Weapon System Virtualization and Continuous Capability Delivery for US Navy Combat Systems

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Synopsis

The US Navy envisions a Fleet that applies advances from the technology sector to improve the delivery of warfighting capability. Due to constraints imposed by legacy hardware design inherent and the inherent limitations of x86 servers, significant inefficiencies exist in the hardware and software delivery process. The US Navy leveraged advancements in virtualization technology to field combat system software in virtual machines, effectively removing computing hardware as a capability limiter. Adoption of hardware-agnostic virtual machines also significantly reduced the delivery timeline for improved warfighting capabilities at a lower cost. This paper will review the evolutionary enhancements in AEGIS Combat System computing architecture and describe why it is critical for the Surface Navy to adopt a new capability delivery model. This paper also outlines the key engineering and testing advantages of the US Navy AEGIS Virtual Twin effort, which recently demonstrated continuous capability delivery to the Fleet. Finally, this paper will explore the multifactor framework of the Balanced Scorecard as a tool to align the benefits of virtualization and advances in computing technology with a new model for future US Navy Combat Systems.

Keywords: Weapon Control Support Systems, Virtualization, Hypervisor, Rapid Prototyping

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Mr. John R. Clarke is an Assistant Program Manager for Systems Engineering assigned to the US Navy Department's Program Executive Office for Integrated Warfare Systems in Washington, D.C. During his tenure in the AEGIS program, Mr. Clarke has brought high fidelity tactical modeling and simulation capabilities and most notably led the innovative AEGIS Virtual Twin project. Mr. Clarke holds a Bachelor of Science in Mechanical Engineering degree from Johns Hopkins University and earned his Master of Business Administration degree from Georgetown University in 2018.

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1. Introduction: Enabling a Better Fleet through Virtualization

> *"To increase America's naval power, we will build a better fleet – one that is more capable, agile, networked, and resilient across all of our naval platforms. This means fielding state-of-the-art systems and continually modernizing legacy equipment."* (Richardson, 2019).
>
> Admiral John M. Richardson
> 31st US Chief of Naval Operations
> Statement before the House Committee on Appropriations, 30 April 2019

The AEGIS Combat System (ACS) is the US Navy's most sophisticated shipboard anti-aircraft and anti-missile system and has been upgraded in a series of nine evolutionary baseline enhancements across two classes of ships to keep pace with current threats. Currently, there is widespread recognition that traditional methods developed over the past 40 years will not meet the future Navy's need to continuously integrate, test, and deploy new warfighting capabilities across the US Navy Surface Fleet. The pace of threat development is evolving, with increasing range, complexity, and sophistication. Recognizing the continuous capability evolution challenge, Admiral John Richardson, 31st US Chief of Naval Operations, stated, "We simply have to get better at [being technologically agile]. I think it's a strategic Achilles Heel, the lack of tempo I would say in terms of how we can field technology to the Fleet. We cannot get outpaced in this, and that comes right to bear at this far right end of the spectrum. We just can't let ourselves be dominated by someone who can get technology to their forces faster." (Richardson, 2016). While great progress has been made through the traditional ACS baseline enhancement process, a fundamental shift in technology and acquisition processes is required to outpace the threat and continuously deliver Sea Power to the Hands of Our Sailors.

The first five ACS baselines installed onboard Ticonderoga Class guided-missile cruisers (CGs) and *Arleigh Burke* Class guided-missile destroyers (DDGs) in the 1980s and early 1990s (originally installed onboard CG 47-73, DDG 51-78) provided US Combatant Commanders unmatched multi-mission warfare capabilities. These early baselines employed a disciplined development process with military specification (MIL-SPEC) standards leading to 32-bit computers, cathode ray tube (CRT) display screens, and the Compiler Monitor System (CMS-2), a unique programming language developed for US Navy Tactical Data Systems (NTDS). While MIL-SPEC provided the US Navy a degree of commonality and eased platform-unique integration challenges associated with the fire control loop and tactical data links, the MIL-SPEC baselines were largely designed as consumables tied to the ship and were designated as the combat system to serve through the end of the ship's service life. These technologies were largely developed by the US Department of Defense, as they led the way in development of early computing architectures to advance national security through the introduction of increasingly sophisticated combat and weapon systems.

By the mid-1990s, the US Navy recognized the need to evolve the consumable nature of the legacy baseline process and reengineer the process to allow for major upgrades and leverage advancements in commercial technology. Over the next 20 years from Baseline 6 to the most recent Baseline 9 architecture (Table 1), the US Navy has engaged a diverse set of industry partners and applied best practices in the use of commercial engineering tools for design, development, and test. While these changes met the defined performance measures, the state-of-the-art commercial servers used by the most recent baseline enhancements have also revealed unique challenges. After introducing a new commercial infrastructure across the AEGIS Fleet, stakeholders quickly identified the need to create a refresh rhythm and disciplined selection process to address obsolescence challenges. A notional baseline evolution process was developed, comprised of four-year hardware cycles and two-year software cycles, in an attempt to align ship schedules with accelerating commercial product trends. Although progress has been made over time to implement new ACS software architecture based on modular design, open standards, and well-defined software components, the underlying approach of delivering hardware and software upgrades based on a specified timeline does not provide the agility needed in today's fast-paced threat environment.

Table 1: Current AEGIS Baseline Breakout

Baseline	*Total Ships*	*Cruisers*	*Destroyers*	*Computing Architecture*
Legacy Baselines	*26*	*5*	*21*	MIL-SPEC Design
Modern Baselines	*49*	*4*	*45*	Hybrid MIL-SPEC/COTS

Source: Naval Vessel Register & Navy.mil

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Surface Combatants will need to meet the continuous capability challenge while also lowering lifecycle costs throughout each ship's expected service life. To do this while testing developmental software at sea without impact to certified configurations, a new model will be required. The proposed model directly leverages proven, cost-saving virtualization platforms. Virtualization and its associated benefits, further discussed in the following sections, has demonstrated the ability to reduce development and testing costs while delivering software upgrades at the speed of relevance. The rapid pace of the AEGIS Virtual Twin (VT) effort will demand a more flexible and competitive approach to legacy baseline technology and acquisition processes. Introduction of new capabilities must be separated from the ship's delivery or mid-life modernization schedule, and the VT proved the inflection point of continuous capability delivery, providing software upgrades in 18 to 24 hours rather than 18 to 24 months. Virtualization will enable multiple suppliers to rapidly develop and prove their solution early in the development cycle while the US Navy will be able to test and train the most capable products in an operationally relevant environment without impacting tactical ship operations. Through rapid prototyping, the most nimble and capable industry partners will drive the most innovative and effective capabilities into the warfighter's arsenal.

To realize a vision where the US Navy leverages advances in virtualization to effectively remove computing hardware as a capability limiter, the following sections will address the paradigm shift necessary to test and deploy new tactical software and describe why the Surface Navy must embrace hardware-agnostic virtual machines running on Commercial Off The Shelf (COTS) hardware in order to maintain warfighting dominance in the face of major challenges in the coming decades. Next, the paper analyzes the software and hardware changes required to simulate hardware functionality and create a virtual computer system. Finally, changes to the current operating model are outlined to define how the US Navy needs to adapt core business processes in order to leverage virtualization to rapidly transition to the powerful interoperable Fleet envisioned by Distributed Maritime Operations. Based on the formative work of Kaplan and Norton, this paper will explore the cause-and-effect logic structure of the Balanced Scorecard as a way to ensure new capability delivery model improvements are aligned with broader strategic intent from US Navy leadership.

2. AEGIS Virtual Twin: Removing Computing Hardware as a Capability Limiter

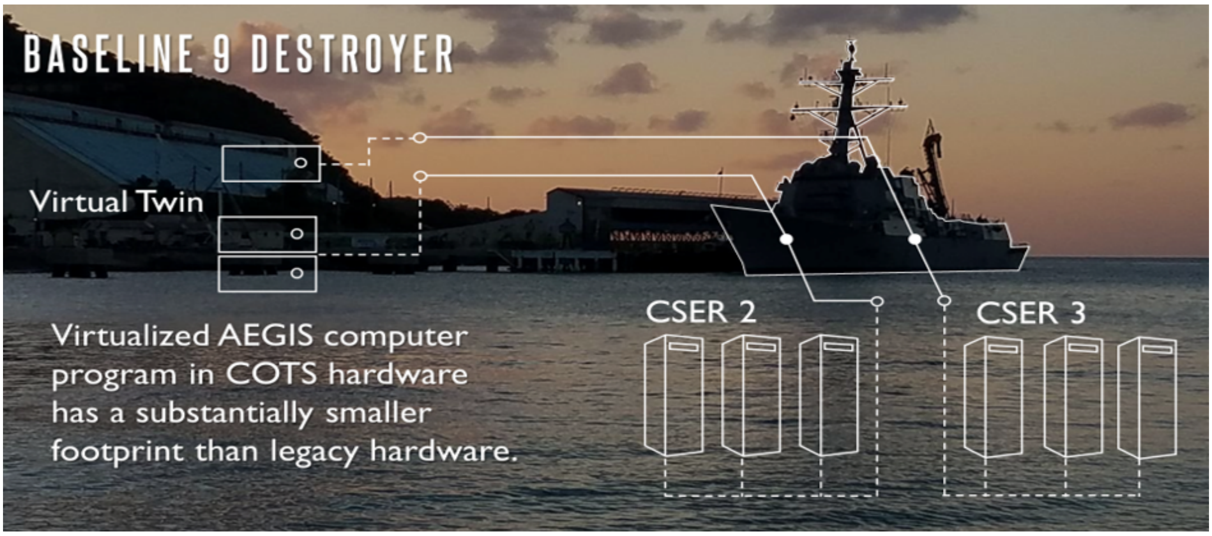
> *"Imagine the future where you've got your ship, you've got your certified combat system, you've got a digital twin of that system with maybe the next test load so you don't have to take a Fleet asset out to go run tests, it's running all the tests for you."*
>
> Hon. James Geurts
> US Assistant Secretary of the Navy for Research, Development and Acquisition
> The US Navy League's Sea-Air-Space Exposition, May 7, 2019

Naval combat systems worldwide are fielded to operate over the entire expected ship's service life, often 30-40 years. Structured upgrades, such as the AEGIS Modernization program, are often only employed at a ship's mid-life to recapitalize the initial Combat System investment, however these investments can fall short due to rapid advancements within the technology sector and demand for emerging capability enhancements. As a result, there are native constraints on those legacy ships which places pressure on the underlying force structure required to maintain maritime superiority. Due to the limitations of modern x86 servers and legacy design approaches, combat system computing infrastructures employ multiple processing servers operating at only a fraction of their individual capacity. These native constraints drive significant inefficiencies and result in higher lifecycle costs. As a result, the ability to streamline future combat system development by leveraging virtualization to effectively remove computing hardware as a capability limiter while reducing lifecycle costs and invest in future warfighting improvements has served as a catalyst for the AEGIS VT effort.

Researchers Arslan and Özbilgin (2017) defined virtualization at the Institute of Electrical and Electronics Engineers' 2017 International Conference on Computer Science and Engineering as "the creation of components, such as hardware platform, operating system, storage, processing power, memory, or network resource, in virtual environments," and highlighted that, "The applications of virtualization are spreading rapidly, and the critical systems are working on virtualization infrastructures." The move towards virtualized systems offers several key engineering and testing advantages that are aligned with the Chief of Naval Operations vision for the future Navy such as reduced space requirements, decoupling software from hardware, greater flexibility and adaptability, and increased speed and frequency of software updates. Additionally, industry leaders like Tesla and General Electric employ Digital Twin models that replicate fielded systems such as car navigation systems, airplane engines, wind turbines, and other complex systems in a digital environment located in their factory or development site. In this model, the confluence of virtual and physical data allows characterization of performance, data mining, and rapid prototyping. Similarly, the US Department of Navy set out to implement this Digital Twin concept to develop and rapidly deploy AEGIS VT.

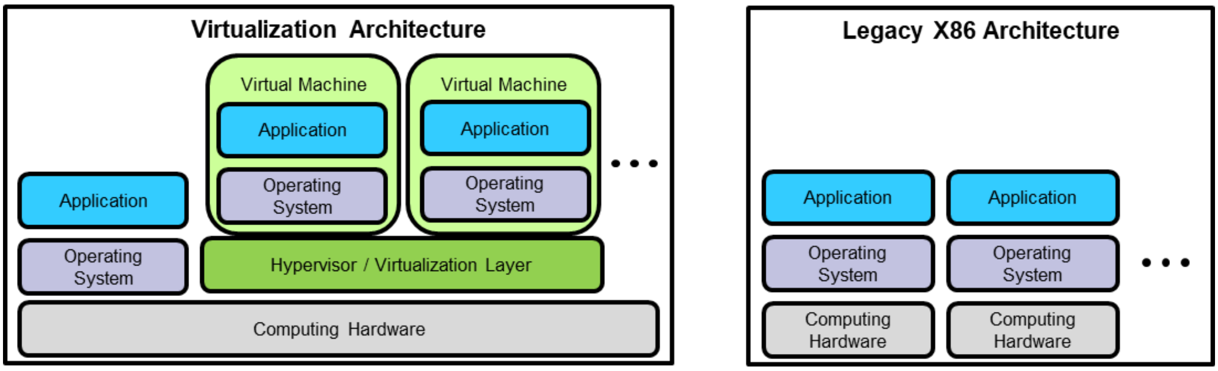
Shipboard environments demand efficient use of space, and the most overt benefit of virtualization is server consolidation and its ability to reduce computing infrastructure space, weight, and power requirements. To establish the virtual environment, the VT team used a hypervisor (also called a virtual machine monitor) running on bare metal hardware to create multiple virtual machines that share underlying hardware resources. As a result, the ACS computer program that had previously run on multiple physical servers enclosed in multiple server racks across multiple ship spaces were consolidated into a much smaller footprint (the "Virtual Twin"). This difference in space requirement between current computing environments in Combat System Engineering Rooms (CSERs) and the VT's significantly smaller footprint are shown in Figure 1.

Figure 1: Legacy - Virtual Twin Computing Hardware Footprint Comparison



Arguably more important than the space, weight, and power savings afforded by server virtualization is the ability to decouple software from hardware which allows the AEGIS program to remove computing hardware as a capability limiter. The baseline or capability delivery process described in previous sections requires both hardware and software to be developed, tested, and certified together, ultimately creating the monolithic update cadence used today. By segregating hardware from software through virtualization, the AEGIS program can continuously deliver software upgrades to all virtual enabled platforms regardless of their underlying computing infrastructure and break the legacy baseline delivery process that has led to the average age of AEGIS software in the Fleet being over 10 years old. Figure 2 depicts how virtualization and virtual machine monitors segregate the hardware from software.

Figure 2: x86 - Virtualization Architecture Comparison



3. AEGIS Virtual Twin: Virtual Twin Pilot Events

PEO IWS established a government-industry team to implement AEGIS virtualization. Dedicated to increasing the speed at which capability is delivered to our Sailors as well as addressing the large cost burden imposed by the monolithic baseline process, the government-industry team developed, prototyped, and demonstrated the ability to run the latest AEGIS computer program in a virtual environment. The Program Executive Office for Integrated Warfare Systems (PEO IWS) then designed a portal system to field the virtual system on a ship, to field the VT onboard deployed ships to conduct rapid prototyping, proving the ability to conduct an end-to-end live fire engagement. The first application of the VT onboard USS Arleigh Burke (DDG 51) demonstrated the ability to run the AEGIS computer in a configuration small enough to fit under a dining room table, a fraction of the massive, multi-room requirements of the original hardware space. The VT established a one-way connection and passively tapped the Ship's tactical network and replicated system data including navigation, surface gun tracks, air and surface radar tracks, and timing data. In addition, the VT was successfully able to collect, store, and parse system data during the ship's underway training exercise.

Proving the ability to rapidly prototype, 16 months later, the team installed a VT onboard USS RALPH JOHNSON (DDG 114) and remotely delivered and prototyped an updated surface tracking algorithm. PEO IWS built on the successes aboard DDG 51 and demonstrated the capability to remotely send and receive modified computer programs while underway in less than 24 hours. During DDG 114's Combat System Ship Qualification Trials (CSSQT), the VT was able to record, assess, and transmit data back to a land-based test/development site. The land-based site updated and delivered a modified computer program back to the VT onboard DDG 114 while underway. Onboard engineers installed the modified computer program, in the VT, and continued data collection and assessment.

Working with innovative small businesses via the DoD's Small Business Innovative Research (SBIR) program, PEO IWS was able to quickly address a threat space and proved performance improvements. PEO IWS demonstrated the capacity to address gaps in the performance of current surface tracking systems. Specifically, the PEO addressed the challenge associated with discriminating small surface targets from waves and associated clutter in sensor returns. Adding to the challenge, there is a lack of a unified program that can continuously track all objects, and efforts to use the current sensors onboard the AEGIS platform to create an integrated picture of the threat environment have not reached a level of quality that meets the warfighter's operational needs. A multi-sensor tracker that can associate and integrate disparate sensor data into a comprehensive surface picture is required for the AEGIS Weapon System.

Eight months later, the US Navy furthered the use of AEGIS VT with two-way communications. In this test, the VT not only passively tapped the network and replicated traffic and radar signals but controlled radars and missiles to execute an engagement. The USS Thomas Hudner's (DDG 116) crew operated the VT to fire a SM-2 Block IIIA against an incoming air target, a significant step towards the future of the Navy's premier weapon system. The ability to close the fire control loop in a time-sensitive, deterministic computer program, marks an inflection point for the US Navy. "It is great to be a part of the evolution of AEGIS," commented Cmdr. Nathan Scherry, USS Thomas Hudner's commanding officer. "Virtual Twin has a tremendous role as the next step for the Guided Missile Destroyer's weapon system and I am really excited to see it advance both tactically and as a feedback loop for continuous improvement of the weapon system's software."

Proving the ability to implement a virtualized combat system in a reduced hardware footprint, rapidly prototype, and close the fire control loop represents significant progress towards changing the way Sea Power is delivered to the Hands of our Sailors. Realizing a vision of continuous delivery of capability to the warfighter will require a fundamental shift in business processes. In order to break the monolithic delivery of hardware and software and achieve continuous capability delivery, a comprehensive process overhaul will be required that incorporates program, technical, and cost considerations to improve combat system performance while reducing lifecycle costs. The first step to implementing the new business model of continuous delivery vice monolithic baseline delivery is defining value. Highlighted below (Table 2) are four use cases and associated cost, schedule and/or quality benefit allowed via the VT.

Table 2: Benefits of Virtualization

Functional Area	*Description*	*Cost / Schedule / Quality Impacts*
Software Development and Integration	*Increased competition and ability for 3rd Party development* *Improved ability for early integration* *Removes land-based test site throughput issues*	Schedule Quality
Test and Evaluation	*Ability to rapidly prototype in operationally realistic environment* *Improve data production/collection*	Cost Schedule

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Training	*Improve/advanced feedback* *Advanced training opportunities*	Cost Quality
Operations and Maintenance	*Reduced maintenance* *Elimination of lifetime buys* *Ability to modernize computing infrastructure through attrition*	Cost Quality

4. Expanding the Advantage: A New Capability Delivery Model

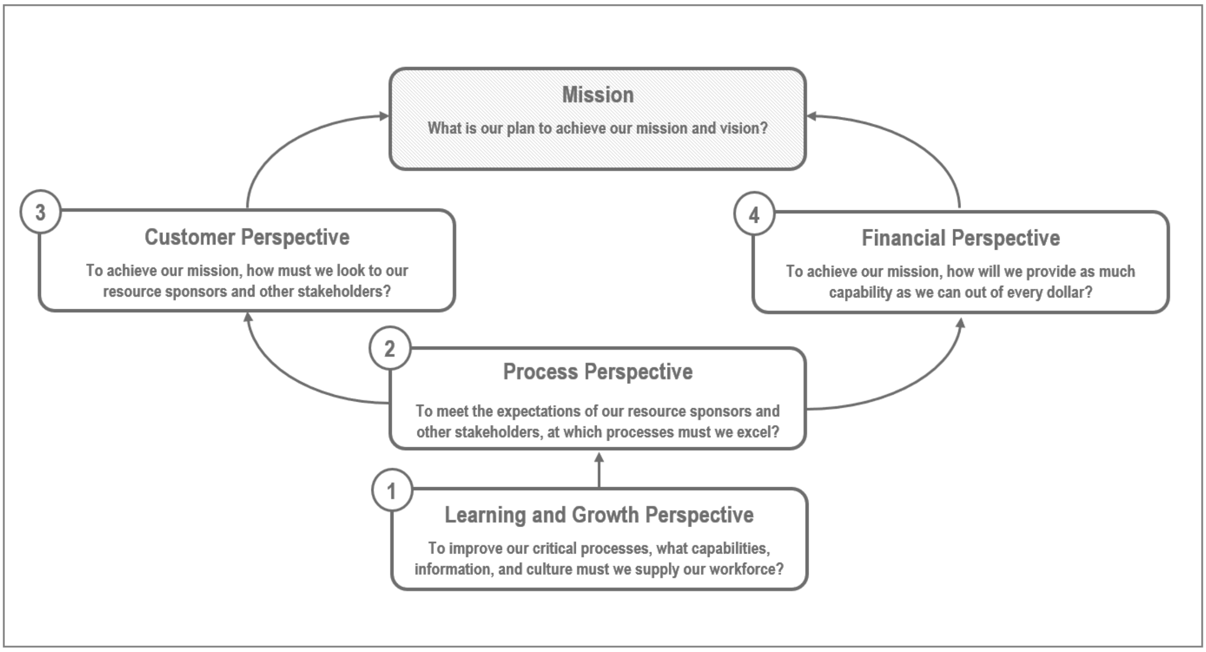
"As we look forward to the future, we must continue this momentum by leveraging every resource, expert, leading practice, and efficiency we can find – from all sources, private and public – in order to think anew about our business operating model."

Hon. Richard V. Spencer
76th US Secretary of the Navy
Department of Navy Business Operations Plan Revision 1.3, October 2018

In an increasingly complex environment, the US Navy is involved in a full range of global operations against adaptive adversaries who could take advantage of the ever-increasing pace of technological change. To ensure that ships remain ready for US Combatant Commander tasking, Naval Sea Systems Command (NAVSEA) released a strategic framework in January 2019 (Campaign Plan 2.0) aligned with the *National Security Strategy*, *National Defense Strategy*, and *Design for Maintaining Maritime Superiority 2.0.* The framework, associated priorities, and lines of effort released by Vice Admiral Thomas J. Moore emphasized an increased sense of urgency required for the 73,000-strong NAVSEA workforce to adapt to a changing global environment. By articulating how the strategic framework fits together to effectively respond to unexpected changes in the external environment, the highly visual framework is intended to mobilize the existing workforce to "Expand the Advantage." However, creating "visible performance improvements" in the near-term (Kotter, 2007: 4) while ensuring that the organization can envisage paths towards solutions as part of a new business operating model will require deeper engagement at all levels.

In their seminal article on performance measurement published in Harvard Business Review, Kaplan and Norton (1992) introduced the Balanced Scorecard framework, visually represented with four perspectives (i.e. learning and growth, process, customer, and financial) to translate vision and strategy. By integrating both financial and non-financial strategic measures, the Balanced Scorecard provides a tool that organizations, including Government, can use to more effectively balance short-term perspectives with longer-term drivers of organizational performance within a defined business operating model. Further developing the concept of the Balanced Scorecard in their first book, Kaplan and Norton highlight that "success for Government…should be measured by how effectively and efficiently" the needs of constituencies are met using well-defined, "tangible objectives" (1996: 180). Described by Kaplan and Norton as a model for value creation (1996) built on a consistent management philosophy (2000; 2001), the Balanced Scorecard now serves as an integrated management and performance measurement system (see, for example, Figure 3), consistently ranking as one of the top performance management tools for private and public sector organizations. While Kaplan and Norton's Balanced Scorecard is an important contribution to the field of performance measurement, it cannot be discussed in isolation as the US Navy looks to strengthen internal business processes and "quickly evolve towards an urgent, laser-like focus on greater speed, agility, and efficiency in the face of a rapidly changing operating environment" (Spencer, 2018).

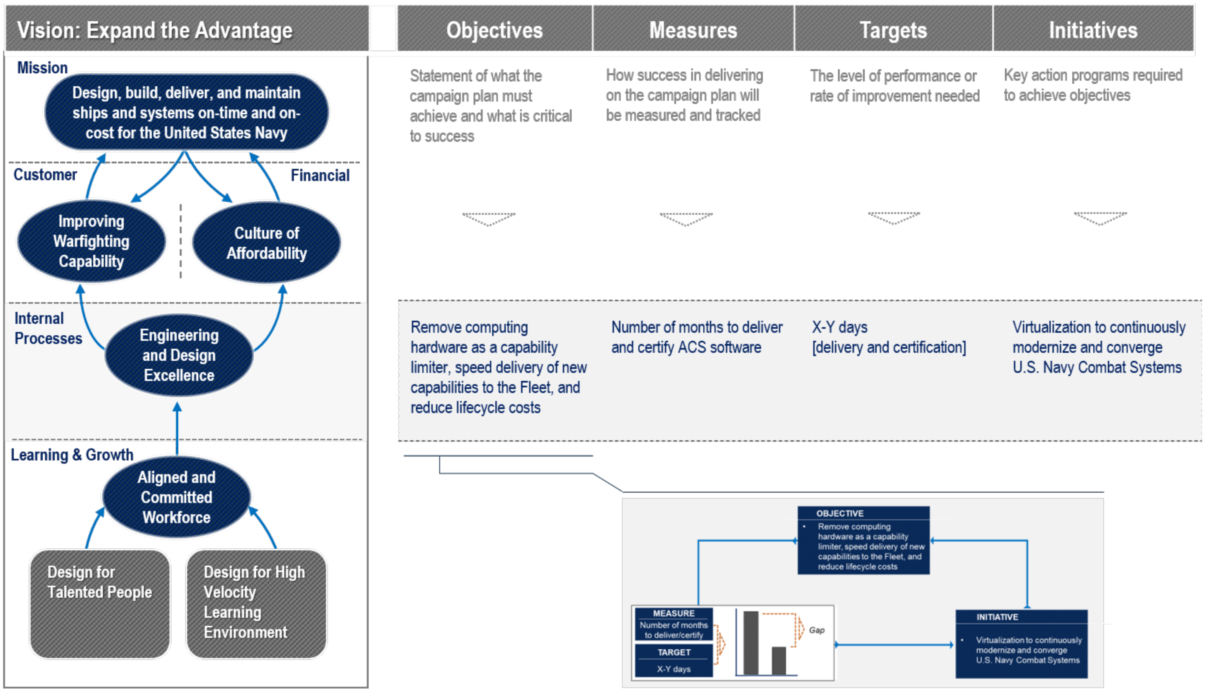
Figure 3: Balanced Scorecard framework organizing four perspectives to achieve mission objectives



Adapted from *The Strategy Focused Organization*, Harvard Business School Press (2001)

Recognizing that innovative methods are required to inject affordability and efficiency into internal business processes, the high-level NAVSEA vision statement has been aligned within the construct of a strategy map (Figure 4), using the Balanced Scorecard architecture to create a visual space for interaction. The design and execution plan for AEGIS VT translates two lines of effort: (1) a design for talented people; and (2) a design for a high velocity learning environment into the foundational learning and growth perspective for measuring intangible assets. Internal perspectives for the Balanced Scorecard focus on core processes required to deliver engineering and design excellence for continuous modernization, supporting the ability to "remove computing hardware as a capability limiter, speed delivery of new capabilities to the Fleet, and reduce lifecycle costs" (also, see Figure 4). Next, the adapted model balanced the customer centered mission priority of improving warfighting capability of ships with the financial perspective of ensuring a culture of affordability that respected the finite resources available for system-level modernization and upgrades. Finally, the Balanced Scorecard coordinated these four perspectives to support the organization mission to "design, build, deliver, and maintain ships and systems on-time and on-cost for the United States Navy." To this end, the AEGIS VT Strategy Map and Balanced Scorecard can serve as an integrating tool, effectively capturing improvement initiatives within a continuous modernization construct while channeling efforts towards a clearly defined strategic direction of converging US Surface Navy Combat Systems.

Figure 4: New Business Model



The use of a cause-and-effect logic structure is a key distinguishing factor within the Balanced Scorecard construct (Kaplan and Norton, 1996) and can be used as a method for ordering and scrutiny to align with COMNAVSEA's *Campaign to Expand the Advantage 2.0* and the CNO's *Design for Maintaining Maritime Superiority 2.0*. Without clearly defined linkages, the collection of program performance measures for the AEGIS VT effort will devolve into an administrative reporting burden instead of a powerful tool that enables the organization to quickly test and adapt to changes in the new business operating model. When used effectively, a performance measurement system creates new knowledge that can be applied to increase the organization's capacity to more efficiently and effectively solve the problem at hand. Paradigm changes to the existing software delivery process, for example, will require extensive engagement across a diverse set of stakeholders ranging from one-on-one internal leadership meetings to broader external forums with industry partners. By linking opportunities to enhance the organization's operational and strategic learning through methods of deeper inquiry, the AEGIS VT team will be able to capture the answers to two key questions: 1) "Are we doing the right things?" and, more importantly, 2) "Are we doing the right things right?" The main tool used to guide these discussions will ultimately involve the deconstruction of the quantitative and qualitative aspects of the AEGIS VT program into a series of objectives, measures, targets, and initiatives (see, again Figure 4). The clarity of the visual alignment between the technical objectives referenced in the previous section, including quantitative measures and targets, will continue to refine initial program assumptions regarding the use of AEGIS VT to "increase agility" and "drive affordability" (Geurts, 2019) as part of the efforts to continually modernize *Arleigh Burke* Class destroyers and deploy new capabilities at the speed of technology.

5. Conclusion

Today's monolithic capability delivery process cannot keep pace with the realities of emerging threats in a more complex environment and against increasingly technologically-sophisticated adversaries. An innovative approach must be implemented to maintain the warfighting advantage, and the VT effort has proved the ability to deliver real system performance improvements to the Fleet on a continuous basis. Senior Naval Leadership has recognized the need to change business processes, and the Balanced Scorecard construct promises a proven path forward. Nevertheless, changing an organization is a difficult and time-consuming process even when using the most innovative tools and methods. Key business model challenges will need to be addressed before the US Surface Navy can fully realize continuous capability delivery and its associated benefits. While the largest impacts will be felt within PEO IWS and its role in the development, test, and delivery of the AEGIS Combat System, a paradigm shift across the entire acquisition and naval engineering community will be necessary to embrace hardware-agnostic virtual machines and maintain warfighting dominance.

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