Addressing the Design Challenges of Open System Architecture Systems on U.S. Navy Ships – Building Out of the Box

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Abstract

The application of Open System Architecture to U.S. Navy shipbuilding projects has the potential to reduce lifecycle costs and prevent technological obsolescence. However, the proper application of an Open System Architecture results in increased technical design challenges that require a unique systems engineering solution. New approaches are needed to develop open zones and stations that will accommodate multiple systems for various reasons including increased competition, technology refresh, and mission flexibility. This paper addresses the development of open zones that are space and configuration limited, resulting in multiple modules and module stations in a variable geometry zone in order to accommodate the desired open system architecture.

This design challenge is being met through the Architectures, Interfaces and Modular Systems (AIMS) program. This paper provides practical application results of a variable geometry open system design, managed by control of key interfaces on a current ship build.

1.0 Introduction

The U.S. Navy is challenged by the need for an affordable future fleet that maintains its technological superiority over all threats and enemies. The application of Open System Architecture (OSA) to new ship designs has been found to support affordability, increase flexibility, and facilitate technology growth. The proper development and application of OSA has created a need for systems engineering applications that provide modular solutions.

New ship acquisition programs afford opportunities to achieve improved mission readiness, technology refresh and insertion, and reduced lifecycle costs through the incorporation of open systems architecture. One of the principles of OSA is the identification and management of key interfaces. Efforts have focused on developing a means to manage key interfaces through the establishment of modular stations and zones and the use of an Interface Control Document (ICD).

Smaller ships in the U.S. Navy need flexible station/zone sizes to accommodate several modules not driven by production savings. Transition to modular approaches for certain subsystems later in the design phase has necessitated an effort to modularize systems that were not originally designed as modular. This requirement has shown the need for a variable geometry zone, sometimes referred to as “out of the box” modularity. Various reasons other than mission flexibility and production cost savings created this need.

This report documents this new direction in applied ship modularity resulting in flexibility and affordability benefits associated with OSA for the currently emerging and future U.S. Navy fleet.

1.1 Background

The concept of modular open systems design for naval ships has been examined since the 1970s. However, it was not until 1994, with the advent of Acquisition Reform in the U.S. Navy, that an Open Systems Joint Task Force (OSJTF) was established at the Secretary of Defense level to advance the cause of open systems (non-proprietary) and modular architecture across all services. The Office of the Secretary of Defense (OSD) chartered the OSJTF in 1994 to develop a Modular Open Systems Approach (MOSA) and to ensure implementation by all DoD acquisition programs. [1]
1.2 MOSA

The use of MOSA is directed by DoD policy, specifically by DoD Directive 5000.1, dated 12 May 2003, which states that “Acquisition programs shall be managed through the application of a systems engineering approach that optimizes total system performance and minimizes total ownership costs. A modular, open-systems approach shall be employed, where feasible.” [2] MOSA is both a business and technical strategy for developing a new system or modernizing an existing system. The OSJTF developed the *Program Manager’s Guide: A Modular Open Systems Approach To Acquisition* to enable acquisition programs to implement MOSA. [3] MOSA is characterized by modular design, key interfaces, and the use of open standards for key interfaces where appropriate. In doing so, MOSA provides benefits to the delivery of naval combatants, including the latest available technology, affordable lifecycle upgrades and avoidance of obsolescence during the life of the ship.

The Program Manager’s Guide to MOSA outlines five principles that lay the foundation for effective incorporation of modularity and open systems. Figure 1 depicts the overall vision of MOSA, the five principles, and their associated benefits.

**Figure 1. MOSA Principles and Benefits [3]**

The Principles of MOSA are described below:

**Principle 1:** Establish an Enabling Environment. The Program must establish supportive requirements, business practices, and technology development, acquisition, test and evaluation, and product support strategies needed for effective development of open systems.

**Principle 2:** Employ Modular Design. Partitioning a system appropriately during the design process to isolate functionality makes the system easier to develop, maintain, and modify or upgrade. Given a system designed for modularity, functions that change rapidly or evolve over time can be upgraded and changed with minor impact to the remainder of the system.

**Principle 3:** Designate Key Interfaces. MOSA manages the interfaces by grouping them into key and non-key interfaces. Key interfaces should utilize open standards in order to produce the largest lifecycle cost benefits.

**Principle 4:** Use Open Standards. Interface standards specify the physical, functional, and operational relationships between the various elements (hardware and software), to permit interchangeability, interconnection, compatibility and/or communication, and improve logistics support.

**Principle 5:** Certify Conformance. The program should prepare validation and verification mechanisms such as conformance certification and test plans to ensure that the system and its component modules conform to the external and internal open interfaces.

1.3 Modularity Worldwide

Modular adaptable ships are feasible and proven by ships that are operating in the world today. Since the late 1970s, the German shipyard Blohm+Voss has been producing modular-based naval ships known as MEKO®. [4] These ships are designed and built for the German Navy and for export to other countries. MEKO® platforms range in displacement from corvette to frigate size ships. Blohm+Voss has segregated the production process using contractual arrangements with customers and suppliers. Interfaces between the system module and the platform are fully specified and allow each party to work independently of each other. The result of this approach is that module design and production are decoupled from hull design and production, allowing work to be completed in parallel, thereby shortening the production phase. Ultimately, this method has been shown to reduce production cost and completion time. [4]

Another example of modularity in ship design is the Standard Flex concept. Standard Flex uses cross-platform commonality and has successfully designed small combatant platforms to take a variety of containerized equipment and weapon modules. The program was initiated in 1985 to support the Royal Danish Navy in its role of performing a number of different missions with a limited number of ships. [5] A single standard platform was designed, along with a number of payload modules, with the idea of adapting to meet the needs of different missions. Any given
mission was performed by a ship using a specified set of payload modules, and the ships could be quickly refitted to change their missions as different needs emerged. This method reduces mission package change-out time and supports greater mission flexibility. While the Danish Navy has a smaller number of mission requirements than does the U.S. Navy, the concept is still valid for any size navy, and could be readily adapted to the needs of a more mission-diverse fleet.

1.4 Modularity in the U.S. Navy
U.S. Navy Research and Development (R&D) modularity efforts began in 1975 with the SEAMOD program and have since evolved through multiple iterations. The Ship Systems Engineering Standards (SSES) program (1980) was the follow-on program that was formed to continue this research with real world applications on the ARLEIGH BURKE (DDG 51) class in 1985. These initial efforts brought benefits that proved modularity could simplify ship construction and permit modification of weapon loadouts without major ship alterations. More recent efforts to develop engineering standards for modularity continued with the Affordability Through Commonality (ATC) program in 1992. The ATC program evaluated the benefits of not only modularity, but also standardization. Not too long after the establishment of the OSJTF, the U.S. Navy began the Total Ship Open Systems Architecture (TOSA) program in 1998. In 2003, a program for Open Architecture Computer Environment (OACE) was created to address the need for modularity in digital (computer software) systems. Both TOSA and OACE have been focused on developing technical open architectures and interface standards needed for hardware and software implementation, respectively. Finally, the Architectures, Interfaces, and Modular Systems (AIMS) program developed from the TOSA program. Through the AIMS program, the Modular Adaptable Ship (MAS) concept was formed. The U.S. Navy is currently in the design and construction phase of a corvette-sized mission flexible ship, the Littoral Combat Ship (LCS).

For a complete description of the history and various applications within the U.S. and foreign navies and in industry, please refer to “Modular Payload Ships.” [6]

1.5 AIMS
The Architectures, Interfaces, and Modular Systems (AIMS) program is an RDT&E program that is a continuation of previous programs, most notably the ATC and TOSA programs. The AIMS program is managed at the Naval Surface Warfare Center, Carderock Division (NSWCCD).

The AIMS program uses MOSA principles to translate modularity and OSA into total ship acquisition. AIMS promotes increased modularity and use of OSA via standard architectures and interfaces, business case analyses and processes, and outreach and teaming with the Industry and Navy. Goals of the AIMS program include reduced lifecycle costs, technology refresh and insertion, and increased mission readiness. The AIMS program is pursuing a vision of a MAS design and has adopted a phased approach for the development of modular open shipboard systems and/or zones. The MAS concept describes various open functional areas. It splits the ship into various open functional areas including C4I Zones, Weapons Zones, Sensors/Topside Zones, Machinery Zones, and Human Support Zones.

2.0 Applying MOSA using Systems Engineering

Modularity and Open Systems
Open Systems in U.S. Naval ship design is more fully described as “modularity and open systems.” An open system is a system that implements sufficient open standards for interfaces, services, and supporting formats to enable properly engineered components to be utilized across a wide range of systems with minimal changes, to interoperate with other components on local and remote systems, and to interact with users in a manner that facilitates portability. The architecture of system elements, system modules, Seaframe zones and stations, and associated interfaces in an open system is what makes open systems architecture affordable and flexible.

Benefits of Modularity and Open Systems
Incorporating an open systems approach provides lifecycle savings since the application of open systems architecture lowers the cost of upgrades and increases competition. Applying open systems is a maturing approach that can achieve major fleet lifecycle cost reductions without a reduction in fleet performance.

The following list identifies key aspects and benefits of modular open systems:

- Decouples ship and system design efforts
- Supports spiral development concept
- Increases system acquisition competition
- Enhances technology insertion
- Promotes system refresh / update
- Improves maintainability
- Supports mission flexibility
- Allows for rapid change-out
- Reduces production cost
- Fosters lifecycle cost savings
2.1 Choosing Candidates for Modularity
The technical strategy for MOSA is focused on a “systems design that is modular, has well-defined interfaces, is designed for change and, to the extent possible, utilizes widely supported industry standards for key interfaces.” [3]

Previous tradeoff studies have identified the following system groupings that have the greatest potential to produce savings when modularized or opened:

- Command and control
- Weapons systems
- Sensor systems
- External communications
- HVAC systems
- Organic off board vehicles
- Open stowage spaces

The first three areas listed above can be grouped under Warfare Systems. The remainder of this paper focuses on the AIMS Systems Engineering Process and its application to develop an ICD for a Warfare System.

2.2 Developing an ICD
Typically, the government develops an Interface Control Document (ICD) to define the standards and interfaces that will control a contractor’s, or multiple contractors’, design and fabrication. In the case of Navy ship design practices, the ICD is applied to both the platform and the prospective sub-system designs. In order to ensure that the ICD requirements support both the platform capability and the sub-system requirements, the Navy performs market research and, when necessary, engages prospective sub-system suppliers.

By establishing an ICD, the government maintains configuration control of key shipboard systems and ensures interoperability and interconnectivity with multiple Seaframes, if desired. In addition, the ICD acts as a primary mechanism for providing Open Systems Architecture to a design. Finally, the ICD contributes to parallel development of the subsystem and the Seaframe.

3.0 AIMS Systems Engineering Process Methodology
The development of effective modular open systems is highly dependent upon following a rigorous systems engineering process. A Systems Engineering Management Plan (SEMP) is established early-on to help guide task development. The SEMP usually includes a task flow chart that maps subtasks to products and may also include a work breakdown structure that clearly separates out tasking by organization and/or individual(s).

The AIMS program follows the systems engineering approach diagrammed in Figure 2. Requirements are generally defined by high level program documents (e.g., Initial Capabilities Document, Capabilities Development Document, etc.), while market research determines possible system and components choices to satisfy those requirements. The combination of market research and design requirements is used to support the development of high level reference models and open architectures. Reference models will lay out valuable information on systems’ (or system components’) interoperability and interfaces. As the design process continues, open system architectures are developed and key interfaces are identified and defined. This, in turn, leads to the development of ICDs and the ability for technology insertion into the design as it matures.

![Figure 2. AIMS Systems Engineering Process](image)

The following methodology uses the AIMS Systems Engineering process to determine where it makes sense to use modularity and open standards. This approach ultimately leads to the development of an ICD that best meets the requirements of the Navy.

3.1 Requirements
Prior to system design and development, system requirements must be established. These requirements must flow down from high-level documents and establish allocated mission functions assigned to specific ships. For U.S. Navy ships, these high-level requirements are defined by several documents including the Initial Capabilities Document, Capabilities Development Document, General Specifications now provided by the American Bureau of Shipping Naval Vessel Rules (ABS NVR), and other regulations. As for developing an ICD, requirements are generally defined by breakdown and partition of the high-level program documents. There are also a number of commercial and government documents referenced within the ICD. The requirements serve several functions:
Technology Management – Defining requirements involves technology management. Parallel development of the overall ship design and systems to be applied to the ship are simultaneously taking place. It is essential that the systems engineering process continue throughout the design to ensure that parallel development remains on schedule and that they will converge upon completion.

Market Surveillance – An adjunct function of requirements development is Market Surveillance. This is the identification of available technologies from both commercial and government markets. The use of commercial systems and products necessitates integration of the unique and customized needs of the Navy into the open system architecture interfaces. For the AIMS process, market surveillance and subsequent analysis of the specific products are performed throughout the development of the open architecture and are repeated with more detail as the design progresses.

Technology Projection – Establishing requirements that will accommodate technology growth both during development and post development is essential to successful system engineering. This requires continuous attention to all levels of technology for possible downstream systems and products. Technology readiness levels (TRLs) are periodically updated and provide an assessment of the maturity of an evolving technology. Consideration of TRLs allows projection of interfaces that will be needed to incorporate emerging technologies.

The Requirements step of the process includes an upper level decision or specified direction to use modular architecture, of some type, for systems and subsystems under consideration.

3.2 Functional Analysis
The next step of the AIMS process is to perform a functional analysis. Functional Analysis translates the ship’s missions, performance, goals, and other requirements into discrete and well-defined functions. The functions must be divided into logical sequences, with higher level functions supported by lower level functions, and performance must be allocated from high-level to low-level. Functional analysis provides a view of an entity decomposed into elements that can be considered as common functional segments while maintaining interfaces with the total entity. Functional analysis can be considered a two-step process that includes functional partitioning of an entity followed by functional allocation of systems.

The products of functional analysis include Reference Models, which present a high-level, generalized view of a system and related subsystems. In addition, Key Interface definitions are produced that provide the points of control for ensuring the system, as developed, meets requirements.

In order to illustrate the AIMS Systems Engineering Approach, the following provides an example analysis for developing an open shipboard architecture to support an open system warfare system.

Functional analysis begins with separating an entity (e.g., ship, system) into high-level functional categories. In this example, warfare systems are generally partitioned into three categories: detection, command & control (C2) and engage. Functions are broken down to the appropriate level, often to sub-functions and functional elements, depending on the range of functions addressed by the entity. Functional elements contain detailed descriptions of a system’s functions at a level which allows the allocation of system components (i.e., equipment) to these individual elements.

Functional Partitioning
The functional partition separates the system into elements that can be considered as common functional segments while maintaining interfaces with the total system. A functional partition has three notional “levels” identified below:

- Level 1 - Top level or total system level
- Level 2 - Major functions of the system
- Level 3 - Sub-functions of each major function

Figure 3 illustrates a notional functional partitioning of a ship’s warfare system.

![Figure 3: Functional Partition – Warfare System](image)

Functional Allocation
Functional allocation is the process that assigns systems, subsystems, and components to perform each function. The allocation process assigns notional
subsystems to accomplish each sub-function, functional element or several descending functional elements of the functional partition. Major subsystems are identified and allocated to their applicable higher functional levels; major subsystems can also have subsystems and components that can be allocated to the sub-function/functional element levels beneath. Examples of Level 2 warfare system functional allocation include:

- Detect - RADAR, Electro-Optical (EO), Infrared (IR), Electronic Support Measure (ESM), SONAR, Identify Friend or Foe (IFF)
- Control - Combat Management System (CMS)
- Engage - Gun Fire Control System (GFCS)

Next, lower tier sub-system types are identified and allocated. Lower tier subsystems allocated to lower functional levels have subsystems and components that can be allocated to the sub-function/functional element levels beneath. Examples of Level 3 warfare system functional allocation include:

- Detect/Sense - Chemical, Biological, Radiological (CBR)
- Control/Situational Awareness - Tactical Data Links (TDLs), Global Command and Control System (GCCS)
- Engage/Execute Engagement - Guns, missile launchers, countermeasures

The example warfare system functional allocation is best illustrated by overlaying the designated warfare subsystems on top of the functional partitions. This functional allocation is shown in Figure 4.

**Figure 4: Functional Allocation - Warfare System**

Warfare system subsystems from the functional allocation example are summarized in Figure 5.

**Figure 5: Warfare System Subsystems**

**Benchmark Analysis**

After the functional allocation is performed, a “Benchmark” effort is carried out to choose several candidate subsystems to satisfy the functional allocations. The benchmark effort involves selecting several subsystems currently in use on existing ships, followed by conducting market research of potential additional subsystems. These additional candidate subsystems will typically include some emerging technology systems. This analysis provides important details necessary for building the Technical Architecture and defining key interfaces for the Warfare System and Seaframe design.

**3.3 Technical Architecture**

Developing the proper Technical Architecture is a key step in the AIMS process toward enabling the Seaframe to support modular open systems. The Technical Architecture provides a view of the system in terms of functional allocation, standards, interfaces and design rules. For a modular ship, the Technical Architecture also includes a definition of modular spaces and arrangements. These shipboard spaces fall into “zones”, which are defined and prioritized by the following:

- Function
- Physical Requirements
- Service Provision
- Ship Integration Compatibility

A zone is defined as a volume of the Seaframe that provides space, structural support, and services required to perform a function, or a group of similar interchangeable functions located therein. Zones share the following:

- Similar Environment
- Similar Functions
- Bundled Services

Zones include one or more stations designed for specific interface with systems and sub-system components. Stations have a configured structure with support service connections (e.g. electrical, mechanical, data and fluids) provided by the Seaframe to install corresponding subsystem(s) or sub-system
components. Stations have several attributes which are identified below:

- Include defined interfaces
- May encompass the entire mission zone, or be a smaller part of the zone
- May support a single subsystem, multiple subsystems, or components of subsystems

The warfare systems can be designed into the ship using one of the following three approaches:

**Conventional/Non-Modular Design** – Uses traditional ship design methods.

**Closed or Open Containerized Modular Design** – Applies use of fully outfitted containers (“modules”) that generally come in standard sizes. This form of modularity has been used for a variety of reasons that include reducing production cost and providing mission flexibility.

**Variable Geometry Open System Design** – Breaks down the system into components that fit into zones and stations within the ship design. The ship then provides the necessary interfaces to the zones at the stations as identified within an ICD.

In somewhat mature conventional/non-modular ship designs it was observed that the warfare system zones can be transformed into a variable geometry open system design by controlling key interfaces at the subsystem and component level. In this case, variable geometry stations can be developed that accept deconstructed warfare subsystem modules into subsystem components.

The zones defined in our example warfare system analysis are shown in Figure 6.

Table 1: LCS Flight 1 Warfare System Zone Types

<table>
<thead>
<tr>
<th>Zone Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topside Sensor and Communications Zone</td>
<td>Supports station(s) for interface with apertures and wave guides for Radars, EO/IR, and other sensors; and communications equipment located on masts and topside superstructure.</td>
</tr>
<tr>
<td>Underwater Sensor Zone</td>
<td>Supports hull penetration fixed Sonar systems with transducers and hydrophones.</td>
</tr>
<tr>
<td>Deployable Sensor Zone</td>
<td>Supports winches and interfaces for deployable sensors like a towed array Sonar.</td>
</tr>
<tr>
<td>C2 Zone</td>
<td>Supports control functions for warfare systems and provides Human Systems Integration with the warfare system.</td>
</tr>
<tr>
<td>Weapon Zone</td>
<td>Supports Gun and Missile mounts as well as adjacent support spaces.</td>
</tr>
<tr>
<td>Electronics Zone</td>
<td>Supports sub-system components that are not located in the primary use zone of the subsystem.</td>
</tr>
</tbody>
</table>

3.4 Interfaces

After selection of the technical architecture, key interfaces must be defined. Key interfaces are those interfaces that are controlled to allow modular or open system development, whereas non-key interfaces are within a system or subsystem but do not interface with the Seaframe. Key interfaces must be defined and controlled both functionally and physically. The implementation of this control is achieved through an ICD. Notional functional and physical interfaces are summarized in Figure 7.
Interfaces - Functional
- Structural
- Weight
- Dimension
- Access
- Electrical Power
- Service Voltage
- Power
- Data Protocol
- Data Word
- Baud Rate
- Interior Communication
- Sound Powered
- General Announcing
- Data
- Exterior Communication
- Local
- Core Ship
- Material Compatibility
- Grounding / Bonding

Interfaces - Physical
- Structural
- Bolts
- ISO Connectors
- Welds
- Access
- Removal Plates
- Electrical Power
- Power Connector
- Data Protocol
- Connector Types
- Interior Communication
- Connector Types
- Exterior Communication
- Connector Types
- Wave Guide
- Material Compatibility
- Metals
- Composites
- Grounding / Bonding
- Braid
- Studs

Figure 7: Functional and Physical Interface Types

Interface Control Document
An ICD identifies, describes, and controls all key interfaces between the Seaframe and an installed component or system. In general, an ICD can provide the following benefits:

- Establish open systems design to address the entire ship design cycle (including life of ship)
- Establish a Technical Architecture for Seaframe integration
- Allow for independent development of the Seaframe and system

A variable geometry open systems ICD extends interface control beyond the system and ship and into the system components and shipboard stations/zones, respectively. This layer of interface control introduces the following benefits (in addition to those listed above):

- Provide for different levels of modularity to be applied
- Provide additional interfaces for control that might not have been available using a “traditional modular approach.”

A typical ICD controls all aspects of the system required for installation. A variable geometry ICD controls, at a minimum, all interfaces required to establish the Technical Architecture, and depending on the level of modularity, may define lower level interfaces as well.

In order to develop an ICD, three levels of interfaces must be considered for controlling the Technical Architecture. These levels are overall Seaframe station interfaces, Seaframe installation interfaces, and subsystem-to-subsystem interfaces. Table 2 lists some example key interfaces for each category, but is not intended to be all inclusive. It is important to note that not all interfaces identified in the reference model are required to be defined on the Seaframe side, but rather that the Seaframe designer and system designer know the interfaces exist and are required for proper performance.

<table>
<thead>
<tr>
<th>Interface Types</th>
<th>Key Interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Level Seaframe Station</td>
<td>Footprint</td>
</tr>
<tr>
<td></td>
<td>Space</td>
</tr>
<tr>
<td></td>
<td>Power</td>
</tr>
<tr>
<td></td>
<td>Access</td>
</tr>
<tr>
<td></td>
<td>HVAC</td>
</tr>
<tr>
<td></td>
<td>Seaframe Data</td>
</tr>
<tr>
<td>Detailed Seaframe Installation</td>
<td>Mounting Patterns</td>
</tr>
<tr>
<td></td>
<td>Electrical/Plumbing Connections</td>
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<tr>
<td></td>
<td>Data Connections</td>
</tr>
<tr>
<td></td>
<td>Shock/Vibration</td>
</tr>
<tr>
<td></td>
<td>Environment</td>
</tr>
<tr>
<td>Sub-System to Sub-System components</td>
<td>System Data</td>
</tr>
<tr>
<td></td>
<td>System Power</td>
</tr>
<tr>
<td></td>
<td>System Connections</td>
</tr>
</tbody>
</table>

Using a variable geometry open systems design, interface control at the component level allows for modularity at the station level. Interface control at the component level is best demonstrated by using a reference model. The ICD should include a reference model that shows the inter-relationship of the stations’ sub-system components with each other, other stations, and the Seaframe; it should also identify key interfaces.

3.5 Verification
The reference model and Technical Architecture must be compared against applicable systems to verify the required interfaces at all levels. This step ensures that the reference models are reviewed against the actual systems and inconsistencies and required interfaces can be verified. Sub-system interfaces could be verified at the factory level.

3.6 Methodology Summary
The above steps were described for a notional small combatant (corvette-sized), single mission ship with a reconfigurable mission zone. The design was significantly mature and the ship small enough in size that typical boxed, single sub-system modules could not be used and the variable geometry stations and modules were selected for this application.
4.0 Application
Applying the AIMS Systems Engineering Process described herein, a close-in weapon (CIW) ICD was developed for cross-platform application. The CIW ICD details the zones and interfaces required for the Seaframe to support multiple potential CIWs. In addition, for this particular application, an ICD was developed to support a modular open system application on a ship design that was mature in its design cycle.

4.1 ICD Requirements
A warfare system ICD must include core combat systems and command and control systems interfaces consistent with the ship’s overall mission requirements and Initial Capabilities Document and Capabilities Development Document. ICD requirements are generally defined by these higher level program documents. There are also a number of commercial and government documents referenced within the ICD, including requirements addressing the level of modularity and the use of open standards.

4.2 CIW Functional Analysis
Functional analysis of the CIW is comprised of two key areas: functional partitioning and functional allocation.

Functional Partitioning
The functional partitioning of a warfare system can be broken down into several levels. Level 1 is the top system level and in this case is simply the warfare system. The follow-on levels describe the functional breakdown of the warfare system and its components. Level 2 is comprised of three primary functions: detection, C2 and engage. Each of these primary functions is then further broken down by sub-function under Level 3. For instance, the primary function of engage includes sub-functions of refine plan, execute engagement and assess. Figure 8 depicts the functional partitioning of the warfare system engage function.

Figure 8: Example Functional Partition

Functional Allocation
At this stage of the functional analysis, warfare subsystems can be allocated to the functional partitions shown in Figure 8. For the execute engagement function, a number of warfare subsystems are identified including guns, missile launchers and countermeasures. Figure 9 provides an example functional allocation of the warfare system execute engagement sub-function.

Figure 9: Example Functional Allocation

The execute engagement functional allocation consists of a diverse range of system types from a vertical launch system to a medium caliber gun to a decoy launching system. These systems perform vastly different engagement functions. The remainder of this paper will focus on the close-in weapon (CIW) Warfare System. A CIW is designed to engage anti-ship cruise missiles, aircraft and surface craft at short range.

Market Research/Benchmark Analysis
In order to move forward with a warfare system’s Technical Architecture, a benchmark analysis should be performed. In this particular case, the benchmark analysis begins with identifying those technologies that are readily available and fit the requirements of a CIW. The benchmark analysis can then move forward to include systems that are under development, but that meet a certain TRL, which is usually set by the customer (e.g., the ship program office).

As part of the ICD development process, three CIW systems were identified as being readily available and meeting the needs of the customer. In addition, a preliminary analysis was performed to verify Seaframe design constraints (such as weight, space, power, etc.) were met due to the advanced stage of ship development.

4.3 CIW Technical Architecture
The CIW is a subsystem that can benefit from a modular design due to competition and availability factors in today’s market. Installing a containerized CIW open/closed module is a potential option for achieving those benefits on an early stage ship design. However, for a mature combatant design, the customer is forced to establish a unique arrangement of stations and zones that allows flexibility in design; such is the case under a variable geometry open system design. The variable geometry open system design allows substantial design flexibility under the space and weight limitations typically encountered.
when designing a surface combatant. The key to achieving the benefits of this modular approach lies in the execution of the following:

1. Designation of functional component areas
2. Establishment of an open architecture design with warfare system and corresponding Seaframe zones and stations
3. Identification and definition of key interfaces at the sub-system and component level.

Completion of the first two steps falls under the development of the Seaframe warfare system Technical Architecture, while the third step is covered under MOSA Principle Three, “Designate Key Interfaces.”

Functional Component Areas
Upon completion of the functional analysis, the three different CIW systems identified during the benchmark analysis were divided into their common components. Components that perform a similar function (e.g., localized weapon control) are grouped into the same functional component areas. Figure 10 illustrates this for the CIW.

The functional component areas identified for the CIW are the above deck equipment, local control, remote control and auxiliary equipment. Component areas may contain more than one piece of equipment for each system benchmarked. For those instances, equipment is grouped into one area based upon certain physical characteristics, functional characteristics and/or their placement in a particular zone or station.

Creating functional component areas helps form the proper setting for the Seaframe’s variable geometry open systems design. This type of modularity breaks down the CIW system into functional elements that are common to multiple systems, such as weather deck components, below deck components, and remote components. Once the functional component areas are designated and populated with potential system components, the technical architecture details (e.g., locations for zones and stations) and interface definitions (e.g., service requirements) required for a variable geometry open system design may be developed and managed.

Zones and Stations
A CIW variable geometry open system design uses multiple zones and stations to accommodate various CIW modules. A zone can be a single compartment or located in multiple adjacent compartments. A zone includes one or more module stations and additional spaces and services that support modular equipment. CIW module stations are the specific volumes that provide the structure and support service connections in the Seaframe to receive CIW components. The CIW zone and stations could allow for future CIW system change-out/upgrades to the maximum extent practical. The major subsystem component areas of the CIW and the stations that support them are shown in Figure 11.

The CIW Above Deck Station is an exterior station residing in a weapons zone. This weapon station is to be located in a manner that allows for the firing of a gun or missile system. The area above and around this topside station must remain clear of any object that would restrict the firing of any gun or missile system to be installed. The CIW Electronics Station contains modular subsystem components including local control and support components that are typically located near the launcher/gun. The CIW C2 Station should be a remote station located in the ship’s Combat Information Center (CIC) or equivalent space.

4.4 Designating Key Interfaces
Following the establishment of stations and zones, criteria must be established for identifying key interfaces for the CIW Warfare System and Seaframe. CIW key interfaces were selected based on the following criteria:

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**Figure 10: CIW Arrangement**

**Figure 11: CIW Block Diagram**
• Where the technology for the system components is evolving
• Where the system components have high usage rates and are often replaced

Under these criteria, the interfaces between the Seaframe and the components of the CIW Warfare System are designated as key interfaces and are controlled and managed through an ICD. Key interfaces use open standards, when available, and are defined for a range of components and solutions, allowing for several alternative systems to meet the requirements.

A variable geometry open system design is distinct from other modular design approaches in how it designates key interfaces. Under the variable geometry modularity example described herein, Seaframe key interfaces are established at a high-level (space, weight, power) for the CIW above deck station, CIW C2 station and the CIW electronics station. Additionally, lower level key interfaces for the CIW are established at the system, subsystem and component level depending on the Technology Management/Technical Architecture requirements. This information is best presented, controlled and managed via a detailed installation control drawing that defines key interfaces for specific installations.

Interface Control Document
As previously stated, a variable geometry ICD, as opposed to a typical installation ICD, controls the interfaces required to establish the Technical Architecture and may go further to control lower level interfaces, if required. With the Technical Architecture established by the variable geometry ICD, lower level ICD documents provide installation requirements for systems/components and ship stations.

Based on the criteria for designating CIW key interfaces given in Section 3, the CIW ICD must account for various types of key interfaces including geometric interfaces (e.g., space), interfaces between the CIW weapon stations and the ship’s hull systems (e.g., electrical power), human interfaces (e.g., manning), and design standard interfaces (e.g., shock). For the shipboard systems that the CIW interfaces with, both functional requirements and physical connections are important parts of the design.

The ICD should include a CIW reference model that shows Seaframe and system interoperability and interfaces. The reference model shown in Figure 12 is an expansion of the CIW block diagram. This reference model displays the relationship of the three generic key interfaces, as described categorically in Table 2. The interfaces shown represent all of the key interfaces that would be defined in an installation type ICD. For variable geometry, Figure 12 shows the interfaces (Seaframe Station – black; Seaframe Installation – green; Sub-system to Sub-system – red), which may affect the Technical Architecture for the CIW.

Using the reference model, the Technical Architecture is refined, allowing for the applicable system to be reviewed against the reference model to determine the variable geometry interface control requirements to establish the Technical Architecture.

4.5 CIW Verification
Using the reference model, the three existing CIW system designs were reviewed to ensure the Technical Architecture was comparable with existing systems; this review confirmed that all three applicable CIW systems conformed to the Technical Architecture.

In addition, the CIW example showed that lower level interface control was not required; the Technical Architecture could be implemented by defining only high-level station requirements. This allowed the Technical Architecture to be established at a minimum cost to the acquisition program. This also allows the system to be upgraded at a later time with minimum impact to cost. By establishing the overall Technical Architecture, the variable geometry ICD helped balance upfront acquisition cost versus lifecycle upgrade costs.

When working with a variable geometry open systems ICD, the customer can avoid major ship impact changes, even if the ship is further along in the design cycle, by developing a Technical Architecture within existing design constraints. By defining key interfaces at specific stations within zones, relatively minor alterations (if any) should be needed. This type of design methodology is especially effective for
components and systems with a high rate of technology turnover such as warfare systems and their components.

5.0 Conclusion

The AIMS systems engineering methodology can provide an overall system integration Technical Architecture to arrive at open system architecture within the context of existing designs. The challenge of inserting open or modular systems after the design cycle has progressed to a fixed ship design may be addressed within the AIMS methodology. Open system design for warfare sub-system installations may be accomplished later in the design cycle by applying the concept of variable geometry stations with deconstructed modules. This method allows the application of open systems later in the design process while offering the following positive attributes:

- Low or no weight penalty
- Installation into fixed arrangement
- Parallel system development
- Application of competitive systems

The application of variable geometry modular stations with deconstructed modules provides an additional method of opening ship systems, particularly for systems already in the mature stages of the ship design cycle.

Given the current design and budget constraints that today’s navies face, early stage “clean sheet” designs will be much less prevalent. Ship class designs are being extended to achieve new requirements. Some of these requirements are strictly mission oriented, while others are created in an effort to design more affordable ships. Introducing modular open systems into a ship design is one means of achieving the latter objective. When forced to work from an established ship design, a variable geometry design approach can provide the desired modular open systems result. The key to implementing a variable geometry open system design lies within the development of the ICD to establish the Technical Architecture and define the key interfaces between the Seaframe and the module(s). In the case of variable geometry design, the key interfaces may be defined to minimize modification to the Seaframe side and the component/system side.
6.0 References

7.0 Authors’ Biographies
Raymond T. Marcantonio is a Senior Engineer with BMT Designers and Planners, Inc. He has a Bachelor of Science in Environmental Engineering from Rensselaer Polytechnic Institute (RPI). He is currently the task lead on a number of AIMS systems engineering projects. These projects analyze the feasibility of modularity and open systems architecture for Navy ship application. The emphasis of this AIMS work has typically focused on modularity of weapon and sensor systems. He is also a program manager for several other Navy R&D projects involving the submarine and surface ship communities.

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Andrew J. Levine is a Systems Engineer at the Naval Surface Warfare Center, Carderock Division. He has a Bachelor of Science in Chemical Engineering from the University of Maryland and is completing a Masters degree at the University of Maryland in Systems Engineering. He is currently the Deputy Program Manager (DPM) for the AIMS program and the Technology Integration Manager (TIM) for the Naval Advanced Concepts and Technology (NACT) program. The AIMS program examines modularity and open systems from a physical standpoint to determine where application of modular open systems makes sense onboard Navy ships. The NACT program explores alternative surface ship force capabilities, advanced surface ship, surface craft and unmanned vehicle concepts, and the potential technologies that could enable these advanced concepts.