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# Open Architecture Machinery Control System


## ABSTRACT

Machinery Control Systems are currently individually crafted for each class of ship. Just as the combat systems community is improving performance while reducing cost through an open architecture approach, an opportunity exists to develop and field an open architecture machinery control system for use on all naval ships. This paper proposes a business and technical approach to developing an Open Architecture Machinery Control System (OAMCS) common across all classes of ships. Once adopted this approach would provide commonality across the fleet while preserving competition and a viable industrial base. This commonality facilitates user training, improved maintenance, and regular software and hardware updates.

The technical approach includes a description of the open standards needed both within the boundaries of the MCS and between the MCS and the user equipment. A description of the activities required during ship design and acquisition is also described.


## INTRODUCTION

The views expressed herein are the personal opinions of the authors and are not necessarily the official views of the Department of Defense or any military department thereof.

As described by Nguyen et al.:

> "Machinery Control Systems (MCS) on both commercial and military platform have evolved into multi-layer distributed and redundant control systems that provide versatile and reliable control and monitoring of ship HM&E equipment. Ship equipment typically includes propulsion plant, electric plant, damage control or safety equipment, and a host of auxiliary systems that support the operation of the previous three major systems. There is a wide-range of MCS product offerings for the military and commercial markets by various control system suppliers who tailor their products to meet the customer's specifications and frequently utilize existing technologies based on their experience on other ship platforms. As the result, the installed MCS products have a variety of Commercial-Off-The-Shelf (COTS) flavors and in many cases proprietary software and hardware components. Because MCS suppliers have been able to leverage existing product hardware, software, and development investment, customers typically get competitively package pricing during initial system procurement. However, it becomes more costly to obtain and replace MCS components as the systems age and require maintenance or upgrading due to the specialized nature of each supplier's products. Furthermore, the propagation of different vendor-specific products in a particular fleet requires extra effort and cost to train the operation and support personnel."

To address the supportability issues of the current approach to developing machinery control systems for shipboard applications, increase access to innovation, and reduce both development and life-cycle cost, the authors propose that the Navy invest in developing an open architecture approach.

## OPEN ARCHITECTURE APPROACH

Open Architecture is a collection of best practices, technical and business, when combined with a willing corporate culture, can result in a highly effective life cycle strategy where total cost of ownership is minimized and capabilities to the warfighter are maximized.

As defined by the Open Systems Joint Task Force (OSJTF), an open system "employs modular design, uses widely supported and consensus based standards for its key interfaces, and has been subjected to successful validation and verification tests to ensure the openness of its key interfaces." An open architecture "employs open standards for key interfaces within a system." Open standards "are widely used, consensus based, published and maintained by recognized industry standards organizations." An important objective of an open system is to enable any competent supplier to provide modules or elements conforming to the standards that can be easily and successfully integrated into a working system meeting customer requirements. Furthermore, the owner of the system can take advantage of competitive bids among suppliers seeking to provide each module.

The Navy has extended the work of the Modular Open Systems Approach (MOSA) work performed by the DoD Open Systems Joint Task Force (OSJTF) to more comprehensively achieve those desired goals as a part of the Naval Open Architecture (NOA) effort. NOA is defined as the confluence of business and technical practices yielding modular, interoperable systems that adhere to open standards with published interfaces. It is the goal of the Naval Open Architecture effort to "field common, interoperable capabilities more rapidly at reduced costs".

Guertin and Clements (2010) addressed the following core principals of the Open Systems Architecture approach:

1. Modular designs with loose coupling and high cohesion that allow for independent acquisition of system components
2. Continuous design disclosure and appropriate use of data rights allowing greater visibility into an unfolding design and flexibility in acquisition alternatives;
3. Enterprise investment strategies that maximize reuse of system designs and reduce total ownership costs (TOC);
4. Enhanced transparency of system design through open peer reviews;
5. Competition and collaboration through development of alternative solutions and sources;
6. Analysis to determine which components will provide the best return on investment (ROI) to open…i.e., which components will change most often due to technology upgrades or parts obsolescence and have the highest associated cost over the life cycle.

Achievement of these six principles requires an affirmative answer to a fundamental question:

> *Can a qualified third party add, modify, replace, remove, or provide support for a component of a system, based only on openly published and available technical and functional specifications of the component of that system?*

In order to successfully permit a third party to add, modify, replace, remove or provide support as noted in the question above, the Navy must follow these business and technical elements as the program foundation

**Foundational Business Elements of Open Systems Architecture:**

- Government strategic use of Data rights to support competition;
- Periodic and strategic competition throughout the life cycle;
- Increased capability to the warfighter on a faster development timeline;
- Reduced life cycle costs;

- Shared risks with other programs through strategic alignment;
- Minimized duplication for technology development investments, shared life cycle costs; and
- Establish best fit solutions through open peer reviews.

**Foundational Technical Elements of Open Systems Architecture:**

- Modular designs with low coupling and high cohesion based on open standards and published interfaces;
- Separation of hardware and software to prevent hardware obsolescence complexities;
- Maximized reuse of assets to limit program unique development;
- Full Design disclosure;
- Limited use of proprietary components, but establish well-defined open system interfaces where those solutions perform the best value;
- Use of Modular Open Systems Approach (MOSA) and OSA-specific compliance metrics.

The confluence of these business and technical foundational elements will support the achievement of Office of the Secretary of Defense Acquisition, Technology & Logistics (OSD AT&L)' Better Buying Power efficiency initiative.

The next innovation in the NOA transformation is to establish Open Product Line methods (Guertin, Clements 2010). These changes should embody the next evolution of MCS and include:

a. A published objective architecture specific to real-time systems like MCS that provides industry standard design patterns that provide for hardware independent software development, virtualization to reduce vendor dependant solutions, and isolation of proprietary design elements to maximize acquisition flexibility.

b. An industry/Government consortia based processing architecture and data model.

c. Development kits and test harnesses that ensure software portability, consistency of implementation, risk reduction for system integration, and ability to field subsets of the system for zonal platform module shipboard construction and integration testing.

These documents provide the enabling environment that is needed to support the development an open technical system and associated open business practices for design, integration and certification processes, and technologies to successfully implement the strategy.

The Navy's previous success in implementing open architecture in the Acoustic Rapid COTS Insertion (ARCI) program is well known and documented by Boudreau (2006). Similarly, the Aegis Open Architecture program is currently being implemented as part of the ongoing Cruiser and Destroyer modernization programs. In June 2009, U.S.S. Bunker Hill (CG 52) was the first cruiser to complete the modernization work including the Aegis Open Architecture

Guidance for incorporating the open architecture approach can be found at https://acc.dau.mil/oa. Products available at this site include the "Naval Open Architecture Contract Guidebook for Program Managers", the Open Architecture Assessment Tool and other items issued by the Naval Open Architecture Enterprise Team and the DoD OA Team.

# OPEN ARCHITECTURE MACHINERY CONTROL SYSTEM

## Introduction to OAMCS

As described by Amy et al. (1995) the present acquisition approach for shipboard machinery control systems is:

- Once a set of ship requirements is established, conduct a design which discerns between alternatives to yield a specific solution that fulfills the stated requirements. The design is optimized on initial acquisition cost, assuming that the stated ship requirements are met. Sister ships are to be as identical as possible.
- Throughout the life of the ship, convert and/or modernize to the degree possible or affordable.

In contrast, the proposed approach for an open architecture machinery control system would be:

- Conduct a functional decomposition of naval ships in general to identify common functions and key interfaces.
- Develop a machinery control system open architecture which is built upon open standards, functional modules with loose coupling and high cohesion and defined interfaces through a published objective architecture that defines the modular construct to an appropriate level of abstraction to minimize development complexity and facilitate acquisition choice along natural business markets.
- For a specific ship design, aggregate selected modules within the framework of the open architecture machinery control system. Verify that ship requirements are met. A small number of non-common (unique) modules may be identified. They will, however, have interfaces that are openly published through an updated common data model and comport to the objective architecture.
- The MCS now becomes a family of systems that can be applied across a range of different ship classes and enjoy the benefits of product line development and strategic reuse across a market of similar products. As changes to the ship's mission or requirement is identified for one class of ships, those performance characteristics can be easily made available throughout the rest of the fleet as part of the variation points embedded in the software design. This focus on cross-platform reuse will have down-stream cost savings associated with common training, logistics, and in-service product support.
- Advanced features can be incrementally added to the fleet to improve performance through automation and reduce lifecycle support costs such as Maintenance Free Operating period (Guertin & Bruhns, 2011).

## Guiding Principles

Some guiding principles for producing an affordable machinery control system include:

a. Design software configuration items to be re-usable across multiple classes of ships as part of a product line approach. This requires a level of abstraction of machinery control system functions for generic applications and defined "configuration" mechanisms to adapt to specific ship requirements and system designs.
b. Align MCS system boundaries with the physical zones of the ship. Enable zonal survivability by appropriate partitioning of control functions.
c. Partition functionality among local, zonal and shipwide controls to minimize dependence on other elements of the MCS in performing installation check out and testing.
d. Controls at the shipwide network level should operate at a level of abstraction that is independent of the particular configuration of the ship. Ideally this software is ship independent, but

configured through static configuration files or self discovery.

e. Network Connectivity to the shipboard network to enable distance support as well as reporting of health and system status to both shore subject matter experts and operational commanders.
f. Utilize common hardware that is considered a commodity, where the vendor manages obsolescence as an element of its business model.

## OAMCS Description

Figure 1 shows the authors' concept for an Open Architecture Machinery Control System. In this model, the OA-MCS is aligned with the overall zonal architecture of a ship (Doerry 2006). A zonal approach has the following advantages:

a. Enhances survivability of the machinery control system and the overall ship by implementing zonal survivability. Zonal survivability ensures machinery controls implemented in one zone are isolated from faults outside of the zone. The network bridges and firewalls between the shipwide network and the zonal networks provide a layer of defense for Information Assurance.
b. Enables different network technologies to be used for the zonal and shipwide networks. Different technologies may be desirable because the design objectives for each network are somewhat different.
c. During ship construction, the zonal controls can be tested as an integrated system before the ship is completed. Full integrated testing of the shipwide controls must wait until the ship is largely completed.
d. By aligning the boundaries of the Machinery Control System with the zonal boundaries of other systems, situational awareness of the operators is improved. Problems that manifest themselves in one zone are likely caused by something going wrong within the zone. Without a zonal implementation, problems manifesting themselves in one part of the ship could have a root cause anywhere in the ship.

As shown in Figure 1, the OA-MCS has the following features:

a. Ship-wide Network: This fault tolerant network spans the total ship and crosses zone boundaries. It communicates to zonal level elements and external/offboard networks through network bridges that incorporate firewalls. While individual equipment and sensors may not yet reside on the shipwide network, automation and supervisory level controls in addition to shipwide Human Machine Interfaces (HMI) connect directly to the shipwide network. For the initial implementation of an OA-MCS, the authors anticipate that this network will employ Ethernet and internet protocols.
b. Zonal Network: A zonal network is provided for each ship zone. Communication to other zonal networks, external systems, and shipwide control elements is accomplished via the network bridges / firewalls. Although a business case must still be completed, the authors anticipate that the zonal network will employ a modern data distribution service for real time systems and provide for hierarchical quality of service attributes as required by each sensor/machine type. HMIs could be connected to the zonal network as well. This will provide for true local control and survivability if the zonal network is cut-off from the ship-wide network.
c. The OA MCS objective architecture must incorporate the Information Assurance principle of defense in depth. A robust MCS design must also be able to support incremental ship construction and, should the need arise, graceful degradation in the face of ship damage or component failure. Firewall services, and decomposition of network topology network by using strategically placed routers, switches and network bridges will limit performance risk from issues arising in affiliated external ship-wide

networks and ensure the zonal networks are able to respond under conditions of system degradation and to minimize exposure to network intrusion risks. IA and security needs to be thought of at the outset of any new MCS design. Confidentiality, Integrity and Availability of data must be assured in any MCS. Data Acquisition Units (DAU) / Programmable Logic Controllers (PLC) provide direct interfaces with Equipment and Sensors. Software in the DAU / PLC must provide standardized abstractions of the devices to the higher level zonal controls or shipwide controls. Replacement of a sensor with a new model should only impact the DAU / PLC and not any other element of the MCS. The software should also perform error detection (and error correction if possible) and filtering of sensor data. The software in the DAU / PLC should be maximized to the extent possible to be fully testable independent of other DAU / PLCs. One of the emerging standard of particular interest in this area is IEC 61131 and IEC 61499. The evolution of the soft PLC construct allows vendor independent development of MCS functions in a open and standard format (e.g. OpenPLC XML). Once the functionality is designed, the hardware specific implementation can be translated to run in a vendor unique environment. This innovation from the commercial embedded technology market can dramatically change the standard practice of developing MCS applications in such a way as to severely limit cross-platform reuse and development of components that can be used across multiple MCS implementations.

d. Smart Load. A Smart Load incorporates the functionality of the DAU / PLC within the boundaries of the load. It directly provides the standardized abstraction of the device to the zonal network. In selecting user equipment, a business case analysis should be conducted to determine if requiring the equipment to meet the smart load requirements or by using a DAU/PLC to convert the available interface protocols to the smart load interface is more affordable.

e. One of the major hurdles in affordably installing MCS systems and building a new ship design can be dramatically improved through the use of a Zonal Control architecture topography. Zonal Control coordinates the control activity of multiple DAU / PLCs within a zone. Zonal Control in one zone may communicate with Zonal Control of another zone at the direction of a Mission System Resource Manager or Distributed System Manager. However, the software in the Zonal Control should be fully testable independent of the Zonal Control in other zones. The combination of controls in user equipment, the DAU/PLCs and zonal control should enable stable (but not necessarily optimal) zonal operations without communication through the shipwide network. Zonal Control would be appropriate for many automation tasks where the equipment is all within one zone. For example, coordinating the starting and bringing online of a generator set would be appropriate for zonal control. Automation tasks involving multiple zones would likely be coordinated by a distributed system (or mission system) manager, but implemented through direct communication of Zonal Control in different zones. As shown in Figure 2, control action that requires segregation for reliability, maintainability, ship construction or damage control purposes should not reside in the Zonal Control, but should be allocated to the DAU / PLC or equipment control. If appropriate, Zonal Control may reside in hardware common to the DAU / PLC.

f. Zonal Human Machine Interface (HMI): provides the means for the human operator to communicate with the MCS. From a controls perspective, the HMI does not include any control algorithms, but does incorporate software for display, user authentication, permission management, alarm management, and user input. Under normal operation, the Zonal HMI will behave identically to the shipwide HMI. However, if network traffic is blocked through the Network bridge / firewall, the Zonal HMI will only communicate with zonal equipment and controls. Normally the Zonal HMI is a backup to the shipwide HMI.

g. HMI (shipwide). The HMI provides the means for the human operator to communicate with the MCS. It differs from the Zonal HMI only in that the shipwide HMI may not be able to communicate with zonal loads through the Network Bridges / Firewalls during faulted conditions. The shipwide HMI will be the normal mode for users to communicate with the MCS.

h. Distributed System Managers. A distributed system manager exists for each distributed system such as Electrical Power, fireman, chill water, ventilation, JP-5, Fuel storage and transfer system, potable water, CHT, AFFF, etc. The Distributed System Manager gathers operator input from the HMI and implements it by sending configuration and set point commands to zonal controllers, smart loads, and DAU/PLCs as needed. The Distributed System Managers ensure their systems are configured to meet existing demand, can respond appropriately to anticipated changes in demand, and can successfully identify, isolate, and reconfigure around distributed system equipment failures and damage. The Distributed System Managers work with Mission System Managers and other Distributed System Managers to dynamically manage load shed contingencies for the purpose of maximizing the ability of the ship to conduct its missions in the event of equipment failure or damage. This data architecture has the added benefit of supporting installation and test of components during construction or repair availabilities when full ship's power or other network services are not available.

i. Mission System Managers: A mission system manager should exist for each mission of the ship that has associated equipment installed on the ship. These Mission System managers are software that reside on a hardware infrastructure. Nothing would preclude multiple Mission Systems and Resource Managers residing on the same hardware platform. One deviation from past practice could be the creation of a Mobility Controller to manage the ships propulsion, steering, and roll control equipment. This Mobility Controller would communicate with other systems to determine the best operating points for each of its associated equipment to steer the operators desired course; to achieve a given speed; to limit ship motions to specific accelerations; and to minimize fuel consumption. Other examples of the Mission Systems Managers could include ballast / deballast systems for amphibious assault ships, Aircraft Launch and Recovery systems for aircraft carriers, combat systems, communications systems, and damage control systems. Mission Systems Managers ensure the correct mission equipment is online or in standby to meet both current needs and anticipated needs. Mission Systems Managers communicate with Distributed Systems Managers to ensure load shed priorities are appropriate for the current ship operations as well as ensuring distributed systems have sufficient online capacity or "rolling reserve" to handle anticipated increases in load.

j. Service Managers. Service Managers support the operator and the other elements of the Machinery Control System. Examples of Service Managers include Onboard Training (OBT) Systems, Data Logging, Condition Based Maintenance trending and analysis (such as ICAS), ship configuration and equipment status management, tagout management, maintenance management, technical manual library, operational procedure management, etc. As with the Mission Systems Managers, the Service Managers are software that reside on a hardware infrastructure. Sometime in the future, it may be possible and desirable to encapsulate all ship specific information into a service manager (and potentially DAU/PLCs) such that all HMI, zonal HMI, Zonal Controls, Mission System Resource Managers, and Distributed System Managers are identical for all ships.

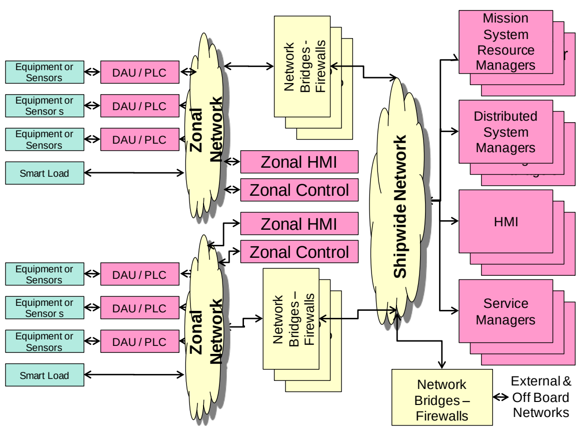


**Figure 1: Open Architecture Machinery Control System Functional Architecture**

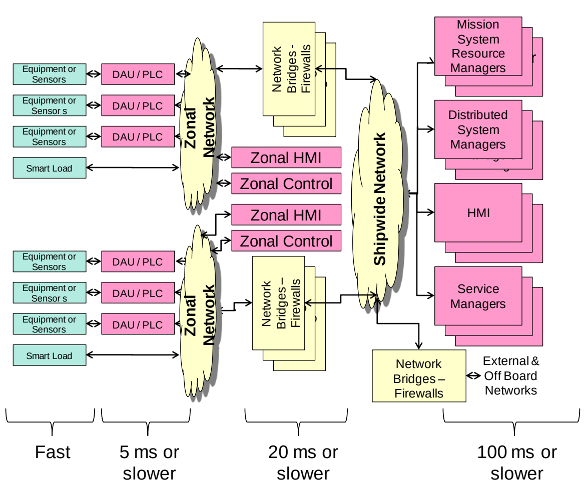


**Figure 2: Time Scale Separation**

## REDUCING VARIATION

A significant state of the practice affecting overall Enterprise cost is that each ship class has a different Machinery Control System. While the number of input/output (I/O) signals serviced by MCS is growing rapidly, so is the variability in MCS hardware, components, software, and human machine interfaces across the fleet. Every new ship class has a unique MCS.

This increasing variation drives life cycle cost by requiring expertise in multiple vendor hardware and software environments. Variation also dictates a larger need for spare parts and a larger variation in vendors and support infrastructure. The cost of training is increased, since each system is unique. There is no leveraging of previous efforts or software re-use to lower cost and mitigate risk.

Unique systems also result in the use of vendor specific development environments and programming languages that preclude strategic software reuse across multiple classes. In addition, unique ship class related system architectures and component design patterns reduce opportunities to gain economies of scale efficiencies in support costs and software development environments. Variation is also typically seen in the HMI, requiring operators to have additional training when changing ship classes. Training requirements for operators and maintainers are increased due to the differences between systems. As commercial manufacturing plants reduce their patchwork of obsolete automation solutions to gain economies of scale from reducing variation, the Navy should consider a similar approach.

A recent deep dive study on MCS variation sponsored by NAVSEA NAVSEA Commonality Programdetermined that there are over one hundred eleven circuit card variants in machinery control systems on ships where either PLCs or microprocessors connected to a VME backplane were utilized. NAVSEA

Commonality ProgramNAVSEA Commonality Program also estimated that nearly fifty percent of this variability could be reduced at a life cycle savings of $18M-$27M. In addition, Open Architecture practices that establish software independence from specific hardware baselines would free engineers and life-cycle support professionals from being tightly bound to ship-by-ship obsolescence management efforts, precluding design efforts for innovation and capability enhancement. Emerging design strategies that use Virtual PLC constructs would allow products developed for one class, with unique target hardware to be reused without wholesale hardware specific reverse engineering and fruitless redesign. These advantages of the Virtual PLC construct must be traded off from a total ownership cost perspective with using traditional commodity based hardware PLCs.

### Example: VME Circuit Card Variation

As part of the study, NAVSEA Commonality Program investigated VME cards for MCS applications. Five unique VME system types were analyzed across various hulls:

- Industrial COTS: High volume, industrial control applications
- Military COTS: Low volume, military control applications
- Custom Proprietary: Low volume, Navy-specific applications
- Navy-GIC: Generic Instrumentation & Controls (GIC) for Navy applications
- Hybrid: A combination of GIC Processing and Industrial COTS I/O cards

The key findings of the NAVSEA Commonality Program study found that VME card variation is driven by unique MCS designs and I/O requirements. These designs resulted in fifty-eight unique VME cards driven by lack of standardization.

VME systems were evaluated on life cycle cost, quality, performance, obsolescence, availability, and customer support. Based on these criteria, the NAVSEA Commonality Program study concluded that:

- Navy GIC solution provided the optimal for overall life cycle costs followed by Industrial COTS.
- Military COTS solutions vary in competitiveness due to a wide range in acquisition costs
- Custom Proprietary solution is competitive for acquisition costs, but uncompetitive for obsolescence and availability
- Overall, the Hybrid scenario is the most competitive solution for life cycle costs, quality, performance, obsolescence, availability, and customer support

The key points from this conclusion are that COTS VME solutions, which are used in industrial applications, can be competitive in overall life cycle costs. The Navy GIC VME solution is also cost competitive. While military COTS and custom proprietary solutions may be cost competitive in the acquisition phase, they are less or not all cost competitive over the life cycle. Reduction in the variation of the interfaces of connected sensors and equipment will also be a key benefit in reducing the number of different VME cards.

### PLC variation

NAVSEA Commonality Program also analyzed PLC module variation. They identified similar modules provided by the PLC manufacturers and recommended eliminating variation by selecting the best module, typically the newer module.

They recommended phasing out older models for use on new ships, while stating that there was no need to upgrade existing PLCs due to obsolescence support lasting for ten or more years. Circuit card obsolescence is managed by the vendor, and as such there is no incremental cost to the Navy. The study noted that overall

PLC life cycle costs are similar for either of the primary U.S. Navy PLC vendors, though single sourcing should be avoided to ensure competition.

### Workstation variation

Workstation variation was analyzed by NAVSEA Commonality Program as part of the MCS deep dive. At the time of the analysis there were twenty-four different operator workstations. NAVSEA Commonality Program concluded that the number of workstations could be reduced to eighteen with six major styles:

- Sitting – single display
- Sitting – dual display
- Sitting – three displays
- Standing console
- Bulkhead mounted terminal – status panel
- Bulkhead mounted terminal – operator interface

There are several variations for each of these workstations/displays that require eighteen different designs. The future target is eight workstations to further reduce variation and associated costs.

Workstations and equipment in the control layer are the best opportunities for gaining economies of scale and reducing variation in hardware, software, and user interfaces. This will have a significant impact in overall total ownership costs.

For VME, PLC and display consoles designs, the majority of the investment is in the software. A new strategic approach based on the OA practices of software independence from hardware provides an opportunity to improve the ability of the Navy to capitalize on the commonality studies. These specific studies will certainly generate lifecycle cost savings for the current architectural constructs of platform and hardware unique design and development. However a common MCS objective architecture that takes advantage of the work going on in industry (virtualization for displays and soft PLC) and other Navy real-time personnel safety (Future Airborne Capability Environment) and weapon safety, PEO IWS's Combat System Objective Architecture, designs provide a an alternative approach that when accepted by the community to be more cost effective, will fundamentally shift how these systems are built and sustained in the fleet.

In a second MCS deep dive (2010) and an analysis of commonality opportunities for Machinery Control System architecture was conducted. Where in the first deep dive looked at variation in components this one evaluated a reduction in architecture areas such as MCS topologies and interfaces. This analysis was performed on 25 different new acquisition and in-service ship classes and was expanded to include ship classes in the United States Coast Guard. For this deep dive the scope of the Machinery Control System includes all the devices, connections and network equipment between Operator and actual shipboard machinery. To understand the current state of MCS architecture, the MCS was deconstructed the various layers into attribute categories

1. Topology is the physical layout of MCS components and connected devices
2. Functionality represents the systems that are controlled and or monitored by the Machinery Control System
3. Methodology represents the key architecture philosophy decisions such as whether to distribute or centralize processing, or whether to have a client-server or publish-subscribe communication scheme
4. Interfaces are the connections between MCS components and external systems
5. And Protocol which are the standards that define the process, syntax and format of data across all layers of MCS

From the current state an analysis of what defines variation in a control system was performed. This variation was distilled down into twenty-four categories. Each category was then evaluated for the relative cost across a set of Total Ownership Cost elements including: System Design and Test, Acquisition and Installation, ILS, Corrective Maintenance and Obsolescence. Cost drivers for each area were evaluated. The result of this analysis produced a comprehensive understanding of cost drivers and relative cost differences for each ship class. The result of this deep dive recommended a 57% reduction in choices across the twenty-four MCS architectural decisions. Some of the key findings are that software-related decisions have the biggest decision-level impact for MCS, in particular development and support costs. Also, initial MCS design is critical a critical element of overall TOC. The ability to reuse previous systems for future design will drive significant improvements in TOC.

### Other variations to be addressed

Lastly, two of the larger challenges in the acquisition of MCS are 1) that the systems and interfaces connected to MCS continually evolve during the ship design process, and 2) that every ship design has a different MCS HMI.

A large number of interfaces has an impact on the number of circuit cards that are required to connect sensors and control devices to the control system. Interfaces should be standardized so that modules are easily inserted in a plug and play environment to adapt to system changes, and there is less impact to MCS hardware, software, and HMI during ship design.

A common HMI with a common presentation to the operator would reduce training and should enable lower cost in design by using common objects and common screens. Currently, each new ship design has an Integrated Product Team established to design the MCS HMI. A common HMI would reduce effort across the enterprise in the design of successive HMIs and result in operators becoming effective rapidly as they move to different ship classes. Common methodologies for controlling processes and for managing alarms will become more critical as MCS size and complexity continues to grow.

Reduced variation has the potential to save life cycle costs in numerous areas with the added benefit of providing the sailor fewer systems to learn to troubleshoot and more standard user interfaces to learn. The opportunity to enable these benefits is during ship requirements development and design.

## BUSINESS CASE FOR AN OA-MCS

Development of software modules in the OA environment will benefit existing programs as well as future programs across other classes. Once a new acquisition or modernization MCS is developed using Open Product Line design practices, built against an Enterprise Objective Architecture, the resulting certified products are in essence locked down, the modules can be placed in a repository for future use by other programs. These modules can be used as is or upgraded and evolved as a part of a product line and published back to the development community for others to expand on and improve. The value proposition of product line development includes the fact that as each subsequent variation is developed, additional features are added that can be applied both to the previous product line users and to subsequent projects. Also as each new feature is added, latent bugs are resolved, thus improving the overall quality. Finally, because new development projects are not starting over, they can more rapidly get capability to the user (Guertin & Clements, 2010). This enables continual improvements of existing modules with all programs benefiting from a singular investment. This will require well defined and well understood interfaces and protocols so that functional modules are able to communicate and operate cohesively.

Utilization of a real-time data distribution service is essential to break into a more productive pattern of MCS system design and warfighter value proposition. This needs to be built together with a fully published and community developed Enterprise data model so that as each newly designed MCS brings in new communication messages that can take advantage of the message sets developed by other projects. To improve this contribution to cost, interface standards should be developed (or a limited set of commercial standards should be adopted as Navy standards) along with a reference architecture and a community enforced set of tools to form a software development kit, all of which will allow the various controllers, mission modules, and user equipment to communicate with minimal if any configuration by the user.

# TRANSITIONING TO AN OA-MCS

Two paths exist to transition an OA-MCS into the fleet – through new acquisition or through modernization programs. Based upon the 2010 shipbuilding plan published by OPNAV N8F, there are several opportunities to implement elements of the OA-MCS. New acquisition programs such as the large surface combatant (DDG 51 class future flight), the small surface combatant (LCS), and amphibious warfare ships such as the LHA 8 or LSD (X) provide opportunities to improve life cycle costs through open architecture, commonality, and software re-use. Many of these opportunities exist in the next five to seven years given the current acquisition plan in Table 1.

Modernization programs also present opportunities to implement an OA-MCS or to utilize aspects of the OA-MCS in concert with other commonality efforts to save in modernization development. Current modernization programs may be leveraged to introduce OA-MCS concepts or modules on small scale basis by implementing the initial fleet introduction of the software test harnesses and associated community standard development utilities in the modernization program, placing the certified software in the Navy's SHARE repository (in essence, a software shelf), and later used in a new acquisition program or modernization program. Licensing costs are reduced or eliminated, documentation development and review costs are reduced, and risk is reduced by utilizing software that has been certified. Examples of these types of software modules could be an HMI shell, on board trainer shell for the engineering plant, or a data logging module.

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**Table 1 FY 2011-2040 Long-Range Naval Vessel Construction Plan**

| Fiscal Year | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aircraft Carrier | | | 1 | | | | | 1 | | | | | 1 | | | | | 1 | | | | | 1 | | | | | 1 | | |
| Large Surface Combatant | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Small Surface Combatant | 2 | 3 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Attack Submarines | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 1 |
| Ballistic Missile Submarines | | | | | | | | | 1 | | | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | |
| Amphibious Warfare Ships | 1 | 1 | | | | 1 | 1 | | 1 | | 2 | | 1 | | 2 | | 1 | | 2 | | 1 | | 2 | | 1 | | 1 | 1 | 1 | |
| Combat Logistics Force | | | | | | | 1 | | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | | 1 | |
| Support Vessels | 2 | 1 | 3 | 2 | 4 | 2 | 3 | 3 | 3 | 4 | 2 | 3 | 3 | 2 | 1 | | | 1 | | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Total New Construction Plan** | 9 | 8 | 12 | 9 | 12 | 9 | 12 | 9 | 13 | 9 | 11 | 10 | 11 | 8 | 8 | 7 | 7 | 8 | 8 | 8 | 8 | 8 | 11 | 8 | 10 | 7 | 10 | 9 | 10 | 7 |

## ONGOING EFFORTS SUPPORTING AN OA-MCS

The Naval Enterprise has a set of innovative practices that are maturing and are in a prime state for the MCS community to join. Four new initiatives are available to springboard the MCS community forward.

The first is a set of Enterprise Objective Architectures (e.g. PEO IWS's Architecture Description Document (ADD), and PEO SUBs ADD) that could be replicated specific to MCSs. These Architectures would prescribe a set of consistent design patterns that will expand the range of potential suppliers, increase opportunities for innovation, and ensure interoperability between an MCS family of systems for things like maintenance free operating period practices and distance support environments.

There is a pair of evolving industry standards that would eliminate the typical vendor lock prevalent in MCS designs of the past by using virtual PLC design practices. From PLCopen.org: "One of the core activities of PLCopen is focused around IEC 61131-3, the only global standard for industrial control programming. It harmonizes the way people design and operate industrial controls by standardizing the programming interface. A standard programming interface allows people with different backgrounds and skills to create different elements of a program during different stages of the software lifecycle: specification, design, implementation, testing, installation and maintenance. Yet all pieces adhere to a common structure and work together harmoniously."The other standard is IEC 61499. This standard prescribes a set of building blocks from which the MCS application suite can be built. Between these two standards, the architecture and the components of an open MCS can be developed that attends to almost all the technical attributes of OA.

Real-time system development and network design practices have radically changed over the past few years using the Real Time Data Distribution Service (DDS) standard. "The DDS publish-subscribe model virtually eliminates complex network programming for distributed applications. The key benefit to DDS is that communication for applications are entirely decoupled. Very little design time has to be spent on how to handle their mutual interactions, relieving one of the major complexities and program risks of MCS designs of the past.. DDS automatically handles all aspects of message delivery, without requiring any intervention from the user applications" (wikipedia: Data Distribution Service). There is an open source DDS and several vendors offer licensed and supported products with turn-key tools that allow rapid and cost effective designs for systems that have real-time performance characteristics and are widely used in the combat system community.

The Open Architecture Product Line initiative is specifically evolving a set of business and technical practices for evolving strategic software reuse by purposefully building reusable components that can be applied across multiple systems and platforms. Open Products Lines are developed with embedded variation points that can be configured to be applied to different instantiations for managing different needs across similar systems. Open Product Lines concepts are embodied by the use of Enterprise Objective Architectures, the using of open standards and programmatic strategic reuse.

The unmanned air vehicle community has established an industry/Government consortium to evolve a set of real-time safety critical design practices that are ideally suited for the MCS domain. The Future Airborne Capability Environment (FACE) is a tri-service initiative to standardize an open software environment that will reduce cost and speed of delivery for new capabilities, encourage competition and innovation, and enable software portability across multiple airframes. The industry/Government consortium is broken into technical and business working groups. The technical working group is defining the standard, a tool set, test suite and associated FACE products. The business working group is developing a set of Government to industry business models and performing outreach to facilitate avionics developers to use the evolving standard. The technical characteristics of a real-time personnel safety system for shipboard machinery control use and the associated characteristics for a real-time flight safety system are nearly identical. The FACE effort could be a launching point from which the embedded controls and MCS communities could quickly leap ahead from the current practices to an OA MCS business and technical transformation.

# RECOMMENDED FUTURE EFFORTS

To implement the OA-MCS, the authors propose that the Navy fund the development and maintenance of the following Specification and Standards:

a. New section to MIL-STD-1399 providing MCS communication data message content protocols. This section would apply to all elements of the MCS, for communication between Smart Loads and the MCS, and for communication with External and Off board Networks. It would not be directly applied to the interface between DAU/PLC and Equipment or Sensors.
b. Development of a MCS Community of Interest (CoI) data model, similar to the ASW CoI data model effort as an alternative, or in conjunction with an update to MIL-STD 1399.
c. Publish a MCS Objective Architecture document, similar to the IWS/SUBS ADD as a NAVSEA Design Practice and Criteria Manual providing a description of the OA-MCS architecture including:
   1. Recommendations for data communication methods to be applied in a Zonal Network
   2. Prescribe the use of a DDS method for a publish/subscribe information architecture.
   3. Recommendations for protocols between the DAU/PLC and equipment / sensors by using the IEC standards 61161 and 61499
   4. Business models and programmatic preferred practices for how to design an MCS using the OA-MCS elements as well as how to integrate the MCS design into the overall ship design process
   5. Recommendations for how to incorporate the OA-MCS design into a ship specification using available Military and Commercial Specifications.
d. MCS community engagement in the NAVAIR/NAVSEA/SPAWAR Defense in Depth Architecture for Information Assurance.
e. Shift in program strategy to take advantage of other Navy acquisition programs for display devices and computing plant packaging.

The new specifications, standards, and design documents should include the minimum of military requirements necessary for operation in a naval shipboard environment. Consideration should be given to creating "slant sheets" for specific solutions to enable commonality across ship types (as is currently practiced with commonality shelf items). As technology evolves, obsolete slant sheets are deleted and news ones added. The specifications should facilitate the economical acquisition of the component while preserving commonality across ship types.

The authors also propose that future MCS software development activity produce software configuration items that adhere to this general architecture and are designed for maximum re-use across ship platforms. Software configuration items should be maintained in a shared environment such as the Navy’s SHARE repository for re-use across ship classes.

The authors propose that the Naval Vessel Rules be updated to include the specifications and standards proposed for development.

The authors propose that future ship acquisition and modernization programs incorporate the design process described in the proposed MIL-HDBK or NAVSEA Design Practices and Criteria Manual.

# CONCLUSION

This paper has proposed a business and technical approach to developing an Open Architecture Machinery Control System common across all classes of ships. Once adopted this approach would provide an additional method to achieve commonality across the fleet while preserving competition and a viable industrial base. This commonality facilitates user training, improved maintenance, and regular software and hardware updates.

The technical approach includes a description of the open standards needed both within the boundaries of the MCS and between the MCS and the user equipment.

The authors specifically recommend the Navy actively fund the development of the standards, specifications, software, and infrastructure needed to implement and sustain an open architecture machinery control system.

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