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Capability Composition and Data Interoperability to Achieve More Effective Results Than DoD System-of-Systems Strategies

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Abstract

This paper investigates how layered business and technical architectures can leverage modular component design practices to establish new approaches for capability acquisition that are more effective than existing “system of systems” (SoS) strategies. We first examine proven methods, approaches, and patterns for crafting large-scale services, real-time capabilities, and military-specific Internet of Things (IoT). We then propose elements of a new approach that applies a coherent set of methods to develop military mission capabilities as sets of composed modules.

Our approach builds on a broad range of prior work related to functional decomposition of requirements into modules of capabilities for deployment in an open environment. We also extend prior work related to using technical reference frameworks as foundations for modules that meet capability needs. We tie this prior work with emerging development practices to describe a new approach for crafting capability. Finally, we assemble these findings into a new overarching model of financial, organizational, programmatic, quality-management, and business patterns needed to deliver payloads onto fighting platforms more effectively. Implementing the recommendations in this paper will establish a DoD acquisition environment shaped to be more efficient and deliver much higher quality—with far greater innovation—in a fraction of the time.

Introduction

The warfighting capability employed by the United States is, for now, the envy of all nations. We have made incremental changes in our acquisition practices for building and deploying military capacity. This capacity can be viewed as “platforms” (e.g., tanks, ships, aircraft, etc.) and the mission system “payloads” (e.g., sensors, command and control, weapons, etc.) that are populated onto those platforms to deliver the desired capability (Greenert, 2012). The requirements to design these systems have historically been defined independently to address specific military gaps. Moreover, upgradability and extensibility were not widely perceived as military requirements at the time they were created. These systems have evolved to become more software-reliant over time, and that trend is increasing (Scherlis et al., 2010).

Performance improvement by upgrading the existing portfolio of systems, using the existing pattern of activities, has been perceived as lower risk, taking less time, and being more affordable than instantiating a new product. Those existing products, however, were not initially designed to support incremental upgrades or even routine ongoing software and hardware sustainment. They were instead purpose-built and are therefore not architecturally structured to scale and address adjacent solution opportunities. As a result, the current capacity for breadth and pace of change is impeding our ability to evolve capability quickly and robustly enough to meet new requirements in emerging technical and warfighting environments.

Technologies that we use to build these cyber-physical/software-intensive systems are widely available to all nations and non-state actors. The practices that were successful in the past for incorporating *commercial-off-the-shelf* (COTS) technologies, on a system-by-system basis, are insufficient by themselves to meet these rapidly evolving challenges. To stay ahead of our adversaries—and continuously increase our pace of change for delivering innovation—the DoD needs new approaches that achieve rapid delivery, flexibility, and capacity to provide continuous improvement to fielded capability.

Military capability provides differentiation between belligerents. In addition, adversaries benefit from our impediments to responsiveness that are self-inflicted from our approaches to acquisition, testing, and evaluation. If the building blocks for crafting military capabilities are all available in COTS form, then all nations could end up on the same playing field for military capability and warfighting advantage. Our nation both needs and deserves unfair advantage wrought by having different and better performing products. Achieving this goal requires new approaches for capability architectures that are intentionally designed to support a military capability requirement for upgradability and responsiveness. In particular, cyber-adversaries are very nimble, so our approach thus enables nimble responses to nimble adversaries.

The remainder of this paper is organized as follows. First we describe several emerging opportunities related to the trend towards modularity and open systems architectures; then we examine key change drivers and technical/organization structures associated with the new model of acquisition we propose for the DoD; next we examine the impacts associated with the implementation and organizational structure of our proposed acquisition model; and finally, we summarize our recommendations and present concluding remarks.

Emerging Trends and Opportunities

Addressing the limitations with conventional acquisition approaches described earlier requires a new set of business and technical practices to achieve different results and more advanced capacities than our adversaries. In particular, new acquisition structure and associated technical architecture are needed to harness the innovation engines of all sectors of the American and global economies. The leading characteristic of applying *modularity* to an *open system architecture* (MOSA) approach is that different components can be created by independent parties and can evolve at different rates.

When the DoD relies on the ecosystem that makes MOSA attractive, it loses some control but gains by “riding the growth curves” of capability and quality. As such, conventional approaches must be rethought at every level, including the ways the DoD (1) funds capabilities, (2) organizes these capabilities to create new products, (3) builds and assesses quality, (4) converts those quality innovations into affordable, broadly usable capacities that are reliable and delivered rapidly, and (5) continues to evolve and modernize products and their components.

Examples of Modular Open System Architectures Adoption in the DoD

Segments of the DoD have aggressively innovated their acquisition practices in the past. In each case, there was a “burning platform” to drive a capability need and/or a financial/programmatic change, including the following:

- The Navy’s Program Executive Office (PEO) for Submarines instituted the Advanced Processor Build and Technology Insertion (APB/TI) process. This multifaceted and phased approach provided dramatic performance improvement that was validated through peer-reviewed and independent measurement and analysis. Full commitment to wholesale replacement of submarine combat systems involved new approaches to delivering these systems into both new construction and existing classes. To apply all available resources to the transition, the Navy abandoned support for legacy MIL-SPEC products to concentrate on employing new capabilities and functional performance to a demanding customer (Guertin & Miller, 1998). This submarine-focused federated system-of-system construct improved enterprise value and supported integration of innovation.
- The Navy’s PEO for C4I systems performed an enterprise architecture approach to provide common compute-plant and capability integration environment under the *Consolidated Afloat Network Enterprise Services* (CANES). This initiative collected together infrastructure needs and provided a landing pad for the Navy’s C4I suite. Though a powerful example, CANES is programmatically applied only to the PEO C4Is family of systems.
- The Army’s PEO for Aviation has declared the Future Airborne Capability Environment (FACE^{tm}) open standard as the Common Operating Environment (COE) for their new capability development (Adams, 2014). The strategic vision for the Army’s use of FACE is to open up opportunities for multiple offerors of innovation, improve interoperability, and reduce the cost and time for capability indoctrination (“Future Vertical Lift,” 2018). Industry supports the FACE^{tm} approach for three primary reasons: (1) to avoid being left behind as others find new opportunities and (2) to take advantage of new methods to improve internal corporate efficiency, as well as to (3) increase market share and increase profits (Nichols, 2017). The government’s incentive for creating and continued participation is to enable increased

productivity and effectiveness, especially for integration and interoperability, as well as to reduce programmatic risk.

- The Air Force is developing the *Open Mission Systems* (OMS) specification, which is a non-proprietary architectural standard designed to enable affordable technical refresh and insertion, simplified mission systems integration, service reuse and interoperability, and competition between suppliers across the life cycle. Industry and the government have developed and agree upon a set of open key interfaces and architectural guidelines to achieve the goals of OMS (Unmanned Aerospace Systems, 2014).

Trends and Opportunities Enabled by Advances in Technology and Strategy

The changes in underlying COTS technologies used by the MOSA-enabled DoD programs described in the previous section have continued to evolve due to innovations in software technologies and architectures. It is now feasible to address backward compatibility and to use a variety of hardware implementations in any one system instantiation or data center while new technologies continue to evolve (e.g., using Graphic Processor Units specifically for performing Artificial Intelligence processing). This change in market dynamics enables greater support for backward compatibility of software onto other operating system and hardware environments by invoking widely used standards (Schmidt et al., 2013).

The COTS software building blocks available to develop, deliver, and manage capability have matured in the commercial market. It is now time to take a fresh look at how the acquisition, testing, and resourcing communities are structured to develop and rapidly deliver highly reliable, intuitively operable, innovation in warfighting capability.

One enabling step recently taken by the Navy was the establishment of the Digital Warfare Office (DWO). The DWO is *inter alia* a leader in the area of decomposing the performance attributes of a system into functions (Serbu, 2017). The DWO focuses on methods for decomposing capability into elements that are internally tightly coupled, but loosely coupled externally, which can then be applied to illuminate software modules needed to deliver the required military performance. It would be tempting to stop there and create a specification for a system that would be comprised of these functional elements. To reach greater performance and speed capability deliver, however, the Navy must then extend this logic to structure the technical architecture to facilitate continuous delivery of innovations and avoid current independent system-based delivery epochs, which classically stretch from two to five years (DeLuca et al., 2013).

An Architecture First Approach

A new “architecture-first” strategy is thus needed that addresses enterprise performance equities, conformant quality attributes, and managed variability while sustaining minimally-coupled and inherently interoperable designs. This strategy should establish a framework of support infrastructure that provides an integration environment in which modules of capability can be a hosted. New development methods and architectural constructs facilitate loose-coupling of capabilities and deployment of software onto containerized or virtualized environments, thereby eliminating the need for hardware-dependent deployments.

The primary function of an “architecture-first” strategy is to establish rules of construction. These rules are set to ensure quality attributes are known and followed throughout the life cycle of a warfighting system. Likewise, these rules also ensure that loose coupling (which enhances systematic reuse), low cyclicality (which is a metric that illuminates corruption of the benefits of modularity through overindulgent interplay across modules), and that strategic architectural attributes (often called "non-functional requirements") are addressed.

While components and functions are separated, it is nonetheless the case that mission capability can be manifested to operators in a tightly-integrated manner. This integration is a consequence of effectively "matrixing" component capabilities and the design of both end-user experience and the application program interfaces for traditional SoS.

Trends and Opportunities Enabled by Advances in Hardware

Advances in COTS hardware are enabling new opportunities for a hardware support model that facilitates continuous deployment of warfighting capability. The past practice has been to configure a specific hardware baseline, procure precisely those parts as a block-buy that will last the life of the deployed configuration (anywhere from 10 to 20 years), and then plan for the program to not run out of spare parts. Block-upgrades, however, are not a sustainable business model for the commercial sector.

Innovations in hardware sustainment strategies have fundamentally changed the methods and mechanisms of retaining high-end capability needed by any organization whose business depends on modern data centers and cloud computing environments. These technologies support advanced software-centric technologies, such as virtualization and modularization. Commercial organizations, such as Google, Amazon, LinkedIn, and Facebook, apply these technologies to continuously upgrade their data centers with new hardware in a manner that allows them to deploy new software capabilities rapidly and reliably (Clark, 2004).

Forerunners of Advances in Acquisition Models

In recent years, various DoD efforts have combined several Programs-of-Record (PoRs) to improve efficiency and to "commonly do what is commonly done." For example, the SubLAN architecture from 2004 was a progenitor of the broader naval effort for providing Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) capacity to host nontactical and crew services capabilities under the auspices of the Consolidated Afloat Network Enterprise Services (CANES; Anderson, 2009). As mentioned earlier, CANES is consolidating and modernizing shipboard, submarine, and shore-based command, control, communications, computers and intelligence (C4I) networked systems to increase capability and affordability.

All Transformation Efforts Must Address Culture

The largest challenges faced by the enterprise-focused transformation effort of CANES were programmatic and cultural. The value proposition of integrating common artifacts and components that were not initially designed for common use was relatively straightforward to articulate (Wang et al., 2004). PEO C4I also established other programmatic elements, including a shared and evolving build environment, the capacity to host a wide array of capabilities, and a PEO C4I organizational policy of rewarding creation of common elements. These behaviors are antithetical to the classic acquisition behavior of protecting the PoR and preferring a system-by-system go-it-alone approach. PEOs will have to face portfolio optimization issues directly if they wish to pursue a completely redesigned approach for *continuous delivery* of modularized, advanced, reliable, and innovative capability into a continuously modernized and shared environment.

The Defense Acquisition Executive (formerly USD[AT&L]) has recently been split into the Undersecretaries of Research & Engineering (R&E) and Acquisition & Sustainment (A&S). This decomposition is illuminating for a path on how to organize around the principles of focusing on innovation for the warfighting domain (the R&E portfolio), while devising a highly reliable and flexible integration environment for those innovations (the responsibilities of A&S). One of the most valuable outcomes of splitting these activities is the acknowledgement that each entity works on different activities, with different skillsets and business drivers, yet each must depend on the other if either is to succeed. The organizational construct of the former USD(AT&L) was predicated on a different strategy and orientation of engagement for oversight of acquisitions performed by the military services. The existing staff will have to undergo a deep culture change if the split into R&E and A&S is to succeed.

Towards a New Model of Acquisition for the DoD

It is widely recognized that the DoD needs to have nimble response to nimble adversaries. Incremental improvement to existing capabilities, granular delivery of new "payloads," and the ability to continuously deliver to the military platform. The current pattern of upgrading ships and aircraft applies a system-by-system, rip-out and installation process. This pattern, however, incurs prolonged periods to upgrade capabilities and reduced operational availability, and makes interoperability more challenging.

Another area that is widely agreed to in principle—but has been even more elusive in practice to achieve—is taking successful prototypes and productionizing the capability with excellent quality, full support, and training. The benefit of rapidly attempting new ideas and quickly declaring success or failure may be lost, however, if those prototypes are fielded in a way that does not match the business needs of the organization. Without good architecture practices, those efforts might provide a near-term salve on an urgent problem, only to be exasperated by the user from the long slow slog usually needed for the transition to be production ready, with no overall improvement in capability.

In both of these cases, the use of an enterprise technical framework, the mission or threat-driven (i.e., market-driven) quality attributes, and data architectures that support interoperability can change the game for delivering the "unfair advantage" to the DoD. A different programmatic and technical alignment is thus needed to deliver smaller capability improvements, along with associated hardware updates, that can be installed quickly, and certified for use automatically when installed. This approach requires new means to leverage commercial investment in data center technologies, as well as products that are built to take full advantage of new development tools, techniques (Schmidt, 2014), and certification approaches so that the DoD only pays for unique military capability that can be delivered quickly and reliably, as shown in Figure 1.

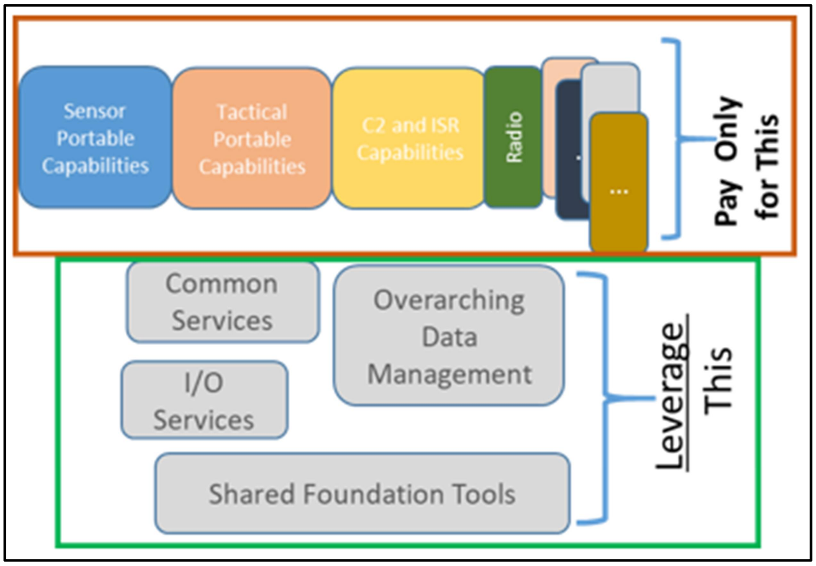

Figure 1. Do in Common What Is Commonly Done and Pay Only for Military Capability

A new procurement and delivery strategy is needed that values shared responsibility, improved warfighter capability, increased operational robustness, outstanding support and continuous improvement. The aspiration is that this strategy is implemented such that the resulting products are defect-free to the warfighter; are tested early and often, certified for operational use when deployed, fully supported, and highly reliable; and can continue to provide the required capability in the face of component failures for protracted periods of time (Guertin, Womble, et al., 2015).

Relevant Technology Trends

Development paradigms are constantly in motion. Service-Oriented Architecture (SOA) was effective for a time, but the development methods and the underlying technologies that made SOA attractive have changed. Emerging design and development practice that are now achieving broad adoption are containerization and micro-services (Amazon, 2018):

- Containerization is an operating system feature where the kernel supports the existence of multiple isolated user-space instances that enable the deployment and running of distributed applications without launching an entire virtual machine (VM) for each module. Containerization can be applied to turn many architecture design elements into fungible commodities that are robustly available to support evolving software development practices.
- Micro-services are a variant of the SOA architectural style that structures an application as a collection of loosely coupled fine-grained services connected via lightweight protocols. Modular capabilities implemented as micro-services more efficiently use the next-generation of computers being produced by the commodity processor markets, including multiple cores, clouds technology, storage evolutions, etc. (“Kubernetes,” 2018b).

Containerization and micro-services also help reduce development risk and increase overall product robustness. Likewise, they can be combined with agile and “DevOps” methodologies, where development and quality assurance teams can focus on a capability as a new unit of functionality that works with other containers as a part of a capability architecture (Kubernetes, 2018a).

Requirements for a New Acquisition Model for the DoD

A new acquisition model for the DoD must address how the organization will evolve into a revamped set of business, organizational, contracting, technical, financial, and ultimately cultural behaviors. The core of this model involves transitioning from a structure based on a collection of independently acquired systems into a highly interdependent ecosystem of rapid capability delivery that integrates and interoperates as a foundational principle. This team-centric approach will require constant communication and collaboration across historically partisan divides (McChrystal et al., 2015).

New practices will be needed to align stakeholders to new organizational identities and reward mechanisms. This transformation will only happen by having a clear-eyed future objective structure, matched to a thoughtful progression from the current state toward that objective (Katzenbach et al., 2016). This model would start with an architectural approach that (1) establishes and ensures loose coupling and independent development for components, (2) establishes early and continuous production/evaluation, and (3) has an orchestration of capabilities crafted to present a user experience that appears fully integrated. The organizational implications of this model are as discussed below (Katzenbach et al., 2016).

Overarching Business Model

The DoD should be organized on the principle that has guided dynamic markets. An analogous example of this kind of enterprise approach is the automobile industry. The trend in that market is to limit the number of different organizations that create similar value elements. That market has evolved to use product line architectures (PLAs) to maximize flexibility and reuse of common elements.

A PLA is a design has built-in flexibility to encompass all the different ways a product could be used. This approach is accomplished through configurable design features that are intentionally built to accommodate customizations that support specific customer use-cases. In this way, the PLA design can maximize reuse, while also providing all the same variations that the customers demand. The move to maximizing the utility of a "platform" to serve multiple vehicle product choices has the combined effect of offering greater flexibility in the products being offered and to do so much faster.

Several industries that market complex, safety-critical, large-scale cyber-physical systems have adopted and improved on the product line approach. Figure 2 shows the breakdown of major functional elements of an automobile into product line segments.

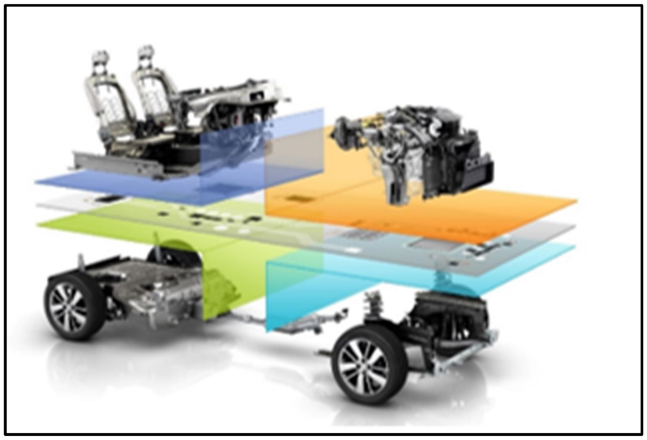

Figure 2. Automotive Example of Product Line Engineering and Payload/Platform Management the Renault-Nissan Common Module Framework

Likewise, Figure 3 shows the strategic trajectory of a major U.S. automotive manufacturer to reduce duplicative infrastructure and embrace product lines as a central organizing theme to continue to create flexible and adaptable products while improving efficiency.

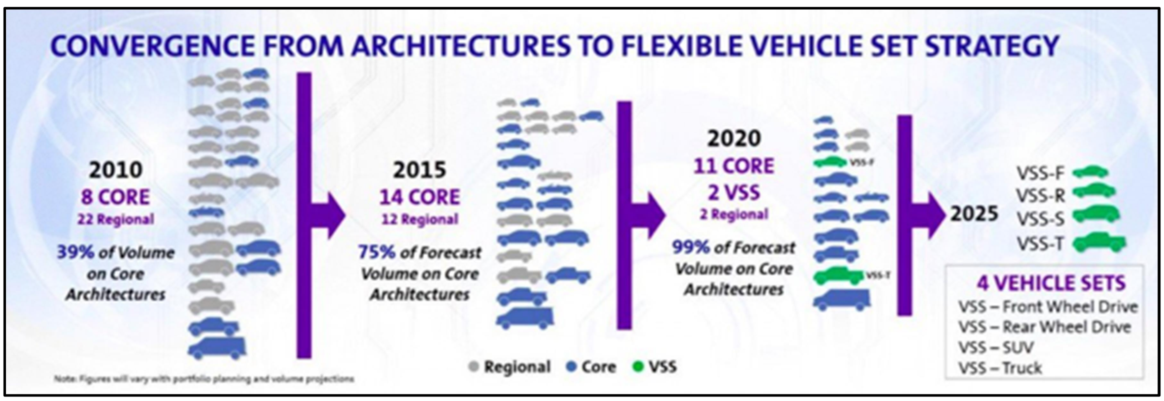

Figure 3. General Motors Platform Reduction Strategy

To achieve the efficiencies experienced in other domains, many aspects of the DoD acquisition structure should be retooled. In particular, the organizational constructs in the Army, Navy, and Air Force services and DoD-affiliated agencies (services/agencies) should be retooled from independent system deliverers into the following three distinct categories:

- Platform acquisition, which provides the outer shell and integration environment of the aircraft, ship, tank, etc.;
- Enterprise architecture product lines, which define a set of software-intensive systems that share a common, managed set of features satisfying the specific needs of a particular market segment or mission and that are developed from a common set of core assets in a prescribed way; and
- Modular capability managers, which provide flexible and adaptable capabilities that get added to or run on the enterprise architectures, and provided to platform integrators. They will need new programmatic approaches, tooling and techniques to manage loose coupling and independence of components, with their ongoing integration. This requires

some discipline with respect to connectors and other internal structural features in the architectural model.

The budget should also be reformed to reflect this strategic approach and embrace a different life-cycle reality of continuous engineering to include early and often validation and verification by the test and evaluation (T&E) community (Guertin & Hunt, 2017). The capabilities developed and deployed into the field can no longer be thought of as produced in their final state (no more fire-and-forget acquisitions). The military environment is constantly changing, and the products the acquisition community provides need to be continuously upgraded and rapidly fielded in quantity, as modularized capability.

Cyber-physical systems can be improved through both software and hardware changes. Although the DoD acquisition framework (DoD, 2017) enables significant tailoring and flexibility, the vast majority of acquisitions still follow a classic spiral development model to achieve a production end-state and a corresponding near-elimination of research and development funding for capability improvement. This approach is particularly problematic in cyber-physical or software-reliant solutions for the following reasons:

- The dynamic cyber threat environment requires constant vigilance for counter penetration and protection measures (even if no capability changes are required).
- The COTS components used to build these systems (hardware, operating systems, tools, etc.) are all in motion responding to market pressures such that the usable in-service lifespan may be much shorter than the longevity of the hardware (e.g., depreciation of software versions or termination of support for obsolete hardware baselines).
- The deployment of new software functions is often an affordable way of improving warfighting performance and addressing evolving mission needs, long after the production run might otherwise be considered complete.

Organizational Impact

The operations of the organization must evolve from a PoR-centric approach to one that values shared resources and focused investment on rapidly deploying military capability (Golden-Biddle, 2013). This change will be hard to manage since three major organizational entities will replace the traditional PoR environment, as shown in Figure 4.

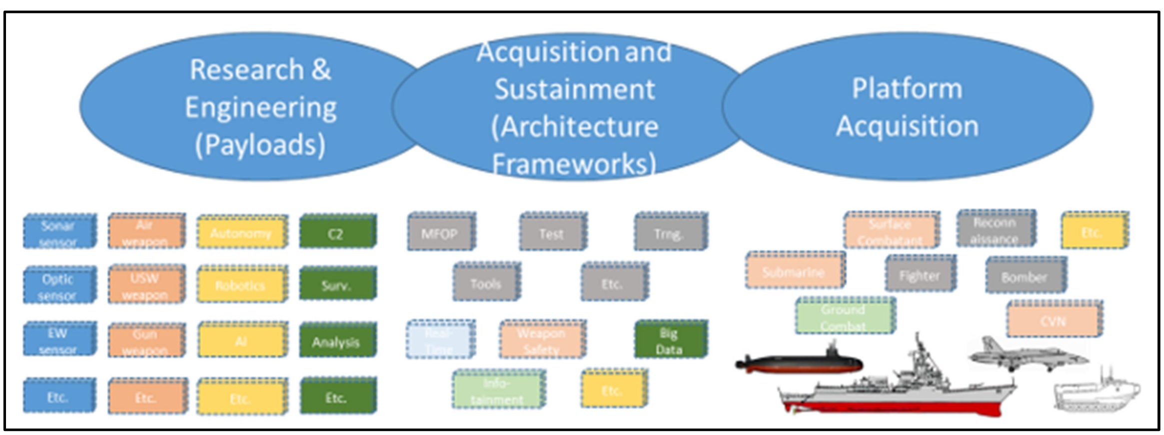

Figure 4. Future PEO Organizing Alignment

Each major entity shown in Figure 4 would shepherd a set of capability managers to ensure interoperability and cooperation pervades the organization, as follows:

- The Research and Engineering (R&E) arm within each service/agency would be populated with capability managers that manage a set of portable modular products (the software of which is decoupled from hardware implementation). A balanced scorecard would be used to adjust modular capability allocation based on a distribution of the particular purposes that address the DoD's strategic needs, such as improving provider diversity or creating new venues for innovation. This scorecard would be shared with the four Defense Committees (in the House and Senate, both Armed Services and Appropriations) so they can identify changes in spending policies and allocation of associated appropriations.
- The Acquisition and Sustainment (A&S) arm will be staffed by architects and systems engineers who manage a technical framework for data interoperability, product development support, module integration, and hardware acquisition. A&S will work with the R&E community to provide artifacts like development kits, integration engines, test harnesses, compliance tools, virtual test bed and hardware definitions, as well as accreditation or certification platforms for delivery of capability modules. A&S will receive architecture investment–related funds and all deployed hardware development/procurement funds. It will also be responsible for delivering certified capability directly to the platform.
- The Platform Acquisition arm will be responsible for acquisition and sustainment of the platforms that host the capability payloads. They also own the platform-unique capability requirements that flow down to both R&E for overall performance and to A&S for platform integration requirements.

Business and Contracting

The acquisition model should be based on having a robust and sustained landing pad for modules of capability that can be risk-prudently and affordably removed, replaced, added, and certified for use, as well as deployed as discrete functional elements that perform integrated functions. At least the following two distinct contracting models should be employed (both of which are already in place and supported by policy or statute):

- The overarching framework should be procured by the Acquisition and Sustainment (A&S) arm described above. All innovators who want to deliver capability to the warfighter need to participate in a continuous evolutionary model (including architectural connectors and data models) for this foundation as a set of living standards. The landing pad for these capabilities could be acquired through a consortium model (e.g., one that is based on Other Transaction Authority [U.S. Air Force, 2015]) and based on industry standards (e.g., the FACE^{tm} Technical Reference Framework [FACE^{tm} Consortium, 2018a]). The intellectual property (IP) strategy for this business environment should be based on collaboration, open standards, and consensus.
- Innovation warfighting functional performance should be acquired through the *Research and Engineering* (R&E) arm described above. Their business relationships should be based on acquiring smaller units of capability (Jones & Womack, 2010) in an agile manner and to sustain a diversity of candidate approaches to cutting edge technologies. The R&E strategy would balance

the need to cultivate organizations that have deep expertise in technical or tactical areas that should be retained for as long as they can competitively deliver warfighting excellence against projecting new capability needs and maturing them through a strategic research and development pipeline. This model is superior to periodic competition because warfighting performance can be removed and replaced by a new competent actor when a capability is ready for (re)use.

A model for establishing a cadre of performers that constantly innovate and compete to deliver new capability will need a different contracting and a remuneration model that awards deployed capability and well-integrated functionality. In one variant of this model, the more software that is delivered, selected as superior, integrated, certified and deployed, the more money the contractor will make. This model will also generate new capability providers through direct industry investment.

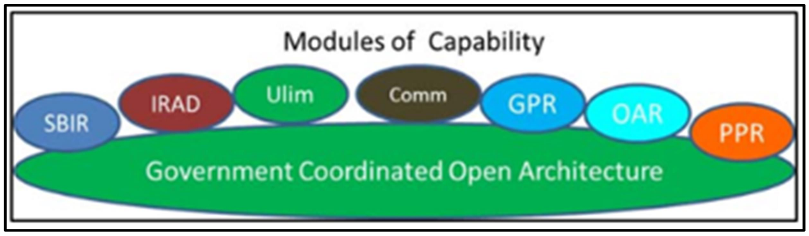

Figure 5. IP Strategy for Capability Module

The intellectual property strategy for this business environment runs the full gamut of data rights, as shown in Figure 5. The government need not attempt to negotiate for greater rights to share IP than the contractor should be bound to offer. The value of a certain capability is based on replicable functional performance, as well as prior investment.

A tension must be managed more artfully than in the past regarding delivery of detailed design data to the government needed to perform test, evaluation, and accreditation activities that ensure elimination of cyber vulnerabilities. This tension has been a divisive issue and the crux of angst associated with IP/data rights issues related to doing business with the government. The government, in turn, must become a trusted steward of industry's IP that is not destined to be shared with competitors (Limited, Restricted, SBIR, Program Purpose, etc.).

To attract a wide array of potential competitors, the government must also be more nuanced in exercising all of its data rights than it has been in the past. In this way, legitimate use of rights to technical data can be used to gain access to necessary information, while shielding innovators and investors that have independently created designs (i.e., not based on government funding) from unfair practices, corrosive relationships, or counter-productive business threats.

Technical Architecture

The technical architecture described below flows from the business architecture, as shown in Figure 6. This overarching architecture begins with a set of *technical reference frameworks* (TRFs) that support the needs of military systems. Several TRFs have been established through industry collaboration and consortia that represent an excellent starting point development and integration of support loosely-coupled modules of capability. These TRFs are transformed into reference implementations for product lines that support classes of related capabilities. From these reference implementations, product line-specific architectures are crafted that can be deployed as integrated capabilities.

Applying this well-orchestrated cascade of dynamically evolving, industry-supported TRFs can bridge to reference implementations and become specific implementations that support capabilities. In turn, these TRFs are built and verified to support quick integration or removal with few dependencies to other modules (Guertin et al., 2015). The resulting “plug and play” model provides a base capability of the installed infrastructure that is designed for flexibility and growth.

Modular capability elements that are composed into a deployable product should be tested for platform integration in virtualized environments as soon as they are reliable and ready for use. This approach requires new means of continuously updating decoupled hardware and portable software in smaller increments. Cyber-physical capabilities should be expressed as loosely-coupled modules (e.g., containerized micro-services) that can be plugged into the systems architecture with interfaces that are managed through discovery.

Certification of these capabilities are performed as an overall product-line (White et al., 2007) with platform-specific uniqueness certification needs addressed prior to shipment through a virtual test-bed/digital-twin construct (Joshi, 2017). The new capabilities are then delivered to the platform (e.g., a ship, plane, or ground vehicle) as a precertified package, along with targeted hardware changes. The crew (not a civilian installation team) then follows a field procedure to install the changes through simplified—ideally automated—instructions/scripts. The results are then tested automatically on initiation to validate that (1) the certified configuration was accurately completed and (2) the platform is ready for all its assigned missions (Guertin & Hunt, 2017).

Figure 6 also shows how a common data model can be used to support module-level interoperability, such that new functions can be discovered on introduction, complete with full semantic and syntactic descriptions. The Navy has invested in at least two data models that are suitable for this purpose: ASW COI (ASW COI Data Modeling Working Group) and FACE™ (ASW COI, n.d.; FACE™ Consortium, 2018b). This technical architecture also provides a means to decouple software capability into modular units of performance that can be deployed in containers onto an MOSA-enabled platform. Modularization (e.g., containerization and micro-services), is a fundamental tenet to support the overarching business model.

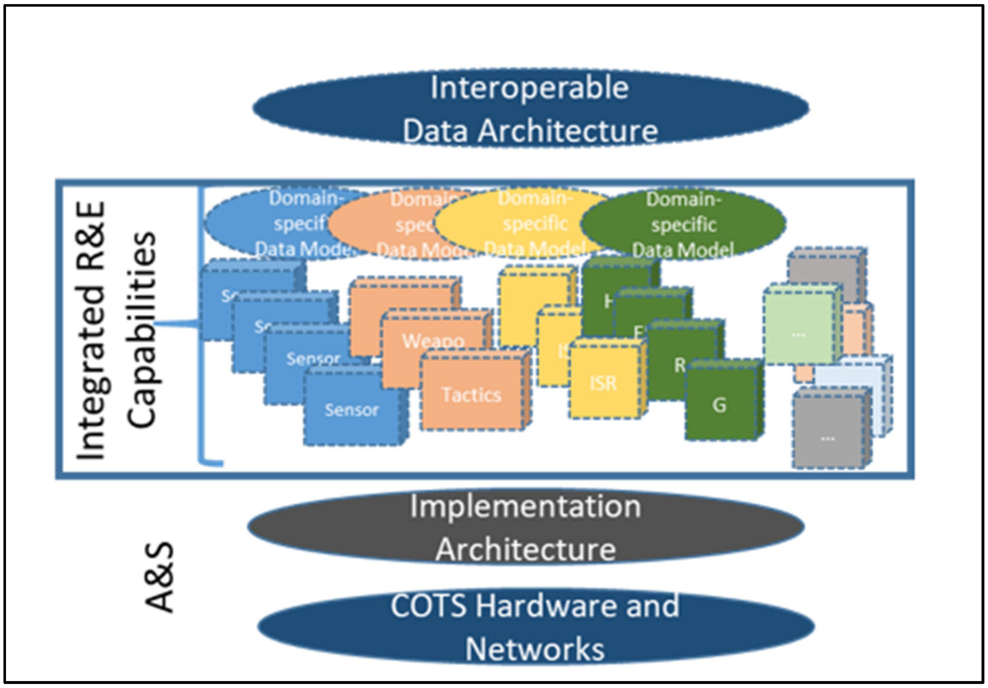

Figure 6. Composition of Severable, Loosely Coupled Capabilities

A virtual testbed (digital twin) will be used to support automated testing and certification of a platform's delivered capability. This testbed can be deployed at as many development sites as are needed by the development community. Capability tests can therefore be performed outside of a single integration laboratory, such that platform differences can be embraced and managed. As a result, the DoD will have the operational flexibility to fit out the capability set that a platform will need for the mission(s) it will perform.

Any hardware kit delivered to the DoD will have gone through an automatic test sequence to ensure it is installed correctly and validated with respect to its digital twin. These kits will be developed by A&S so they can be installed by enlisted technicians to the greatest extent possible. Finally, modern warfighting platform designs are based on standard equipment racks that are already in use on a platform-by-platform basis. These are all predicated on COTS infrastructure, such as electronics-friendly 19-inch rack-mount design. Operational-level and Intermediate or Depot-level actions are thus performed only under the most extreme conditions.

Gradients of Trustworthiness

One of the challenges associated with modular OSA architectures, and the concept of components as payloads, is the presence of "gradients" of reliability, trustworthiness, and security within and across our systems. These gradients are generally unavoidable and require architectural attention to minimize the operational impact they portend. But they can also be beneficial—because they enable nimble approaches to integration of diverse payloads from diverse sources.

The presence of these gradients must be addressed as part of any exercise in architecting and re-architecting. Containers and micro services are an important part of the solution, but there are other aspects as well.

Here are three examples of mechanisms to address the gradients:

1. The design of “connectors” among components in a system, which address issues ranging from governing data flows to enforcement of cross-domain data management policies.
2. Technical methods for isolation and encapsulation, such as sandboxing, which can both protect sensitive components from the broader systems environment and also vice versa, enabling safe use of less trustworthy components.
3. Architectural patterns that enable reduction in those areas where we need the most deep and costly T&E practices, with consequent reduction in cost and delay. Examples of the latter are (a) flight controls vs. other avionics in the DO-178 environment, and (b) doer-checker patterns for advanced heuristic controls, such as might be guided by AI/machine learning components that, in present practice, are relatively opaque to analysis and prediction regarding safety and security attributes.

It highlights the unavoidable deep interplay of architectural technical choices and acquisition strategies.

Financial Architecture

The Financial Architecture will be based initially on the current Program Element structure of the Planning Programming and Budgeting and Execution process, with close coordination between the PEO and the associated Warfare sponsors. The authors assert that if there are sufficient funds to support this number of independent systems, associated infrastructure, and development teams, then there are more than sufficient to support the proposed business model. Eventually, the funding model will need to be changed over the course of several budget cycles to reflect the business model of continuous capability innovation and technology transition.

Impacts Associated With New Implementation and Organizational Structures

Adopting a new acquisition architecture predicated on separating the concerns associated with building new capabilities (R&E) from those associated with a product-line architecture landing-pad, support tools, and shared services delivered to the platforms that would host them (A&S) will yield a number of impacts that are depicted in Figure 7 and described below.

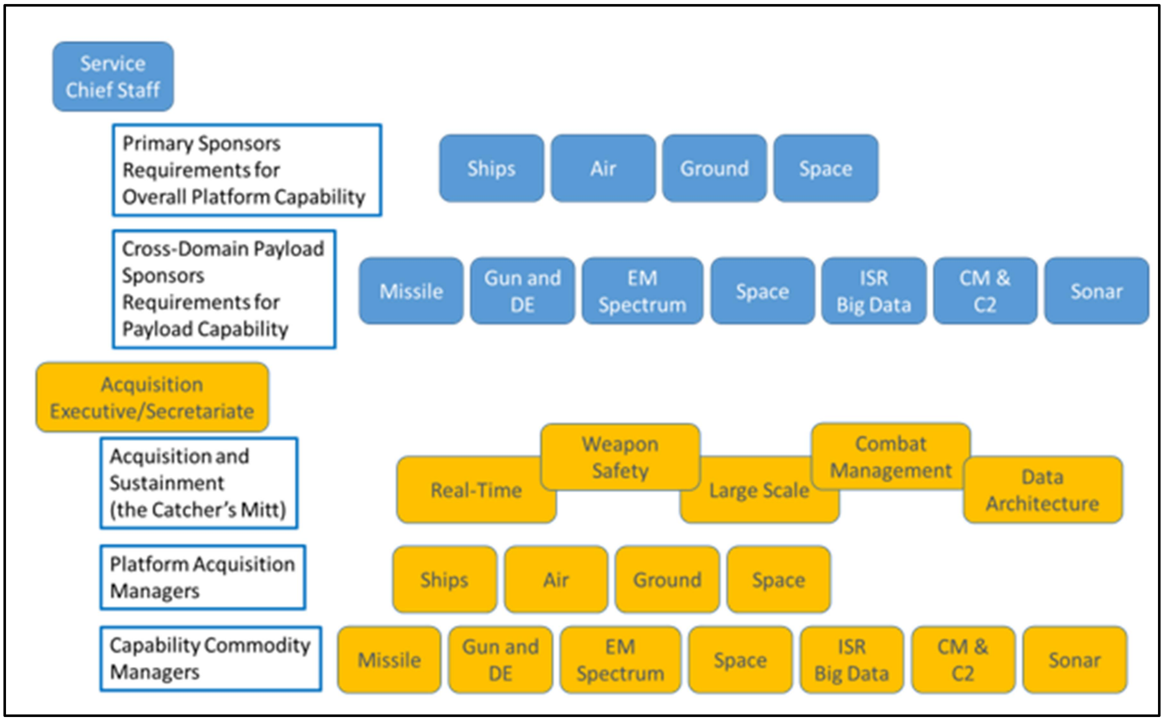

Figure 7. Resourcing and Acquisition Alignment

1. The R&E organizations would focus on delivering cross-platform reusable component capabilities in product-lines that have unique attributes and value, such as Sonar, Imaging, Radar, Communication, Strike, EM/EO/IR, Payload Launch & Control, etc. Those organizations establish requirements for a shared system architecture and work together to integrate products.
2. Likewise, the A&S arm collects the R&E infrastructure requirements and creates a common environment that provides a secure, real-time, safety-critical, and cyber secure environment, including build tools, automated test capability, data architectures, connector models, training environments and integration frameworks. The Platform Acquisition arm would focus on designing, building and sustaining the platform, and specific requirements for installation and non-warfighting system integration (Guertin & Clements, 2010).
3. An important step that some PEOs have begun is to examine modularized capabilities packaged as containers to be deployed as severable, self-healing units of performance such that new products or services can be delivered independently. The system and software architectures need to support loose coupling of those modules so they can be extracted and replaced by new capabilities are well-practiced and

available in the marketplace. The resulting product set could be changed since they are designed as loosely coupled—but highly cohesive—capabilities that are more reliable and self-healing, and that can be integrated quickly with known impacts to existing products and services (Guertin, Womble, et al., 2015).

The supporting elements of the acquisition arena should be refactored to support this model, as summarized in the following:

1. The *Test and Evaluation* (T&E) communities must be a part of this transformation from the inception and be involved in setting the architecture constraints. To ensure that the integration, test, and certification activities validate that the development team has created a highly reliable and critical-bug–free product, the testers should also be a part of establishing a way to check that the deployed product is production-ready. An evolving practice to ensure this alignment is to establish a digital twin environment that would be validated to ensure that all in-lab testing of deployable products represent the installed configuration when the capability is shipped for installation. Only then will the delivery and installation testing be performed in days instead of weeks, with the resulting capability suite certified for full use (Guertin & Hunt, 2017).
2. Product support management takes on a new characteristic. Products that are software-reliant or cyber-physical never encounter a classic sustainment period. Instead they reach a maturity in the productization of the design and enter a continuous engineering and upgrade phase that lasts throughout disposal.
3. PEOs need to perform portfolio management and to decompose functions into modules that can be containerized, apply (not develop) the appropriate a containerization and technical reference framework scheme, establish an infrastructure consolidation plan, to include hardware, networking, storage, and adopt a data architecture that is practiced by a broad community. It is now a good time to consider new standards for architecting this environment that can support the warfighting community for several decades into the future.

The type of change described above will likely imbue classic organizational resistances and text-book rejection responses to strategic change, which are natural human and organizational responses. Fortunately, the mechanisms of resistance to change are better understood now than ever before. To minimize these effects, therefore, a coordinated rollout plan should be developed where members of the organization are welcomed to become a part of how the organization achieves its shared objectives. Likewise, a detailed communication plan should be developed that invites personnel in the existing program offices and subordinate organizations to participate in developing how and where they fit and where the growth opportunities lie. In times of uncertainty, people in these organizations will be primarily interested in how change will affect their lives (Williams, 2017).

Industry will be most interested in the impact to existing tasking and the opportunities that lie ahead. The role of the system integrator would be retooled into an overarching capability integrator, a system architect, and a hardware procurement agent. There is currently an integrator for every system and an overall platform integrator. These duplicative and overlapping roles are ripe for consolidation (Guertin & Womble, 2012).

Successfully implementing the types of change described above will require the full commitment of all members of the acquisition community. Organizations make these kinds of transformations most gracefully when all the members of the organization can see their future in the implementation of the next model. New models for change management have progressed out of the neuroscience and human-centered design communities. These more nuanced approaches draws people in the change strategy such that they feel like they will own the result, which will have the effect of much greater results.

Summary of Recommendations

This section summarizes our recommendations for the DoD along the following dimensions:

- **Organizational/Cultural**—The "burning platform" being addressed is how to reinvent a model of behavior that can achieve a dramatic reduction (at least 80%) in time to flow of capability to the DoD. The resulting environment will shift to a continuous capability delivery engine that is affordable, flexible, adaptable, and reliable. The organization needs to separate the concerns of the payload capabilities, from a supporting enterprise architecture and the host platforms. The resulting managed capability will deliver in smaller increments and will be improved regularly, with higher reliability and in easy-to-install packages that come with training and support.
- **Business**—Conventional federated system-of-systems business relationships currently employed by the services/agencies need to evolve to a model of decoupled capabilities developed by a variety of firms that are experts in their craft. This business model is built on leveraging the commercial marketplace, on valuing private investment, honoring the unique nature of small business, while also maintaining the government's fiduciary responsibility when taxpayers are making investments. Any capability that comes with restrictions on sharing internal design details must come with a certification that the design can be gracefully removed from the system and replaced with equivalent capability derived by a different organization. The overarching architecture on which all this capability will run will become a shared responsibility between industry, the standards community, and government. That open architecture will be co-developed by the stakeholder firms in collaboration with the government who coordinates the effort to ensure that capabilities can be replaced. Other Transaction Authority Consortium models should be investigated as a preferred mechanism for establishing this environment.
- **Technical**—It all begins with a high-level strategic and enterprise approach that is led by the services and supported by the highest levels of the DoD. This transformation is not achievable without the underpinnings of new technical and data architectures. Those underpinnings begin with an approach that is testable and verifiable that the products being developed by industry and accepted by the government comport to the enterprise strategy. Fortunately, we have starting points. Several technical reference frameworks have been established and support a conformance model. These have the support of forward-thinking government and industry teams that used cross-organizational collaboration and standards bodies/consortium models to ensure voices are heard, but not to the exclusion of making progress towards a common goal (consensus-based).

Concluding Remarks

Congressional, DoD, and military leadership of the services have demanded faster and more effective means of achieving the objectives for capability acquisition. Our work reported in this paper describes a new acquisition model that will enable the DoD to plan, buy, field, and certify military capability more effectively by:

- establishing a new budgetary framework based on integrating modular capabilities into open platforms,
- applying containerized and micro-services architecture frameworks that the services/agencies use for integration environments, and
- ensuring resilient and reconstitutable capabilities that can recover from cyber-attacks and combat damage automatically.

Capabilities build in this way will enable services/agencies to update much more frequently to meet warfighting needs and keep the U.S. military ahead of the competition by providing the following benefits to the DoD:

- eliminating classic budgetary overruns and misaligned financial investments for greater life-cycle management and cost of ownership;
- ensuring that software capabilities are durable, self-reporting, and self-healing, as well as enable capabilities to utilize diverse data sources, reducing coupling and increasing reuse;
- allowing the upgrading of products when they are robust and ready, as well as supporting backward compatibility with the other interacting systems on board; and
- enabling software-reliant systems to fallback to a previous version, or even strategically select which software variant is to be loaded next.

This paper has shown how a comprehensive approach—based on current practices and time-proven research—can span the full gamut of the acquisition environment (requirements capture, financial management, programmatic approaches, development methods, and deployment operations) to achieve the national military capability objectives faster, with lower risk and with greater cost performance.

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