ensure our warfighters received the best possible training to assure a high state of operational readiness. Over the years, training, due to technological advances, has become more sophisticated, robust, and adaptable. The goal of providing the Fleet with an integrated training system that can be adapted to the training needs of the individual, work center, ship, battle group, and joint or coalition forces is being accomplished. The integrated training operational vision for synthetic training events is as shown in Figure 4.

The future goal, to provide continued TSTC excellence in combat systems training, is imperative to Fleet combat readiness and crucial to ensuring that our sailors are prepared to combat and destroy current and future threats. The BFTT FoS enables and supports our sailors to "Train the Way We Fight," ensuring that our Navy continues to be the best navy in the world!

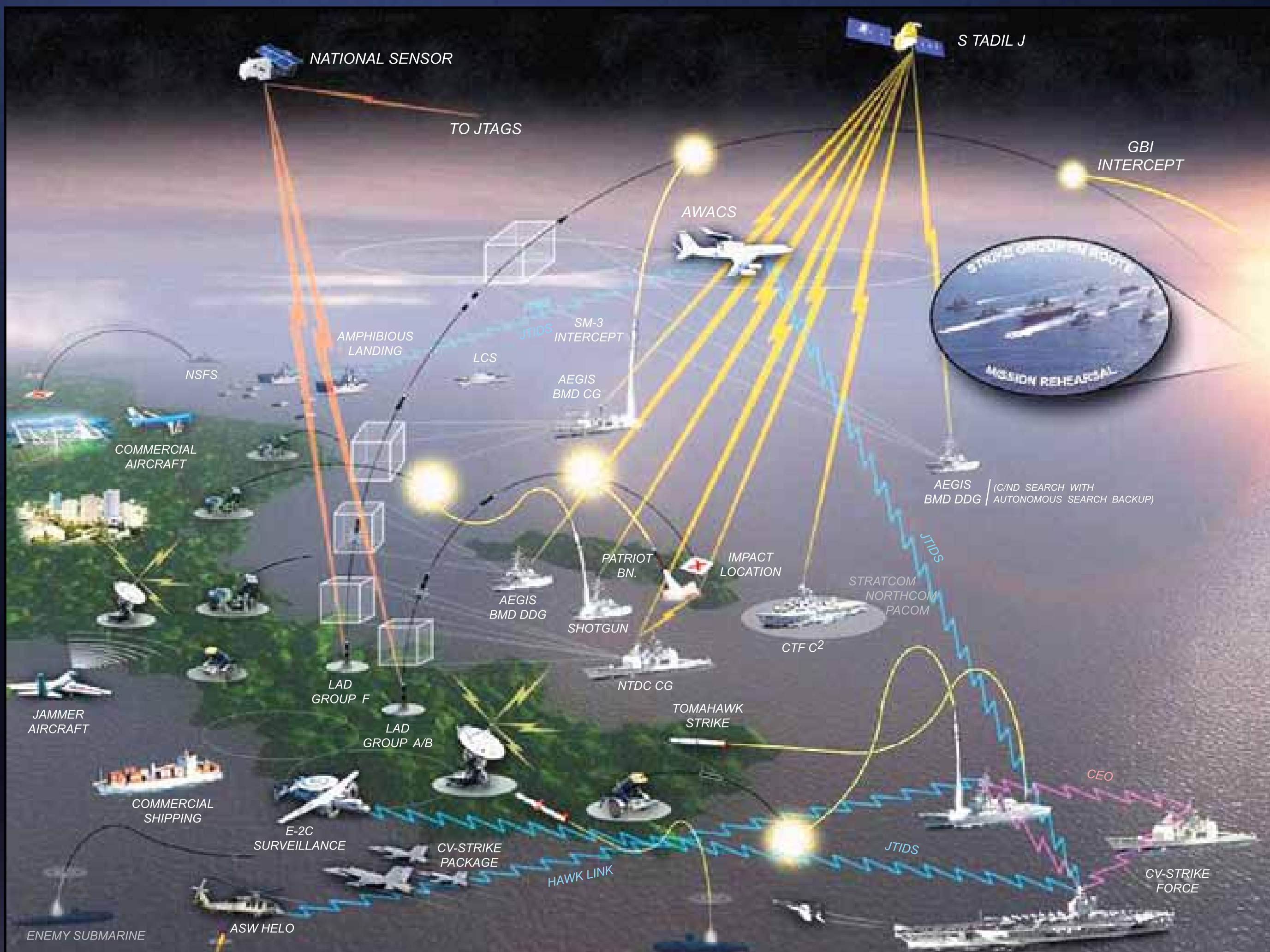
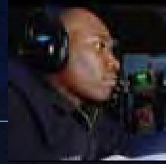


Figure 4. Multiunit Synthetic Training



NSWC Dahlgren's Systems Engineering and Command and Control Expertise Applied to Marine Aviation

by Douglas Haas, Damian Watson, Laura Beth Viventi-Collins, and Barret Lohr

The United States Marine Corps (USMC) is modernizing and consolidating its aviation command and control (C2) systems. Its current systems have diverse lineages across the joint community and were not designed to work together in an integrated manner. They are manually intensive to operate and require an extensive logistical footprint. Consequently, the USMC tasked the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), working with the Program Executive Office for Land Systems (PEO LS), to design a Common Aviation Command and Control System (CAC2S). USMC's intent was to leverage NSWCDD's recognized expertise in systems engineering and naval combat system design and development. This article describes NSWCDD's contribution to the effort and highlights the systems engineering disciplines of requirements management and architecture development, and the use of engineering tools to facilitate these disciplines in support of the design and development of the CAC2S.

The CAC2S (depicted in Figure 1) provides a complete modernization replacement for the command and control (C2) equipment of the Marine Air Command and Control System (MACCS). CAC2S replaces single mission, stove-piped military specification legacy systems while providing commonality in training and logistics support. CAC2S fulfills joint net-ready capability standards required of all DoD C2 systems and remedies the operational, technical, and performance deficiencies of the existing MACCS. CAC2S eliminates current dissimilar systems and provides the aviation combat element with the necessary hardware, software, and facilities to effectively command, control, and coordinate air operations while integrated with naval and joint command and control (C2).[1]

CAC2S capabilities intend to replace the functions and equipment resident in the following:

- Tactical Air Command Center (TACC)
- Direct Air Support Center (DASC) – air-to-ground operations (air attack)
- Tactical Air Operations Center (TAOC) – air-to-air (fighters) and ground-to-air (air defense) - Patriot, Stinger operations

CAC2S is both a producer and a consumer of battlefield information while communicating with sensors, data distribution networks, tactical data links, and aircraft. CAC2S interfaces with other battlefield agencies executing the functions of both command and control. As such, there are interfaces to both legacy and developmental systems within the USMC and Joint communities. The goal of CAC2S is to replace legacy Marine Corps systems with an extensible system capable of integrating a host of C2 tools, local sensors, networked sensors, and tactical data links necessary to modernize and enhance the Marine Corps' ability to accurately and efficiently control Marine aviation, as well as provide a more transportable and mobile system.

Sound systems engineering practices, specifically in the fields of requirements management and architecture development, were key to the CAC2S acquisition effort's success. Requirements needed to be managed from the beginning, as basic capabilities were decomposed, clarified, and refined to produce system requirements. Architecture development then explored the communication needs, interfacing systems, and system functions, providing a continual feedback loop with the requirements.

The Foundation — Engineering Stable Requirements

Through early and rigorous requirements engineering and management activities, the NSWC Dahlgren CAC2S requirements engineering team worked with the user community and Headquarters Marine Corps, Combat Development and Integration (HQMC CD&I) to develop clear, complete, unambiguous, and testable system requirements. This was necessary because whenever system requirements are inadequately identified or are not managed early in the system lifecycle, acquisition costs can rise due to continuous requirements refinement. Worse, when system requirements fail to accurately capture the functions and capabilities required by the warfighter, mission success can be compromised. Consequently, in order to accurately capture and stabilize the CAC2S performance requirements early in the system acquisition cycle, the NSWCDD requirements engineering team immediately employed the use of the Dynamic Object-Oriented Requirements Suite (DOORS) provided by IBM Telelogic.

Requirements engineers utilized DOORS to store, baseline, trace, and exercise configuration control over the CAC2S requirements. This helped to facilitate sound requirements engineering. The resulting CAC2S requirements set consisted of 867 system-level requirements derived from 243 operational requirements. Each requirement was subsequently evaluated

Figure 1. Notional CAC2S Operational Layout

for clarity, appropriateness, traceability, and testability. Over 1600 Change Proposals were adjudicated as part of the effort; proposed changes included the modification of existing requirements, the deletion of redundant and immeasurable requirements and statements, and the insertion of new requirements. Refined requirements were then captured in the CAC2S Capability Production Document (CPD) and the CAC2S System/Subsystem Specification (SSS).

In concert with the two formal processes outlined in the CAC2S Requirements Management Plan, the Change Proposal Process and the Requirements Validation Process, requirements engineering and management activities were strictly executed to support the comprehensive review of the CAC2S performance requirements by both the aviation C2 subject matter expert and requirements engineering communities. Thus, NSWCDD engineers provided stakeholders with quality requirements documents and subsequently supported the successful CAC2S System Requirements Review (SRR) held in summer 2009. NSWCDD engineers, therefore, established a strong foundation on which to build the CAC2S system architecture diagrams and design documents.

Structure – Development of System Architecture

In addition to the requirements effort, NSWCDD engineers also played a key role in the development of the CAC2S system architecture. Working together with Marine Corps Systems Command (MARCORSYSCOM) engineers and Marines, the NSWCDD architecture team helped to bridge the gap between operational needs and system solutions. CAC2S architecture engineers organized and fashioned system requirements into a workable model, aligned the system concept with the operational construct, and ultimately, influenced and guided system design.

In general terms, while requirements engineering yields an extensive list of requirements, architecture development provides the structure to move forward. Architecture development, therefore, defines the overarching organization of the system concept and outlines a problem statement to be solved by system design.

System architecture development begins with system requirements, supported by direct warfighter input. Warfighter input to system architecture is received in the form of the operational architecture. The operational architecture is analogous to the system architecture; only the perspective is different. The operational architecture describes who the warfighters are, what activities they do, and what information is exchanged between organizations. The system architecture defines system components, what functions they execute, and what data is exchanged between systems.

For CAC2S, the operational architecture was developed by the operating forces, in this case, HQMC CD&I. The CAC2S operational architecture described USMC aviation C2 through a set of Operational Views (OV). The task for the system architecture team at NSWCDD, then, was to define a model of CAC2S that reflected not only the requirements defined in the SSS, but more directly, satisfied the needs of the Marines as defined in the OVs. Figure 2 illustrates the basic development cycle for accomplishing that task. The diagram shows how the requirements and the OVs were inputs to the process that yielded the fundamental Systems and Services Views (SV) of the system architecture.

The process above began with two somewhat independent thrusts: functional analysis and interface analysis. The key steps in the functional analysis are shown on the far left side of the diagram (Figure 2). The OV-5, which described the operational activities (i.e., what the warfighter does), was the primary operational input to the CAC2S functional analysis. The warfighter activities drove the identification of what the system needs to do, as scoped and partly defined by the system requirements in the SSS. The explicit trace between the functions and activities was the SV-5. The organization of the system functions defined a functional hierarchy, part of the SV-4. Meanwhile, as shown on the far right side of the diagram, the interface analysis began with the OV-2, which described the relevant operational nodes (i.e., who the warfighters are). The identification of system entities, the systems used at the operational nodes, laid the groundwork to identify system interfaces. Finally, through the identification of communications media (e.g., radios, routers, etc.), the system interfaces were defined in the SV-2. From there, the identification of system data exchanges finally tied together the functional analysis and the interface analysis; the system data exchanges were, at the same time, the inputs and outputs of the system functions in the SV-4 data flow diagram, as well as the message traffic exchanged across the system interfaces, as documented in the SV-6. Following this process, the architecture engineers defined the system functions, system interfaces, and system messages, as depicted in the CAC2S architecture products.

Ultimately, however, NSWCDD's contribution to the architecture development effort was not the CAC2S architecture itself, but rather, the engineers' influence on system design. Because architecture development is a mandatory yet often misunderstood process in systems engineering, a common temptation is to merely use the architecture to

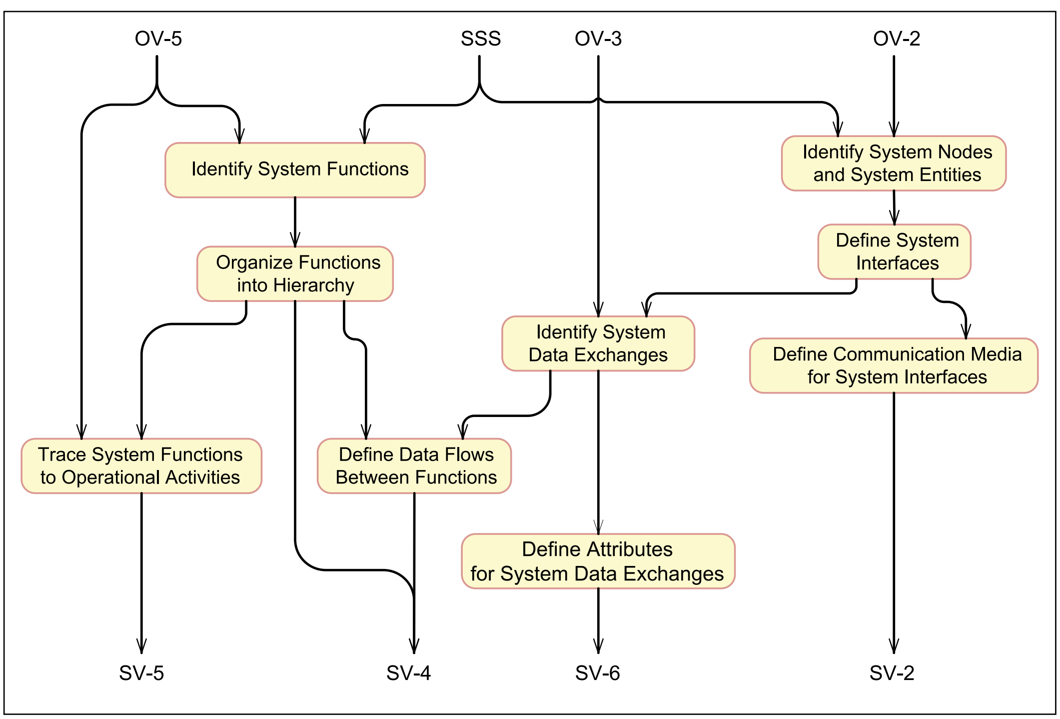
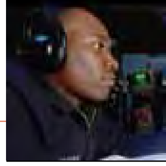


Figure 2. CAC2S System Architecture Development Process



document the systems engineering decisions after they are made. A more mature systems engineering approach is to define the system architecture upfront, so that better design decisions can be made from a cohesive, succinct model. For CAC2S, as candidate components, implementations, and allocations were evaluated in the system design process, the system architecture was a key reference. The system architecture that NSWCDD and MARCORSYSCOM developed for CAC2S continues to be a driving influence in designing a system solution for Marine aviation C2.

Coordination – Maintaining an Engineering Environment

As with any program, orchestrating complex systems engineering processes is a key challenge. Requirements and architecture concordance was maintained using an integrated suite of systems engineering software. Modeling languages were used to link the abstract system architecture to the emerging physical design, and an integration lab was established to provide a test and engineering facility to realize the system. As mentioned previously, the requirements engineering team utilized DOORS to create the requirements database. In a similar fashion, the architecture team used System Architect, another database-oriented tool. The selection of the two tools was a coordinated decision, enabling dynamic cross-referencing between the two efforts. The integrated suite of tools was employed in unison because of their ability to share information and to create linkage, as elements of the system architecture database were linked directly with system requirements in the DOORS database facilitating traceability. The use of these integrated tools for control was important in the CAC2S systems engineering effort. Having a comprehensive set of architecture products and a rigid requirements management process allowed NSWCDD, as the CAC2S Engineering Agent, to fully understand the requirements and constraints within which to develop CAC2S.

Other engineering tools, such as Unified Modeling Language (UML) and Systems Modeling Language (SysML) sequence diagrams, provided the team with a medium and syntax to transform the abstract architecture into the configuration items of the physical design. NSWCDD engineers developed these sequence diagrams to illustrate the time-ordered execution of system actions or operations through system components and software. In effect, these models allowed the systems engineers an opportunity to proof the design against the architecture, while examining system functions, data exchanges, and system interfaces.

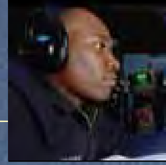
Conclusion

The need to transform Marine aviation C2 systems has yielded a fruitful collaboration between NSWDD and the USMC. By applying sound systems engineering practices early in the acquisition process, especially in the requirements engineering and architecture development disciplines, NSWCDD is helping to provide a more capable, modern, and consolidated system to the Marine Aviation C2 community.

Reference

1. PEO Land Systems, Common Aviation Command and Control System (CAC2S), http://www.marcorsyscom.usmc.mil/peoland-systems/cac2.aspx, accessed 28 September 10.

NSWC Dahlgren's Systems Engineering Command and Control Expertise Applied to Marine Aviation



Warfare System Interface Diagrams (WSIDs) in Support of Combat Systems Modernization

by Jody Michael and Rob Byers

Increases in the volume and complexity of system-of-systems engineering solutions to the complex problems faced by warfighters create an opportunity to lose control of the "as-is" and "to-be" combat system configurations. In order to make informed decisions, stakeholders need a way to view the pertinent information in a format that is clear, concise, and at the appropriate technical altitude and aperture.

Warfare System Interface Diagrams (WSIDs) were originally developed by Combat Direction Systems Activity (CDSA), Dam Neck, in support of Program Executive Office, Integrated Warfare Systems (PEO IWS) 10.0, Ship Self Defense System (SSDS) development, to manage the planned SSDS ship configuration upgrades. These WSIDs originally tracked the hardware nomenclature, software versions, physical interface types, and governing interface documentation of the warfare system. The diagram depicted the detect-control-engage systems that are considered part of the warfare system and are included in the combat system certification package that is planned for delivery during a Chief of Naval Operations (CNO) scheduled ship maintenance and modernization availability. The WSIDs have come to be known as providing an integrated view of both current status and proposed modernization plans. In response to the early success, and with the support of PEO IWS leadership, CDSA Dam Neck expanded the applicability of the tool.

CDSA Dam Neck has now developed WSIDs to track the configuration of PEO IWS combat system elements, along with some Program Executive Office for Command, Control, Communications, Computers and Intelligence (PEO C4I) and Naval Air Systems Command (NAVAIR) systems. WSIDs have been developed for all carriers, large deck amphibs, cruisers, destroyers, guided missile frigates, USCG Maritime Security Cutters, and littoral combat ships. (Three of these ship types are shown in Figures 1 through 3.) WSIDs are maintained for each ship's afloat configuration, showing the deployed combat system elements, and for the next five fiscal years of planned CNO availabilities. The WSID is now a package consisting of a hardware (HW) and interface type diagram depicting the hardware nomenclature and physical interfaces; a software (SW) and interface specification diagram depicting the software versions and interface documentation; and a WSID tabular changes page listing the IWS-approved changes by system and approval date. The scope of the changes planned for a specific availability period is annotated by the shading of the systems receiving changes. Blue shading is used for HW upgrades, yellow for SW upgrades. The more blue or yellow shading on a particular WSID, the more approved changes are planned. The WSIDs are recognized as the PEO IWS authoritative enterprise configuration management planning tool. WSID development is expanding in 2013 to include additional USCG classes, tracking Navy-Type, Navy-Owned (NTNO) equipment, and to document the Aegis Ashore configurations.

The WSIDs are governed by PEOIWSINST 4130.1B, the PEO IWS Enterprise Configuration Control Process (ECCP). The ECCP manages the proposed configurations for ship modernization. Traditionally, Participating Acquisition Resource Managers (PARMs) have proposed C5I hardware and software upgrades for systems under their cognizance using Ship Change Documents (SCDs) as required through the Entitled Process (EP). The ECCP mandates that each PARM submit their

Figure 1. Aegis Cruiser, USS *Normandy* (CG 60)

Figure 2. SSDS Carrier, USS *Nimitz* (CVN 68)

Figure 3. Amphibious Ship, USS *Iwo Jima* (LHD 7)

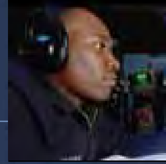
initiated SCDs to the Enterprise Configuration Control Board (ECCB) for approval by the PEO IWS Integrated Combat System (ICS) Major Program Managers (MPMs) before the SCD can be submitted into the EP. The ECCB is also supported by the NAVSEA 05 Platform Warfare System Integration Managers (SIMs), Deputy SIMs (DSIMs), and Baseline Managers, the Ship Program Managers (SPMs), and Ship Acquisition Program Managers (SHAPMs), the IWS Aegis Integration Engineering (AIE) Team, the SSDS Combat System Test (CST), and IWS Certification Readiness. The ECCB brings together the modernization plans developed by each PARM into a forum that reviews all the planned combat system upgrades as a package to ensure the right upgrades are being fielded at the right time on the right ships. The ECCB serves as the forum for coordination of fielding plans for multiple warfare system components within and across ship classes to meet Fleet requirements while optimizing cost and performance.

After each ECCB, minutes are distributed to the C5I community and the SCDs are then submitted through EP by the individual PARMs. The WSIDs are updated in accordance with the ECCB-approved configuration changes, and released as a new, approved WSID baseline on the second Friday of each month. The WSIDs are then posted on the Warfare Interface System Engineering (WISE) web tool that is managed by CDSA Dam Neck. The data elements represented graphically on the WSIDs are also stored and managed in the WISE database. WISE gives users the ability to view all current and planned ship configurations in a variety of ways, such as systems and changes by ship, ships by system and change, and comparing two or more ship configurations.

During the planning phase for new ships, or for large combat system upgrade packages, the CDSA Dam Neck WSID Baseline Managers work in conjunction with the IWS ICS Integrated Product Team (IPT) leads to provide engineering support in the development of the proposed configurations. Targeted Configuration Interface Diagrams (TCIDs) are developed during the planning phases to allow for the use of the WSID type of document by the planning community, while not requiring the data to have been approved through the ECCB. For new construction ships, CDSA Dam Neck develops a Construction WSID based on the signed contract for the ship. The construction configuration is managed through the planning, development, and deployment phases of system upgrades. At the completion of Post-Shakedown Availability (PSA), the ship moves into an afloat WSID configuration and configuration management of the follow-on modernization availabilities continues.

The WSIDs have facilitated PEO IWS's need to gain control of the "as-is" and "to-be" combat system configurations through a rigorous, process-based approach. This fidelity provides additional user communities the confidence needed to look at other system-of-systems considerations such as realigning schedules to increase configuration commonality, reducing the number of required certification events, and providing more stable, operable, and supportable combat system capabilities.

The WSIDs can be accessed on the CDSA Dam Neck WISE Web site through the following: https://wise.navseadn.navy.mil.



Major Combat Systems Technology Refresh for the Dock Landing Ship Fleet:

Hardware Design at Combat Direction Systems Activity, Dam Neck

by Barry Stevens, Larry Swinford, and Dale Bloodgood

The ships of the LSD 41 *Whidbey Island* and LSD 49 *Harpers Ferry* classes are about to receive a significant upgrade: a technology refresh that replaces the current Ship Self Defense System (SSDS) Mk 1 with an open architecture baseline of SSDS Mk 2. Deployed aboard LSDs since 1997, SSDS integrates and controls self-defense weapons and sensors aboard those ship classes to provide a self-defense capability. Dock landing ships support amphibious operations including landings via landing craft, air cushion (LCAC), conventional landing craft, and helicopters. The *Whidbey Island*-class amphibious dock landing ship USS *Comstock* (LSD 45) is shown in Figures 1 and 2.

Figure 1. Persian Gulf (November 22, 2006) - The Military Sealift Command (MSC) fast combat support ship USNS *Supply* (T-AOE 6), left, conducts an underway replenishment (UNREP) with the *Whidbey Island*-class amphibious dock landing ship USS *Comstock* (LSD 45). *Supply* and *Comstock* are under way in the U.S. 5th Fleet's area of operations in support of maritime security operations. (U.S. Navy photo by Mass Communication Specialist 2nd Class Kitt Amaritnant (RELEASED))

Figure 2. The *Whidbey Island*-class amphibious dock landing ship USS *Comstock* (LSD 45) returns to Joint Base Pearl Harbor-Hickam, Hawaii, after participating in Rim of the Pacific (RIMPAC) 2010 exercises. (100729-N-0641S-059 Pearl Harbor; July 29, 2010; U.S. Navy photo by Mass Communication Specialist 1st Class Jason Swink (Released))

This article summarizes requirements and the resulting hardware design for the SSDS upgrade conducted by Combat Direction Systems Activity. SSDS is designed to integrate ships' sensors and weapons to provide sailors with battle management command and control and automated, layered self-defense. The upgraded system for the LSDs is designated SSDS Mk 2 Mod 5C. Having completed the design phase, the Mod 5C project is in development and preparing for combat system certification testing in 2012.

The purposes of the Mod 5C project are to improve the ships' self-defense capability with respect to current threats, to provide an equipment refresh to the class, and to improve the logistics supportability of the combat system during the ships' service life. The upgrade provides improved SSDS Human-to-Machine Interface (HMI) capabilities through the use of touch screen displays, high-definition large-screen displays, and Voice-over-Internet Protocol (VoIP), which will enhance warfighter situational awareness and the ability to direct fire control. Hardware supportability is improved by using open architecture hardware components. Software supportability is improved by bringing these ships into those supported by the SSDS Mk 2 single-source software library. The importance of the single-source library, implemented by Raytheon Corporation, is to make applicable capability improvements or corrections done for any SSDS ship class available to the other ship classes more efficiently. SSDS engineers are working closely with sensor, weapon, navigation, and common processing and console programs to deliver a coordinated set of upgrades to produce a well-integrated warfare system for these ships.

The SSDS Mk 2 Mod 5C system is composed of a command and control table, two network switching cabinets (NSC), CV-4437 Multi-Purpose Enclosures (MPE), two Tactical Computer Consoles (TCC), three Large Screen Displays (LSD), and a Portable Maintenance Aid (PMA) which runs the Maintenance Tool Kit (MTK) application. The network switch cabinet is produced by Raytheon Corporation; the Common Display System (CDS) consoles and Common Processing System (CPS) processor cabinets are procured by PEO IWS 6.

Open Architecture Command Table

Combat Direction Systems Activity (CDSA), Dam Neck, Virginia, part of the Naval Surface Warfare Center, Dahlgren Division, is conducting the design, production, hardware testing, and fielding of the command table hardware for SSDS Mk 2 open architecture baselines. Developed for this project, command table hardware will also be used in the new CVN 78 *Ford*-class aircraft carriers and backfit to other SSDS Mk 2 ships. A depiction of the open architecture command table is shown in Figure 3.

The command table supports three seated operators. It features high-resolution graphics, digital voice communications, video switching for the large screen displays, batteries-release functionality, and integrated tactical chat and Common Operational Picture (COP) display capability. Principal components of the command table are:

- Common Display System (CDS) consoles
- Tactical Computer Console TCC (OJ-830(V)2)
- Electronics Equipment Enclosure (EEE)
- Large-Screen Displays

Operators seated at the CDS consoles use a keyboard, trackball, variable action buttons (VAB) and display monitors for each position. The CDS consoles in the command table design are a modified version of the CDS Variant "B" dual-monitor console. Modification was required to achieve a three-monitor configuration, while remaining sufficiently narrow to place the design within equipment footprint constraints. The right-hand operator position on LSDs, however, will be provided two display monitors vice three because that operator position is immediately adjacent to other combat system equipment.

The tactical computer console is the left-most component shown in the figure. Its purpose is to provide processing power and network devices required for data recording, maintenance actions, and information assurance functions.

The two electronics equipment enclosures sit between the three CDS consoles. Their purpose is to provide processing and network devices in support of digital voice communications, video switching for the large screen displays, batteries-release functionality, and uninterruptable power to the command table in the Combat Information Center (CIC). High-resolution, large-screen displays provide the ability to view tactical displays and other video feeds on large physical display surfaces.

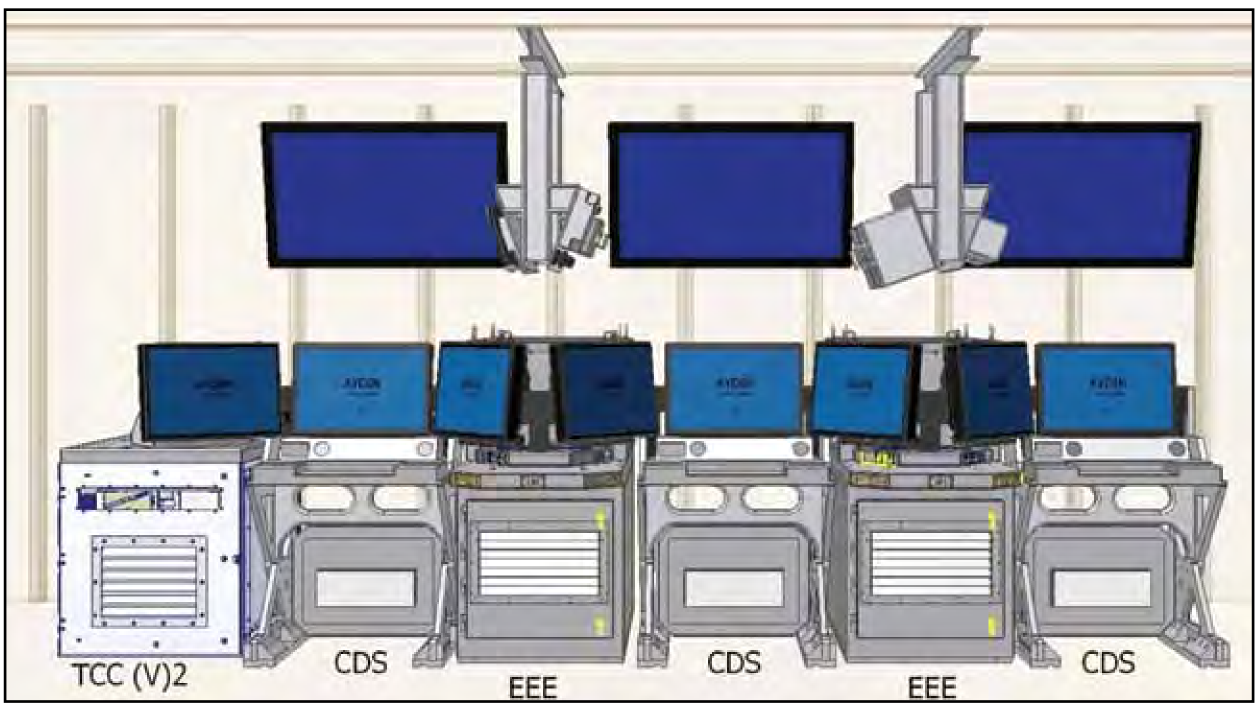


Figure 3. The open architecture command table provides three SSDS Mk 2 operator positions.

Multi-Purpose Enclosure (MPE): SSDS' Digital "Utility Infielder"

The warfare system being fielded for LSD 41 and 49 classes is a cost-effective mix of systems, some of which have been in the Fleet for a long time and some that are under development. During the warfare system design phase, it became apparent that a new, versatile component would be needed to provide an array of interface translations and processor backplanes to minimize the amount of hardware change to core SSDS components. CDSA Dam Neck is developing the MPEs for the Mod 5C project.

The requirements for the Multi-Purpose Enclosure include:

- Support for interface types: NTDS A/B, D, E, 100BaseTX, 1000BaseT, 1000BaseLX and radar video,
- Support for processor backplanes: VME and cPCI,
- Support bulkhead or rack mounting.

The Multi-Purpose Enclosure and its components are shown in Figure 4.

Onboard processing allows the MPE to host SSDS Mk 2 software, which is specific for that interface. The full set of interface options allows the MPE to perform media conversion within the warfare system. Bulkhead mounting is important for this ship class due to the limited deck space available for additional equipment.

Summary

The SSDS Mk 2 technology refresh improves the ships' self-defense capability with respect to current threats, provides an equipment refresh to the class, and improves the logistics supportability of the combat system during the ships' service life. CDSA Dam Neck provides government-owned designs and performs the acquisition and acceptance of Command Table and interface hardware for LSD 41/49 classes, which will also be reused throughout the SSDS Mk 2-equipped Fleet.

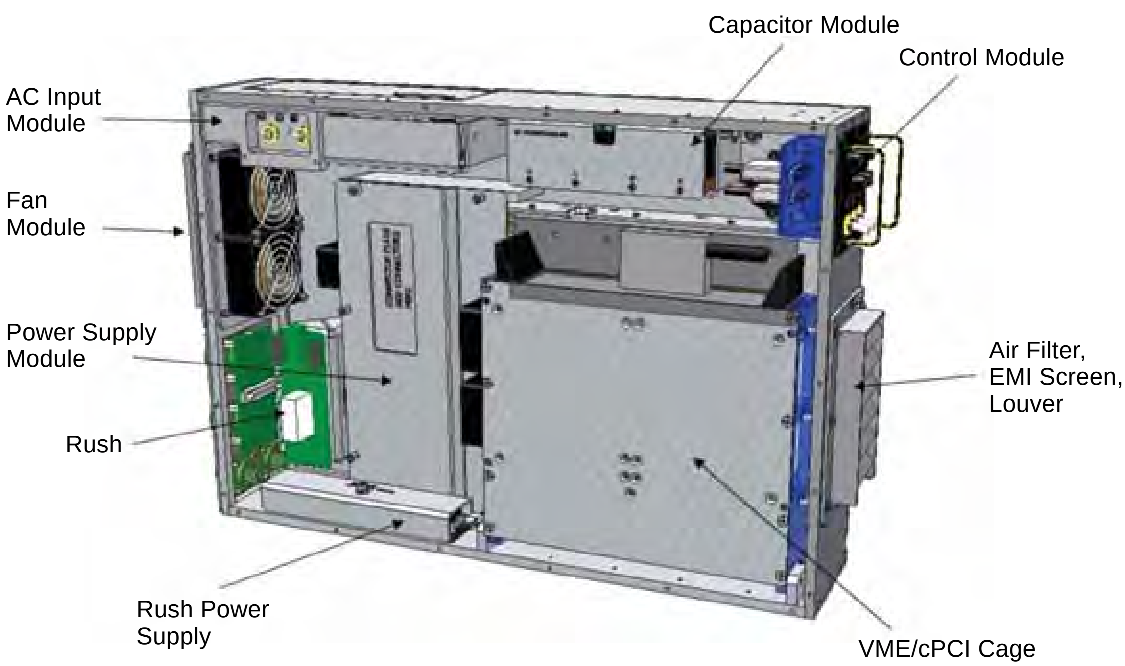
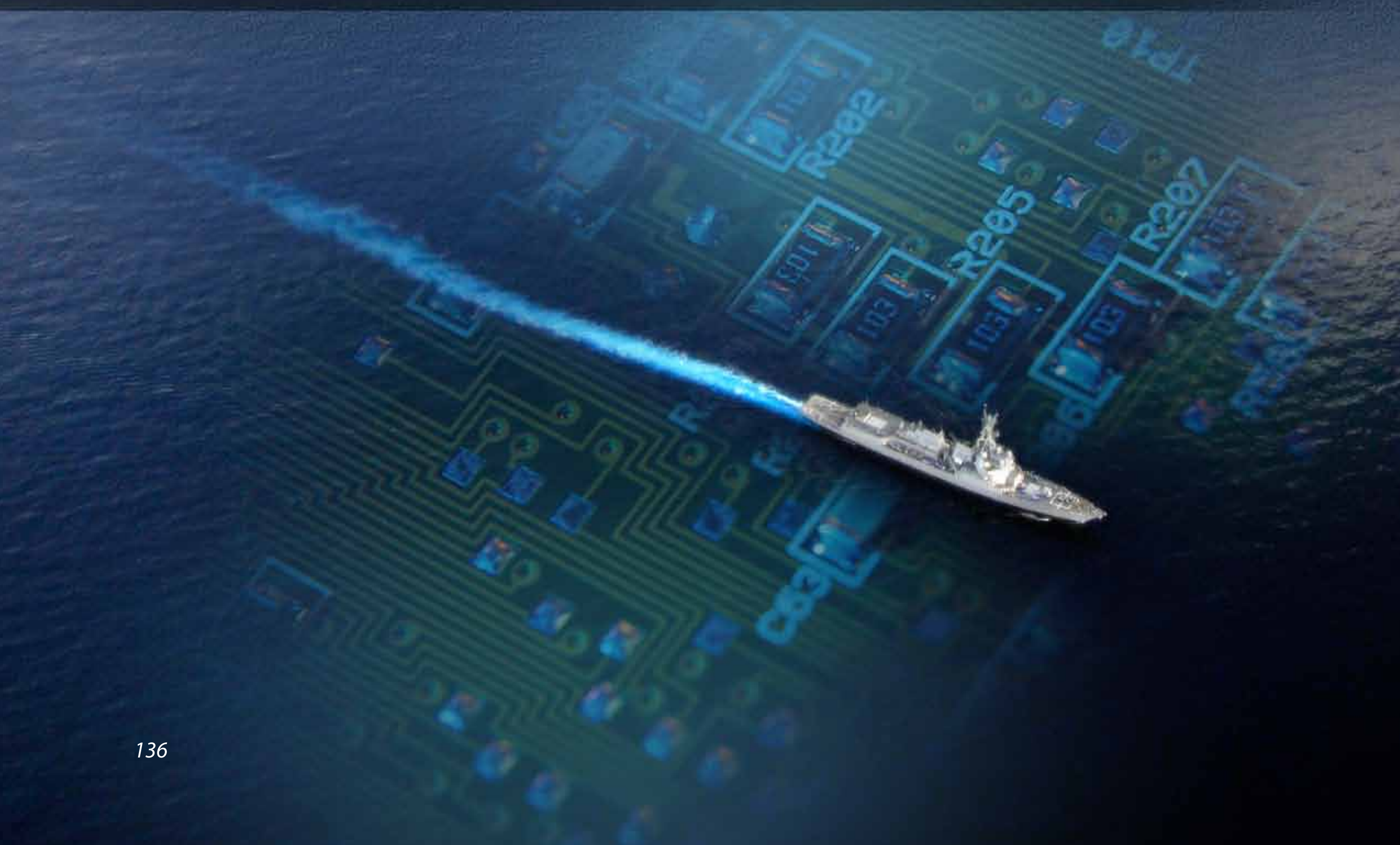


Figure 4. Multi-Purpose Enclosure components provide maximum adaptability within a single design.

Common Architecture System Assurance: Information Assurance for the Next Generation of Combat Systems

by William Ward, Brian Hobson, Adam Simonoff, and Owen Seely



27 April 2014, Gulf of Aden. A U.S. Navy destroyer cruises through the entrance to the Arabian Sea, passing close to war-torn Somalia. The ship is on alert, as recent intelligence reports indicate terrorist cells are working actively in Somalia. In the Combat Information Center, watch standers are keeping close tabs on the systems governing the ship's self-defense battery of sensors, radars, and weapons. At 0937 Zulu, an indicator on a little known but newly installed system named Common Architecture System Assurance (CASA) flickers from green to red, indicating an electronic intrusion attempt was detected in the combat system. The watch officer immediately orders one of the watch standers to open up the CASA display to determine what had happened and to begin any remediation. The operator quickly identifies an attempted hostile probe of the combat system was conducted over one of the external network interfaces but was blocked and reported by built-in safeguards. The watch officer, understanding the probe meant that hostile forces had somehow acquired material enabling them to interface with the combat system, shuts down the affected interface and notifies the Commanding Officer, who orders a full alert, realizing the electronic probe could be a prelude to an attack by slowing or even crippling the ship's combat systems. The ship is well prepared when a hostile incoming contact is detected at 0943.

Fiction? Perhaps now, but in the future, likely to become fact. In leveraging our technological expertise, military platforms have become ever more capable, but conversely, have become more vulnerable to Information Assurance (IA) threats.

The Navy work force has leveraged its unsurpassed ability in software and hardware to create reliable, fast, agile, and effective combat systems. This has been accomplished by building on software that is available to our adversaries, both current and future. Assuring the integrity of software and hardware in combat systems has thus become a matter of life and death. Our enemies know they cannot easily defeat our systems in a straight-up conflict and must find ways to disable or degrade them in order to attack us. CASA is designed to help prevent that from occurring.

What is CASA?

CASA is a specialized Security Information and Event Manager developed by engineers at Naval Surface Warfare Center, Dahlgren Division (NSWCDD), and Combat Direction Systems Activity, Dam Neck. The system is designed to collect, analyze, and report all IA-related events for a system, network or, potentially, an entire platform. By providing incident details, mission-critical impacts, and corrective actions to the warfighter, CASA helps to ensure the integrity of mission-critical Navy systems.

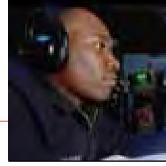
IA Made Simple

To make CASA simple enough for an end-user, Human Systems Integration engineers were involved in the planning, development, testing, and validation of CASA in collaboration with Certified Information Systems Security Professionals and combat systems engineers. CASA allows the warfighter to see at a glance the possible problems, the system effectiveness, and potential workarounds for IA events as they are understood by the subject-matter experts ashore who designed, built, and tested the systems. This ability gives the warfighter a virtual "expert in a box," capable of evaluating the system and assessing the combat readiness and effectiveness of the system. The display is designed to be as intuitive as possible, allowing for quick and concise dissemination of IA information. The basic display, or dashboard view, provides a breakdown of the alert categories that CASA is currently monitoring along with a quick indication of their status. Figure 1 depicts a typical CASA dashboard display.

If an alert were detected, an operator would use the dashboard display to select the category containing the alert of interest. Once this is done, CASA would provide a list view offering all unhandled events in that category. This view provides summary information, timestamps, and priority information for each event (Figure 2). By selecting a particular event from the list view, the operator is presented with a final expanded view offering mission impact information and remediation steps, as well as all of the technical details available to the operator as needed. The alert categories, alert rules, mission impact statements, and corrective actions can all be tailored for the specific IA requirements and system impacts for any Department of Defense (DoD) Program of Record.

DoD Policy Compliance

CASA is designed to meet cyber security laws and DoD policies. The Federal Information Systems Management Act requires government systems to be secure from IA threats. SECNAV 5239.3, Department of the



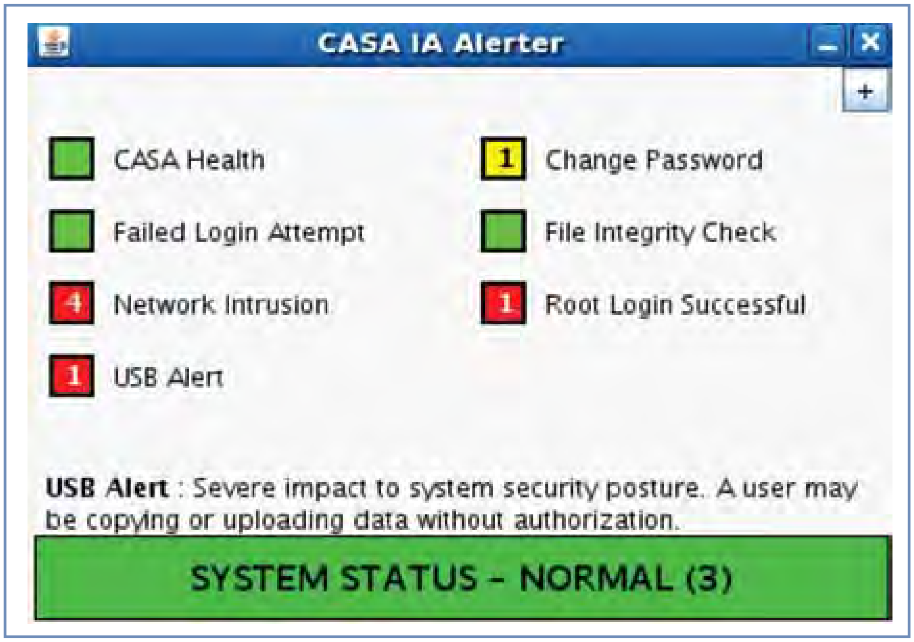


Figure 1. CASA Anti-Cyber-Warfare User Dashboard

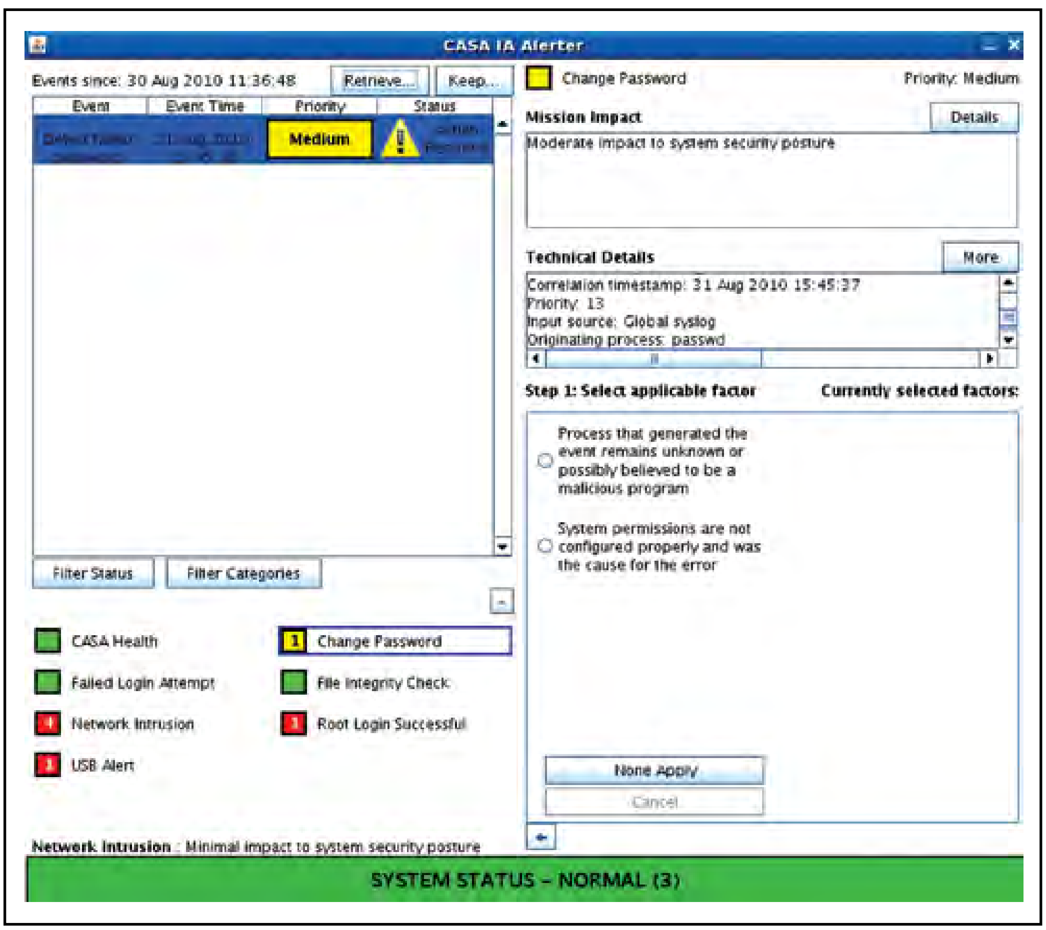


Figure 2. CASA Anti-Cyber-Warfare Detection Details

Navy Assurance Policy, requires Department of Navy program offices to provide IA detection and monitoring capabilities. DoDI 8500.2, "Information Assurance Implementation," requires system engineers to build in mitigations against IA threats. CJCSM 6510.01 CH 3, "Defense-in-Depth: Information Assurance (IA) and Computer Network Defense (CND)," requires warfighters to report IA events to external security authorities in their chain of command. All of these capabilities are part of the services CASA provides.

How It Works

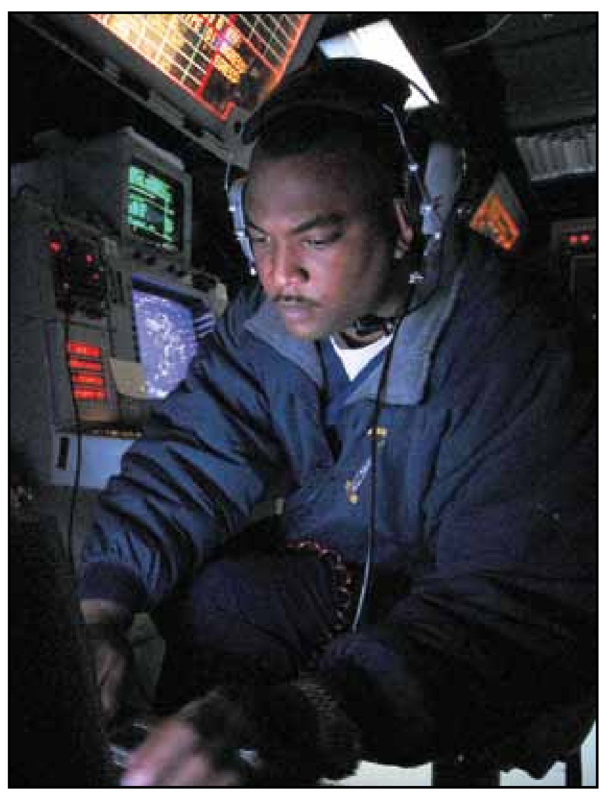
CASA can be thought of as a type of security alarm system for the network. In a traditional security system, sensors are placed around a building to monitor doors, windows, motion, and other signs of intrusion. When these sensors are tripped, an alarm is triggered. CASA functions in much the same way. Sensors are placed on systems around the network that monitor log-in attempts, file corruption, port scans, and other signs of potential attack. In many cases these sensors already exist; CASA is filling in the gap where there had been no central repository and correlation capability that puts the pieces together to detect potential threats to information systems. Attempting to access each individual sensor and make sense of the considerable amount of data each one produces would normally overload an operator. CASA solves this problem by finding the important incidents that need to be elevated to the warfighter's attention. As a result, CASA provides an IA situational awareness capability to the warfighter that has previously been missing. Even the best educated and trained warfighters cannot be experts on every aspect of every system; they especially cannot develop and maintain expertise on all of the esoteric and constantly changing threats associated with IA. The inherent IA language and terminology is obscure and often unhelpful to the warfighter. From an anti-cyber warfare perspective, the bottom line is that CASA supplies the sailor the answers to critical questions such as: Is my ship battle ready? Is my combat system running in a degraded mode? Has the network and/or tactical data been tampered with?

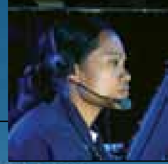
Open Architecture Standards Compliance

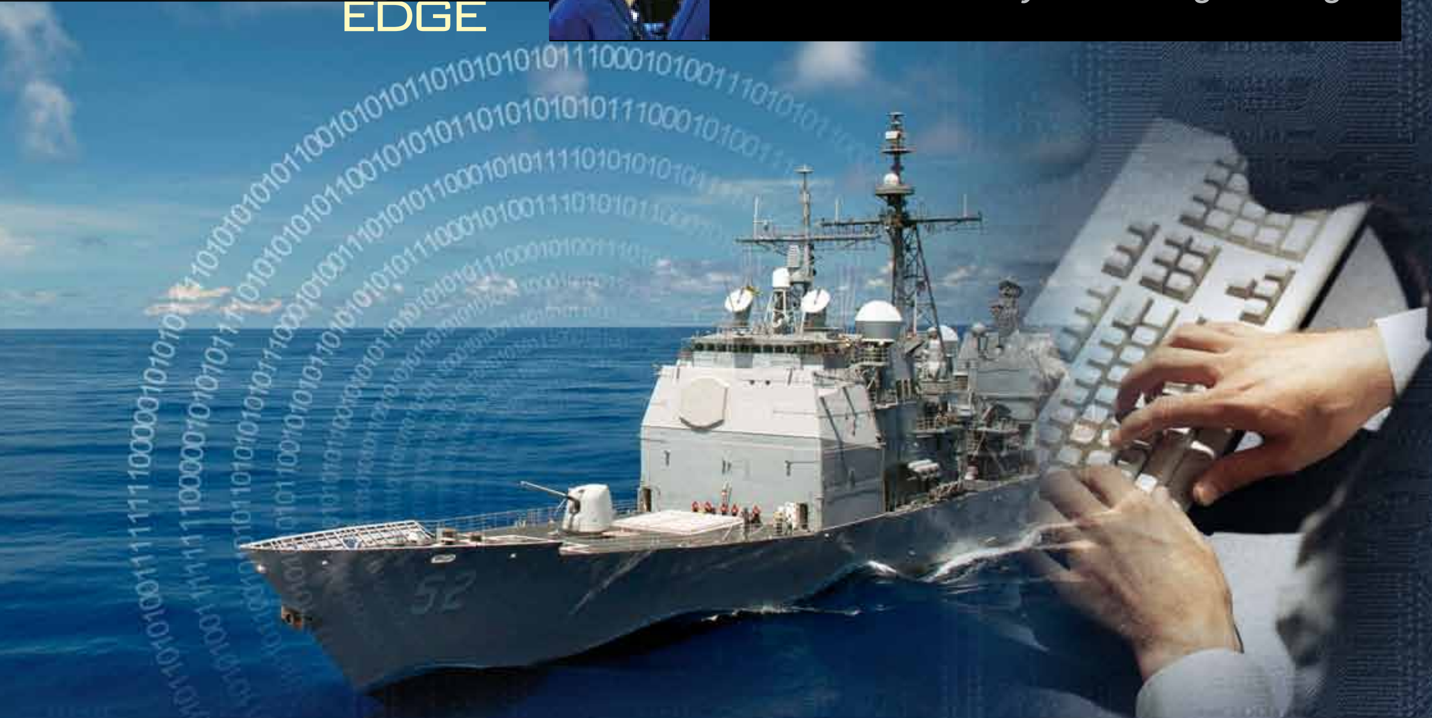
CASA incorporates event data from external devices into its database of monitored IA events. CASA communicates with the sensors that generate raw information about system events through the use of external software connectors. These connectors are responsible for translating and transmitting this event data in a format CASA can comprehend and efficiently process. This approach develops an extensible and adaptive framework that emulates the Open Source Software Development model, where extensions in capability are easily supported and can be shared by all users. CASA can collect data from sensors that use common formats such as Syslog, Simple Network Management Protocol, and Security Device Event Exchange. CASA could also be easily configured to monitor Microsoft Windows events by developing a connector capable of retrieving and converting the Windows-specific format into the consolidated CASA format.

CASA is revamping how the Navy manages IA for deployed systems, while growing and developing new capabilities. Recent features such as built-in redundancy and failover and an automated response capability have been prototyped. Additionally, enhancements for CASA such as real-time trending are planned.

Investment in programs such as CASA will help the Navy defend against emerging cyber threats as we continue to develop new, more capable systems for the Fleet. The threat is evolving; so is our response.







Managing Computing Technology Change for Surface Navy Combat Systems

by Philip M. Irey IV, Leslie A. Madden, David T. Marlow, Greg D. Miller, and Jerry W. Oesterheld

Surface Navy combat systems include complex computing systems consisting of millions of lines of code that must be engineered to meet rigorous mission-critical requirements. Since Fleet deployment spans decades, these computing systems must undergo numerous planned capability upgrades as well as maintenance to prevent or correct problems. Modern combat systems depend upon commercial off-the-shelf (COTS)-based computing environments. The rate of change in these computing technologies far exceeds the development and deployment timelines for the combat systems that employ them. As a consequence, a multitude of challenges exist in leveraging and sustaining COTS technologies in this environment.

This article discusses these challenges, provides examples of how they impact programs, describes architectural and acquisition approaches for mitigating them, and recommends engineering approaches for anticipating and adapting to technology change.

Computing Technology Challenges

Although the life spans of combat system applications used in Navy warships are very long, the COTS computing technologies on which they depend are changing at a rapid pace driven by the commercial marketplace, rather than the lengthy Navy acquisition cycle. Consequently, the Navy must manage problems of obsolescence in its deployed systems. During update cycles, in addition to enhancing warfighting capability, these systems must absorb major requirements and software changes driven by technology evolution. The traditional combat system update cycle spans multiple COTS product evolution cycles. Significant challenges result from requirements and utilization scenario differences between the targeted commercial environments and the combat system environment. COTS products must often be adapted or used in innovative ways because of these differences.

Engineering of combat system computing technology is a key activity for addressing these challenges. Critical aspects of this discipline are foreseeing and managing the impacts of rapid computing technology changes on the combat system, while leveraging these changes to improve warfighting capability. The degree to which the Navy can predict these changes, assess their impact, develop strategies for leveraging them, and influence their future direction will drive sustainment costs and capability improvements.

Evolution of Combat System Computing Technology

The Aegis combat system, which is the most capable, current surface combat system in the U.S. Navy, is deployed on over 80 of the Navy's cruisers and destroyers. The distributed computing infrastructure of Aegis was originally based on military standard computing technology (e.g., UYK-43 computers, Naval Tactical Data System (NTDS) interconnects) but has evolved over time through a series of baselines and upgrades to use mainstream COTS computing technology illustrated in Table 1 and Figure 1.

During the last two decades, the number of processors increased over 12 times while computing power increased over 1000 times. The increased hardware capacity has been accompanied by significant increases in software complexity. While the main focus of the following table and figure is on hardware technology associated with combat system evolution, software technology evolution is also ongoing at a rapid pace.

The evolution of computing technology is inevitable, and it has a profound effect on the development and maintainability of systems that utilize it. In many cases, the selection of particular computing equipment or software is appropriate at the time it is chosen; however, as time passes, it is revealed to have significant, unanticipated consequences because of the evolutionary path of that technology family and the failure to adequately anticipate and plan for that evolution. An additional impact in the selection of a technology path is whether it will result in "vendor lock-in," where future technology refreshes will be restricted to niche products only provided by a single vendor.

Architectural Constructs for Mitigating the Impacts of Technology Change

Managing technology change begins with defining architectural constructs that decouple the evolution of rapidly changing technologies from more stable system functionality. For example, utilizing interfaces that are well defined, tightly controlled, and stable allows the internal design of modular components that use them to evolve independently. Coupling such interfaces with an architecture that incorporates a separation of concerns between application components and the computing technology used by the system can significantly decouple the combat system from the impacts of computing technology change.

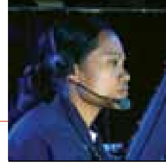
Modular Open Systems Approach (MOSA) and Open Architecture (OA)

The Modular Open Systems Approach (MOSA) established by the Office of Secretary of Defense[1] and Naval Open Architecture (OA) mandated by the Chief of Naval Operations have defined principles that can help mitigate the impacts of change. These principles, described in the Defense Acquisition Guidebook, include the following:[2]

1. Establish an enabling environment
2. Employ modular design
3. Designate key interfaces
4. Use open standards
5. Certify conformance

Table 1. Computing System Technology Evolution

	Baseline 5.1			Baseline 5.3			Baseline 6.1			Baseline 6.3			Baseline 7.1			CR1		
	CPUs	RAM (Mb)	MIPS	CPUs	RAM (Mb)	MIPS	CPUs	RAM (Mb)	MIPS	CPUs	RAM (Mb)	MIPS	CPUs	RAM (Mb)	MIPS	CPUs	RAM (Mb)	MIPS
ACTS	2	20	4	3	96	4	3	96	1,560	3	768	1,800	3	1,500	1,800	3	1,500	18,000
ADS	2	20	4	2	20	4	52	13,312	180	60	30,720	180	60	30,720	2,000	60	61,400	2,000
C&D	2	20	4	2	20	0	6	1,536	0	6	3,072	0	20	5,120	0	20	5,120	0
ORTS																		
SPY-1	2	20	4	2	20	4	2	20	4	16	3,068	484	6	4,584	840	6	4,584	840
WCS/FCS	2	20	4	2	20	0	2	20	0	8	1,044	0	6	3,072	540	6	3,072	540
ACEG	0	0	0	0	0	0	0	0	0	0	0	0	9	2,300	0	9	2,300	0
TOTAL	**10**	**100**	**20**	**11**	**176**	**12**	**65**	**14,984**	**1,744**	**97**	**38,672**	**2,464**	**128**	**47,296**	**5,180**	**128**	**77,976**	**21,380**



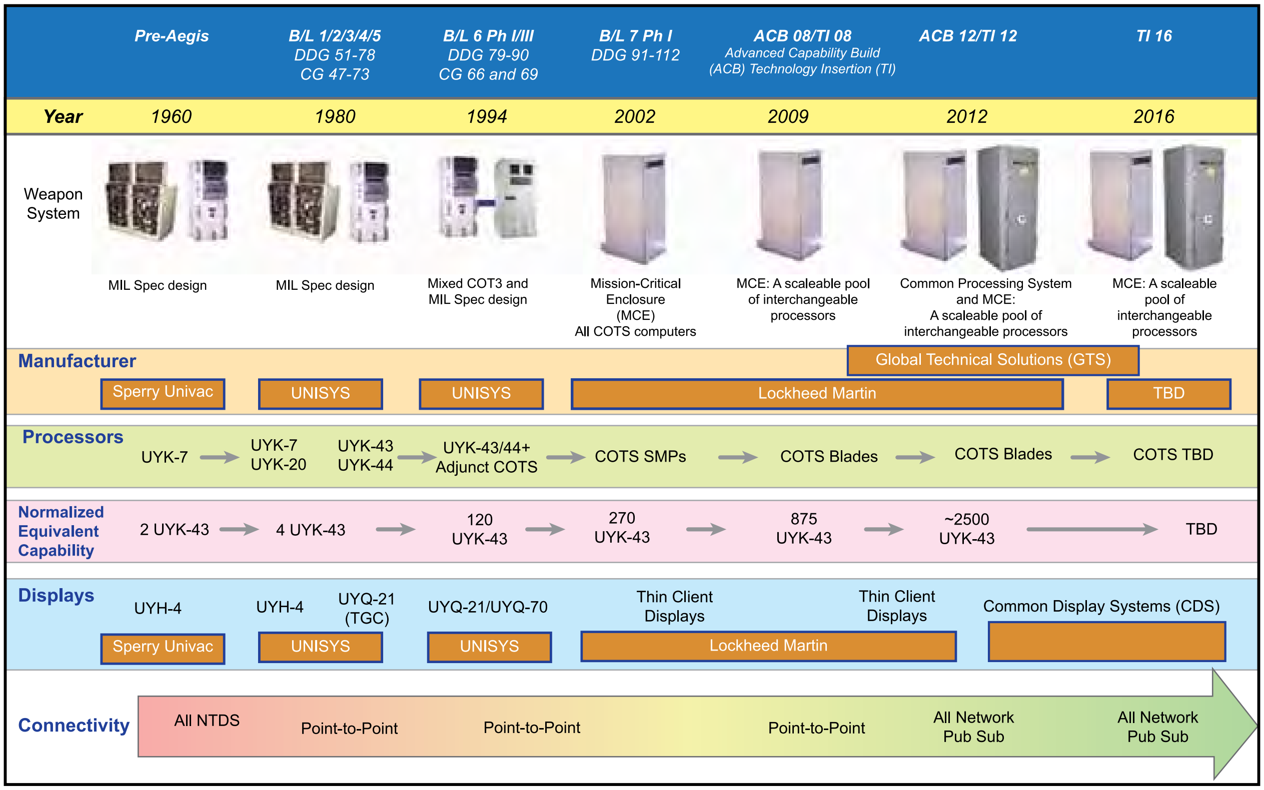


Figure 1. Combat System Computing Technology Evolution

OA principles are compatible with MOSA and include the use of modular design and design disclosure to permit evolutionary design, technology insertion, competitive innovation, and alternative competitive approaches from multiple qualified sources.[3] As part of its implementation of OA, the surface combat system community has been evolving its systems over time to improve their adaptability to the changing COTS landscape. This evolution is gradual by fiscal necessity.

The first phase of OA migration has been to reengineer existing combat systems to use a computing environment based on open standards. Software applications have been modified to decouple them from their dependency on specific custom products, making it easier to replace underlying technology with mainstream products acquired from the commercial marketplace. The second phase includes modularizing the combat system software, which improves the ability to make technology changes in one area without incurring a significant impact on other unrelated software functionality. Figure 2 shows some of the keys aspects in migrating to OA.

Surface Navy Combat System Objective Architecture

The surface combat system community is aligning its combat management systems to a common software product line architecture. Naval Surface Warfare Center, Dahlgren Division, (NSWCDD), engineers have played a key role in the development of the Surface Navy Combat Systems Software Product Line Architecture: Architecture Description Document (ADD).[4] The ADD describes the end-state objective architecture precepts and patterns to be used in architecture development. Many of these precepts and patterns are motivated in part by a need to manage change in the computing technology base on which combat systems are hosted. For example, the ADD describes a component framework pattern that defines a common set of Application Program Interfaces (APIs) providing access to software infrastructure and management services.

This approach allows the computing technology supporting the implementation of those services to evolve in a manner that is decoupled from the APIs. The ADD invokes the use of a multitiered architecture, shown in

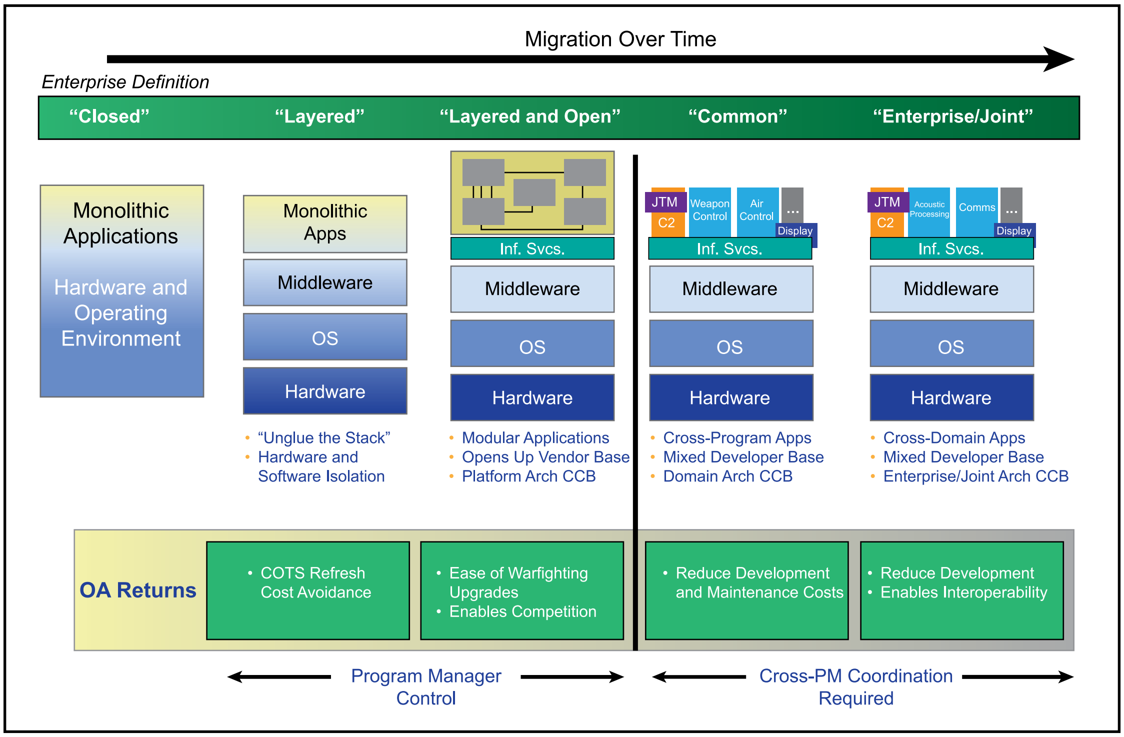


Figure 2. Migration to Open Architecture

Figure 3, which decouples the processing tier from the data tier and the presentation tier. This approach allows the technology for managing data and for presenting information to an operator to evolve separately from the business logic of the combat system.

Acquisition Constructs for Managing Technology Change

The surface domain of the Navy recently established two processes to more effectively maintain and modernize its combat systems. The Advanced Capability Build (ACB) process allows incremental fielding of warfighting capability upgrades to surface Navy combat systems on a 2-year cycle. New and upgraded capability can be deployed based on Fleet need, the readiness of the capability, and the available budget for an ACB. ACBs are decoupled from the upgrade of computing technology, which are managed via the Technology Insertion (TI) process.

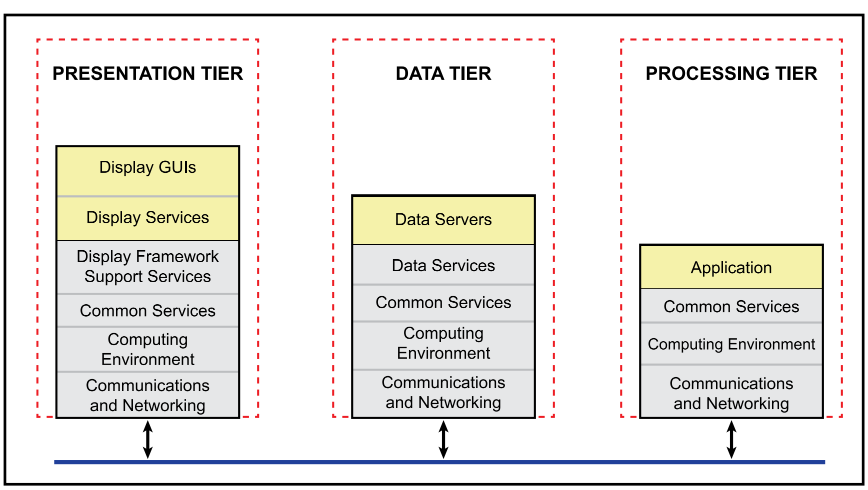
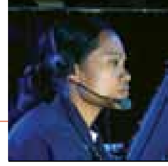


Figure 3. Objective Architecture Multitier Architecture



This TI process is intended to replace and/or upgrade combat system computing hardware and software directly tied to the hardware to take advantage of technology advancement. The Navy develops a new TI baseline every 4 years with each ship receiving every other TI (i.e., an 8-year cycle for an individual ship). The combination of the ACB and TI processes ensures that Navy systems keep pace with computing technology advances and that capability enhancements reach warfighters in a timely manner.

Engineering Constructs for Anticipating Computing Technology Change

To successfully field and sustain combat systems, the Navy must anticipate technology change so it can plan for and adapt to these changes when they occur. Failure to adequately anticipate technology change can have a significant adverse effect on the ability to deploy and support a combat system over its lifetime.

Standards Participation

NSWCDD engineers have successfully shown value by participating in organizations that are defining, enhancing, and maintaining standards for key combat system technologies. In these forums, the Navy articulates its unique requirements for operating and certifying these technologies for use in combat systems. Some key combat system technology areas and the standard bodies that drive the development of those technologies are illustrated in Figure 4.

NSWCDD subject-matter experts (SMEs) represent the Navy in a number of key Department of Defense (DoD) Information Technology Standards Committee (ITSC) working groups that select IT standards for all of DoD.

Engineering Initiatives

An Engineering Initiatives Team at NSWCDD has performed various initiatives to demonstrate uses of emerging technology in combat system domains. In 2009, they demonstrated and quantified the viability of inserting solid state disks into legacy Aegis Weapon System baselines.

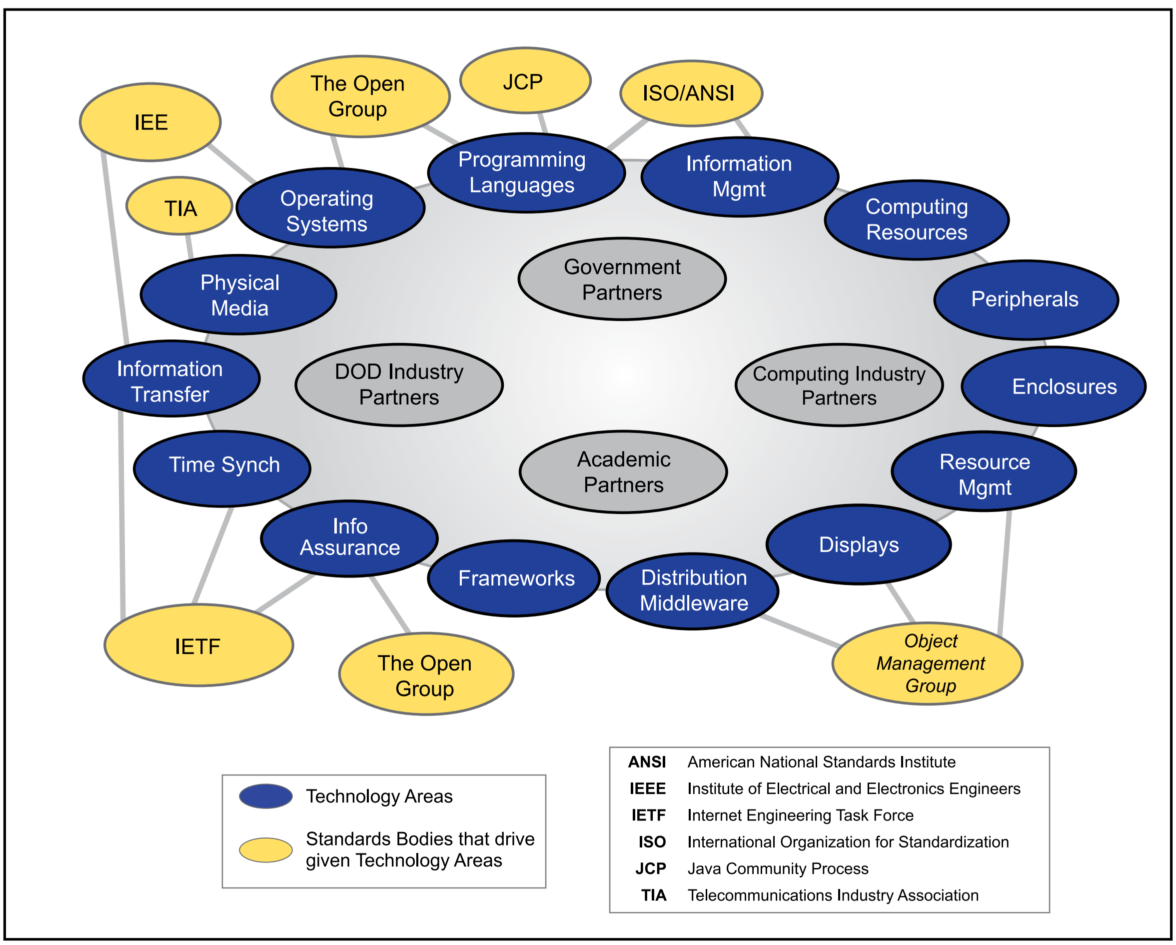


Figure 4. Combat System Computing Technology Areas and Associated Standards Bodies

The experiment showed the advantages of using a solid-state drive, and data from the experiment was used to produce a business case analysis that identified the cost point where total replacement of hard drives with solid-state drives provides a positive return on investment.

Engagement with the Academic Community

Another activity that has proven successful in understanding the long-term direction of computing technologies is working with the academic community. The academic community often focuses on advances in areas whose time horizon is farther out than where the commercial product community is focused. Advances developed may prove to be feasible for incorporation into future commodity COTS products.

Engagement with DoD Research Organizations

Participation with DoD research organizations (e.g., Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research) may enable larger DoD and/or Navy efforts to provide critical information to a participating Navy program in a cost-sharing effort. Working together provides a greater opportunity for the combat system community to influence research activities in a direction that meets their requirements. It also provides a better likelihood of technology transition for the researchers since the resulting technology innovations are targeted to the needs of the combat systems.

Technology Forecasts

For the Navy to mitigate the risks associated with leveraging technology developed in the commercial community, it must anticipate the direction of commercial technology development. While attending trade shows and reading trade journals might give insight into the near- and mid-term directions of these technologies, NSWCDD engineers must investigate other approaches to expand their insight into the mid- and long-term future directions. Technology forecasts written for key computing technologies are one way to gain insight into the mid- and long-term future directions. These forecasts need to be periodically updated and authored by multiple SMEs for each computing technology area.

Relationship Between Engineering and Acquisition Constructs for Managing Computing Technology Change

Figure 5 shows some of the relationships between the engineering and acquisition construct for managing computing technology

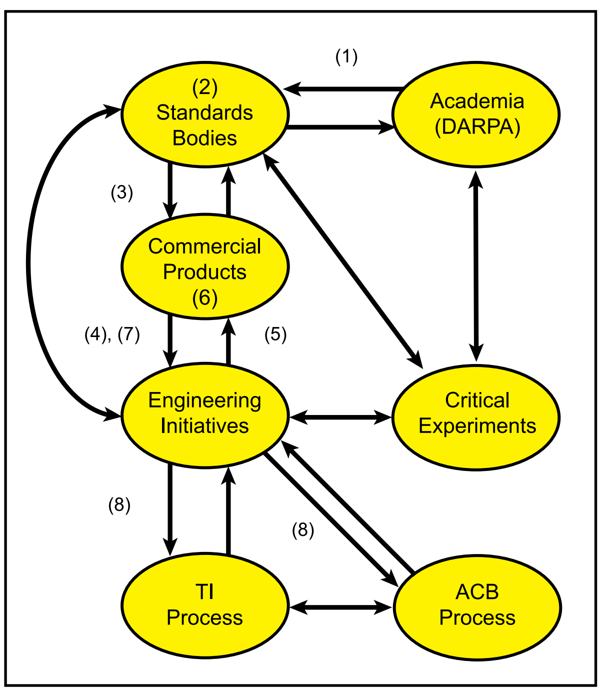
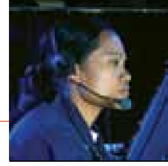


Figure 5. Examples of Relationships Between Engineering and Acquisition Constructs for Managing Technology Change



change. As illustrated, these constructs are highly interdependent.

NSWCDD is engaged at each and every construct. The timeline relationship between the engineering and architectural constructs for managing computing technology change is shown in Figure 6. As illustrated, the relationships between the constructs are highly time-dependent.

Conclusion

NSWCDD personnel are involved in all aspects associated with the management of today's computing technologies associated with the surface Navy's combat systems. The practical experiences associated with current and emerging computing technologies have enabled NSWCDD's engineering staff to take key roles in defining and acquiring the next generation of computing technologies. As a result, warfighters will benefit from more effective and efficient computing system technologies necessary to support surface Navy combat systems long into the future.

Acknowledgment

We would like to thank Neil T. Baron, NSWCDD, for his leadership and guidance concerning the management and integration of computing technology change for surface Navy combat systems.

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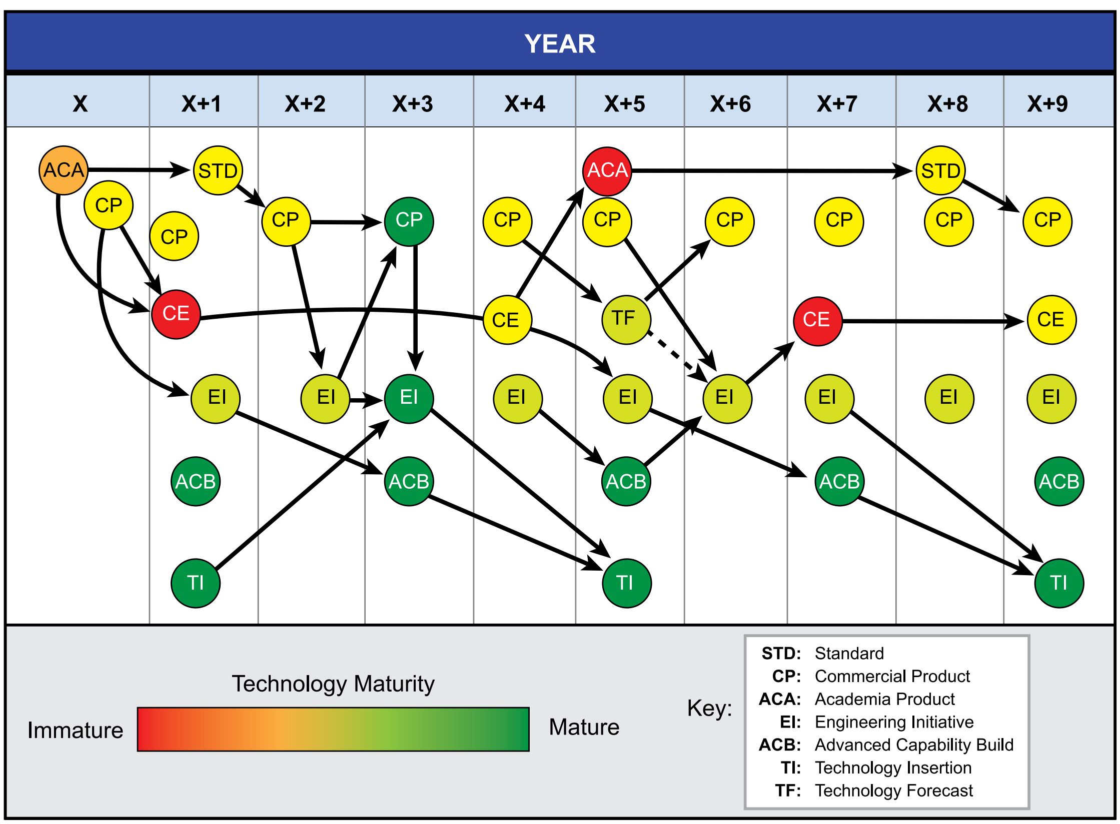

Figure 6. Examples of Relationships Between Engineering and Acquisition Technology Management Constructs over Time

LEADING EDGE

Fallen Warriors

Here we honor those who died while serving their country.

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