Littoral undersea warfare: a case study in process modelling for functionality and interoperability of complex systems

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Abstract: The goal of this investigation is to demonstrate the application of a process modelling approach to architect a System of Systems (SoS) capable of conducting Anti-Submarine Warfare (ASW) operations projecting to the year 2025. Process modelling is a methodology for architectural analysis for complex systems whose operation is characterised by 'processes' whose sequential execution may be scaled-up to understand overall system behaviour. It is ideally suited to address complexity and interoperability issues of an ASW SoS. New contributions of this work include the successful implementation of a process modelling approach to architect an ASW SoS and a cohesive set of results analysing its operation with future projections to the year 2025. We believe this work may serve as a foundation for future systems engineering research addressing interoperability and performance of complex systems whose function is closely tied to time-dependent processes, with particular application to military and security systems.

Keywords: littoral undersea warfare; Anti-Submarine Warfare; ASW; process modelling; system architectures; functional analysis; interoperability.

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1 Introduction

A process may be defined as a sequence of operations and involved events that lead to the production of some outcome. The successful execution of a series of processes will comprise a fundamental part of the operation of almost any Systems-of-Systems (SoS). It has been observed (Osmundson et al., 2004) that

> "architectural analyses of complex systems-of-systems, therefore, often involve analyses of systems processes, with the goals of identifying the most important process design parameters that affect system performance and understanding the sensitivity of system performance to variations in the driving design parameters."

SoS that strongly rely on event or occurrence timelines particularly lend themselves to analysis based on paradigms of processes. Indeed, complex time-dependent systems with many subsystems are often best decomposed as a series of processes whose sequential execution may be scaled-up to understand overall system behaviour. Interactions between processes within a SoS may be mapped and optimised from a design perspective founded on this method.

Process modelling is a methodology for architectural analysis based on this decomposition. Its use has been proposed for problems such as distributed information systems, logistics systems and manufacturing and distribution systems. It has been shown to be a particularly effective tool for analysis of complex systems with interoperability issues between a wide breadth of disparate system components (Osmundson et al., 2004).

In this paper, we apply a process modelling approach to develop a SoS capable of conducting Anti-Submarine (undersea) Warfare (ASW) operations projecting to the year 2025. The driving motivation of our work is to identify areas of future research, define high-level requirements and critical capabilities. While extensive research has been performed in ASW, no available work has addressed architectural issues on this level of abstraction. Our study is focused on an evolutionary approach through analysis of larger-scale functional issues, ideally guiding future efforts in lower-level design and system implementation. The principal aim was to elucidate synergies and trade-offs between broad component (asset), doctrinal and operational mechanisms in ASW systems, provide analysis and recommendation for future ASW architectures, and definitively recommend areas of future research and development for maximum impact to undersea warfare.

Through a process modelling approach we designed, modelled and simulated a range of architectures to analyse overall system functionality and to determine the interoperability between land, space and undersea subsystems to analyse performance metrics for future ASW operations.

1.1 ASW complexity

ASW is a unique problem, requiring the successful coordination of a huge amount of disparate assets in a very challenging operating environment. Critical issues contributing to the complexity of an ASW system include:

- *Functionality*: ASW systems must perform a range of functions with many metrics for optimisation.
- *Constraints*: ASW operating environments and purpose instil a large number of competing and tightly coupled constraints.
- *Connectivity*: ASW subsystems are highly coupled and operation is strictly dependent on timelines. Connectivity and interoperability are very challenging to map and model in such a system.
- *Heterogeneity*: ASW subsystems are heterogeneous and span many disciplines. Human interaction is critical.
- *System dynamics*: ASW system behaviour, doctrine and performance metrics can significantly change over time.
- *Reducibility*: while subsystems may be reduced, system behaviour is very challenging to decompose due to coupling.
- *Observability*: many ASW system behaviours are not observable globally due to the nature of the system and its operating environment. Architectures must be decentralised to so as not to be sensitive to hidden states, yet, must still provide an assurance of global performance.

Recent technological and political developments have resulted in a proliferation of tools and constraints for ASW activities. With respect to future ASW operation, Potter (1999) stated that:

> "The challenge is not in identifying useful technologies, but in bringing them to bear effectively on the tactical problems of naval combat scenarios. These technologies will make their mark when integrated (with): 1) Diverse platform types (surface and submarine vessels, remote operated vehicles (ROV's), autonomous underwater vehicles (AUV's), drones, aircraft and satellite) will be used in concert. 2) Diverse sensing technologies (multi-static passive and active, covert active, VHF active, laser) will be employed in a coordinated search over all useful ranges, bandwidths, resolutions and degrees of covertness required to span interests and needs, and 3) Systems will employ 'smart' processing and AI in the detection, classification and prediction of environmental developments."

These statements are backed up by Forecast International in their recognition of a trend of merging technologies such that limitations on weight, space and endurance constraints will no longer conflict, and any sensor can potentially be installed on any platform to provide on-time, accurate and faster processing for increased capability across a wide gamut of assets (*The Market for Airborne ASW Sensors*, 2004).

1.2 Methods of analysis

We developed and implemented a process-based hybrid systems engineering analysis in this work, combining the approaches of Sage and Armstrong (2000) and Eisner (2002), with process modelling techniques inspired from Osmundson et al. (2004). Fundamentally, the ASW problem may be addressed within the context of the 'architectural views' methodology described generally by Maier and Rechtin (2002), but more explicitly by Buede (2000). Buede specifically proposes an architectural model comprised of a functional architecture, physical architecture and an operational architecture. The functional architecture describes the purpose ('functions') of the system, the operating conditions under which it must execute these functions and how achievement of functional capabilities is met based on performance measures. The actual delineation of physical system elements, including technological components and system assets that must be synthesised into an integrated SoS is subsumed by the physical architecture. The mapping between the physical architecture and its resources to the system functions, in a manner suitable for quantitative analysis within simulation framework, falls within the construct of the operational architecture.

The overall goal dictating the structure of our approach was to ensure that process modelling and analysis remained both iterative and comprehensive such that performance and interoperability were fully considered. The methodology was designed to dissect system processes and highlight the interactions within the system. In this approach, all processes must be repeatable for designing, developing and operating the system under study. This approach ensures that many alternatives will be considered, and that the proposed solution will be a refined system.

1.3 Organisation of paper

The following section describes the problem identification in detail, illustrates the major functions and decomposition of the ASW SoS with focus on the process timeline to be modelled, overall needs and functional flow. Section 3 details the architectures designed to address the needs and fulfil system objectives. Section 4 expands on the end-to-end process model developed to analyse each system architecture as it relates directly to executing desired functions of the system and to analyse the interoperability of all system components. Section 5 provides model simulation results and Section 6 makes recommendations for future ASW research and doctrine.

2 Problem description, objectives and functional decomposition

> "Whosoever can hold the sea has command of everything."

Themistocles (524-460 BC)

In recognition of the complexity, criticality and transforming role of undersea assets, the US Deputy Chief of Naval Operations for Warfare Requirements and Programs directed the Wayne E. Meyer Institute of Systems Engineering at the Naval Postgraduate School to conduct a study of SoS architectures for the conduct of undersea warfare in the littorals projecting to the 2025 timeframe (Naval Postgraduate School, 2005).

The motivation for the research was the development of a full systems engineering analysis of potential littoral ASW addressing as broad a scope of systems as is feasible, starting with the current architectures of record as the baseline.

2.1 ASW introduction

While Director, ASW Division in the Office of the Chief of US Naval Operations, Vice Admiral John Morgan, USN (Morgan, 1998) summarised ASW complexity with the following 'truths':

1 ASW is critically important to sea control, power projection and direct support to land campaigns

2 ASW requires a complex mosaic of diverse capabilities … (demanding) a spectrum of undersea, surface, airborne and space-based systems

3 ASW is hard … the near shore regional/littoral environment poses a very challenging ASW problem.

The US Navy defines the primary goal of ASW as denying an adversarial force the 'effective' use of their submarines (United States General Accounting Office, 1999). While the act of 'denying' can manifest itself in a range of diplomatic, military and political options, the focus of our system was to directly deter an enemy submarine from its mission and, if need be, neutralise it.

A SoS accomplishing this goal will subsume a process driven timeline consisting of the specific actions of detecting, tracking, localising and neutralising (United States General Accounting Office, 1999) submarine threats. Existing architectural constructs seek to accomplish this through a mix of naval platforms including: aircraft, surface ships and friendly submarines. In the near future, a range of unmanned vehicles will also join this set of platforms. Individual platforms can be further broken down into their associated weapons and sensor systems. The coupled combination of platforms, weapons and sensors, as well as the operational tactics and doctrine that dictate their combat employment, are critical to the successful completion of any ASW mission.

2.1.1 Limitations in existing architectures

There exists a breadth of limitations in today's ASW architectures, particularly given the lack of attention the topic has received (in the USA) in the last 15 years. Current architectures have been characterised as 'inefficient' because the process is "sequential, asset intensive and require[s] operational pause (sometimes lengthy) to prepare a limited area to support naval force operations with acceptable risk" (Benedict, 2004). Many recent findings have corroborated this assessment, in particular with respect to the near-shore (littoral) region.

We believe three main factors have demanded an evolutionary shift in ASW architectures:

- *Environment*: legacy systems in place today have been designed for "nuclear submarines engagements in the open ocean environment" (United States General Accounting Office, 1999). Shifts towards littoral operations demand systems that account for near shore oceanographic phenomena.

- *Technology*: modern submarines have increased capabilities (advanced diesel and Air Independent Propulsion (AIP) power plants, etc.) that support quieter and more efficient operation over time. The presence of unmanned assets introduces a wealth of complexity/interoperability issues that traditional systems do not address.
- *Function*: future missions and envisioned adversaries have changed the context of submarine operations. Holland (2005) summarised this transfer stating "while the number … is lower, the value of today's individual targets is high, they are fewer and faster: much more difficult to find and hit". Effective littoral ASW operations require sensors that can easily adapt to different operational environments and carry out their mission with a high probability of success (Naval Doctrine Command, 1998).

2.1.1.1 Littoral region The littorals are characteristically 'green or brown water' – an often perplexing mix of acoustic multipath or limited range areas. Prediction of expected acoustic performance is difficult and even accurate predictions can be quite ephemeral due to numerous changing factors in the near-shore waters. While these acoustic conditions make sound-based ASW difficult to execute, they also make the planning nearly impossible to optimise. As a brief generic example, suppose an area search requires sensors placed in a geometric pattern based on the expected detection range (which can be predicted based on water depth, temperature, salinity, wave action, shipping density and a number of other factors). Further, suppose that there are considerable costs involved with the placement of the sensors – either the cost of the sensor or the cost of emplacement or perhaps both. In a resource constrained world, efficient force deployment is called for and likely draws from a predetermined inventory that was predicated on expected requirements. Now suppose the detection ranges can vary by a factor of 10 over the course of a single deployment or in the contemplation of deployment to different locales – what is the properly sized force for such uncertainty? Availability of assets quickly becomes a direct result of strategic budgetary decision making.

The littoral environment is particularly challenging due to the ability of an adversary to conduct Anti-Access and Area-Denial campaigns from shore-based sites, while limiting exposure of their own naval forces. The conduct of such a campaign in the littorals will likely be conducted with submarines, mines and associated undersea force components that grant the 'local' submarine fleets distinct advantages, such as the ability to hide in background noise.

2.1.2 Summary

Current day systems restrict today's ASW to platform-centric operations conducted as an enabling phase distinct from the main efforts to prevent unacceptable losses of singular high-value units. Also, multiplatform littoral ASW is largely based on experiences and knowledge gained through open-ocean ASW which are difficult to parallel today. As improved equipment and updated tactics, techniques and procedures are developed, the state of ASW must evolve from a sequential, platform-centric reality of today to the concurrent network-centric construct of the future (Chief of Naval Operations, 2005).

2.2 Needs and futures analysis

2.2.1 Concept development

Our team's primitive problem statement was to "develop a SoS architecture for the conduct of undersea warfare in the littorals in the 2025 time-frame" (Naval Postgraduate School, 2005). The SoS is defined as alternate mixes of legacy and technology-driven future platforms and sensors that will leverage advances in order to provide with the most effective means available to prevent the enemy ('red') from successfully employing undersea assets against friendly ('blue') forces.

2.2.2 Stakeholders

Prior to any decomposition, we conducted an extensive stakeholder analysis for our system. A brief summary of the stakeholders identified were:

- *Decision maker*: US CNO.
- *Clients*: North Atlantic Treaty Organisation (NATO), US Combatant Commanders (COCOM), US Department of Homeland Security (DHS), US Naval Intelligence Community.
- *Sponsors*: US Program Executive Office (PEO), US Type Commanders (TYCOM), US Department of Defence (DOD) US Department of Transportation (DOT), US DHS, US Congress, US Integrated Warfare Systems (IWS).
- *Operators*: COCOM, NATO, Fleet Commanders [FLTCDR], Surface Warfare Officers [SWO], Submariners, MPA Personnel, Special Operations Forces [SOF], Explosive Ordnance Disposal [EOD], Sailors, Contractors (Defense Contractors), Fleet ASW Command.

2.2.3 Effective needs statement

Via careful analysis, system decomposition, input-output modelling and interviews with stakeholders, the effective needs statement for the system process was found to be:

> Design a future littoral undersea warfare system that denies enemy ('red') under water forces (submarines and UUVs) effective employment against friendly ('blue') forces within the littorals during the 2025 time frame.

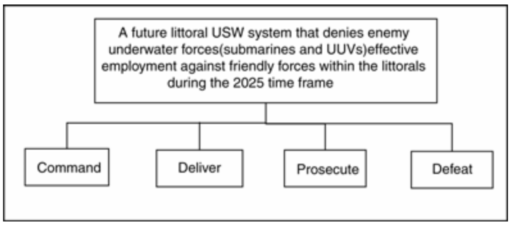
From this statement, system requirements can be generated through functional analysis.

2.3 Functional analysis

Based on needs and stakeholder analysis, a functional hierarchy, composed of top-level functions that had to be met in order for the system to perform, was developed. Top-level functions of the functional hierarchy for the ASW SoS challenge were Command (communicate), Deliver (deploy), Prosecute (search) and Defeat (Figure 1). The extent to which overall ASW mission objectives must be executed can be generally measured in terms of quantity, quality, area coverage, timeliness and readiness posture. All system attributes, wants, needs and desires were characterised in terms of the degree of certainty in their estimate, the degree of criticality to system success and relationships to other requirements.

A decomposition of each briefly follows.

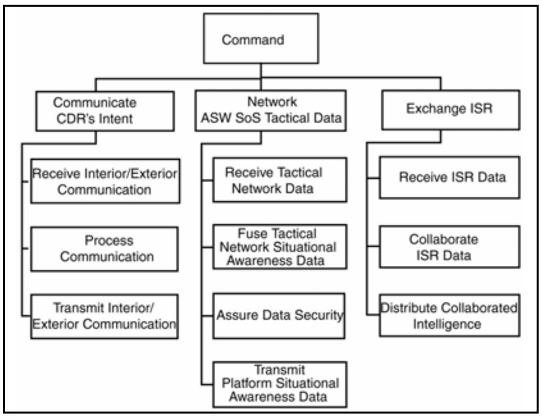
Figure 1 Top-level functional hierarchy



2.3.1 Command decomposition

The Command function is identified as the top-level function for the overall SoS functional hierarchy. The subfunctions for Command are: communicate the commander's (CDR) intent, network ASW SoS tactical data and exchange Intelligence, Surveillance and Reconnaissance (ISR) data. The supporting subfunctions for Command are architectural functions. Current command, control, communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) system functions can be viewed from multiple perspectives. In order to design C4ISR architectures, the SoS needed to be addressed from an architectural framework perspective. For the purpose of this study, the C4ISR functions will consist of a communication architecture, an ASW tactical data network architecture and a separate ISR architecture. Figure 2 illustrates the Command functional hierarchy and supports the C4ISR SoS effective need.

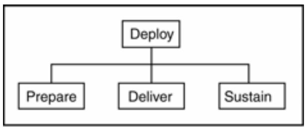
Figure 2 Command functional hierarchy



2.3.2 Deployment decomposition

Figure 3 shows the key functions the Deploy portion within the SoS, in order to accomplish the needs, wants and desires of the stakeholders. Subfunctions include: prepare – the ability to be equipped for rapid deployment via air, surface and subsurface assets external to the theatre of operations; deliver – the ability to interoperate with both legacy and future deployment systems and sustain – the ability to provide the logistical support necessary to sustain those assets already within the area of operation (AO).

Figure 3 Deploy functional hierarchy

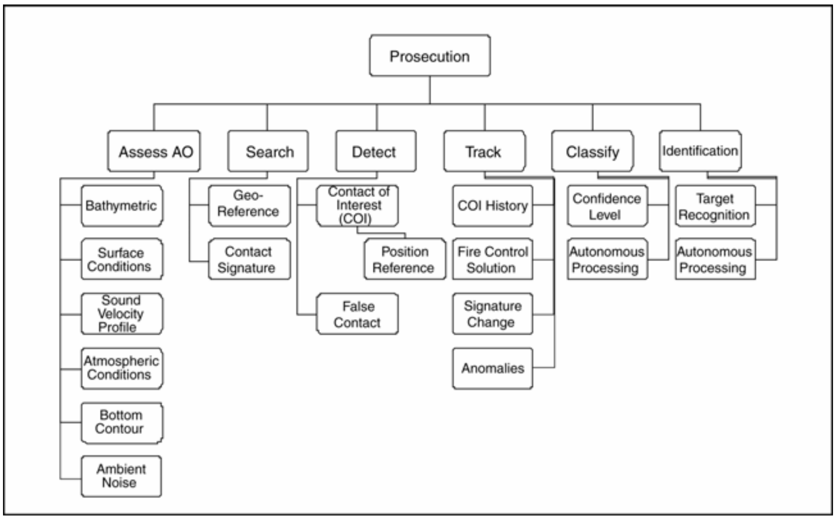


2.3.3 Prosecute decomposition

The ASW Search environment can be broken down into three distinct tasks: identifying, developing and finally, combining the tasks. The task of identifying a threat in the ASW problem is just that – determining that the threat is an ASW threat. Once a problem area has been identified as a threat, the Navy will isolate the location, determine its identity and develop a fire control solution. All of this is done through the use of current ASW sensors and platforms. The Development Tasks help the user understand the functions of the respective sensors and assets in more depth, and how these assets interoperate with the environment, sound profiles and other elements found in the sound equation. The Combining Tasks portion puts the current sensors and their functions and performance factors together, and with some analysis, finds ways to improve detection and localisation.

For the purposes of functional decomposition, the 'Prosecution' main function was partitioned into six distinct subfunctions of assess, search, detect, track, classify and identify. Figure 4 examines an initial amplification of each subfunction. For instance, under 'track', it is expected that this function encompasses maintaining a Contact of Interest (COI) history, developing a fire control solution, managing contacts for signature changes and developing criteria for anomalies. This reasoning was applied to all six subfunctions in the decomposition.

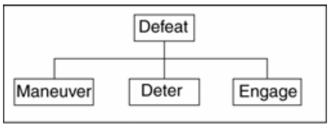
Figure 4 Prosecute functional hierarchy



2.3.4 Defeat decomposition

Figure 5 shows the overall functional hierarchy of the Defeat function. Subfunctions include: manoeuvre – the capacity to use energy storage and propulsion technologies to increase AOR coverage and time on station; deter – the capacity to present a show of force or presence to dissuade enemy opposition or movement and engage – the capacity to neutralise or disrupt the enemy's ability to perform a desired mission. Deterrence and engagement were considered beyond the scope of this project. Additionally, the manoeuvre function and the objectives that followed were considered as a set of the functions of prosecution.

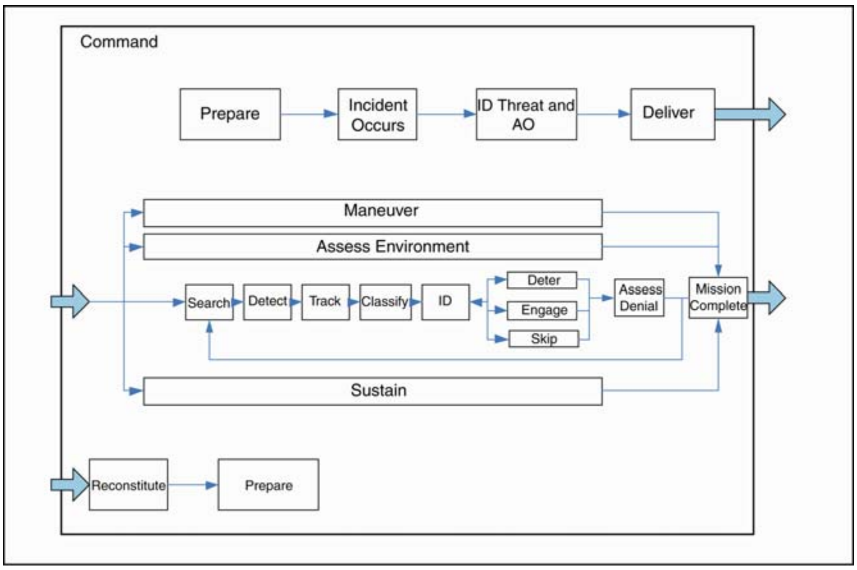
Figure 5 Defeat functional hierarchy



2.3.5 System functional flow

In the process modelling approach to this problem, functions are discrete actions necessary to achieve the system's objective. The branching and, most importantly, time sequencing of the SoS functional flow is critical to addressing the littoral USW problem. Should the branching and sequencing not be addressed, the SoS system will become rigid and unresponsive to the needs of the stakeholders. The functions of our system, for the littoral USW challenge, will ultimately be performed or accomplished through the use of equipment, personnel, sensors, logistical support, sustainability and adaptability throughout the life cycle of the system and are shown in Figure 6. It is important to note that the Command function of the SoS system remains constant throughout the SoS system functional flow.

Figure 6 ASW system functional flow diagram



This operating concept describes our view of Littoral ASW in the 2025 time frame. Emphasis is placed on the full integration of deployed ASW platforms into a total ASW combat system with the ability to produce a 'thinking field' of fully networked combat, communication, sensor and weapons systems designed to strip the oceans away from our adversaries. We envision these thinking fields to be a SoS comprised of air, surface and subsurface platforms, both manned and unmanned, with the ability to rapidly surge from home bases, if not already on station as part of a forward-deployed strike group. The SoS will serve to deny the threat posed by enemy submarines within the world's oceans, including the littoral waters. Specific to our analysis is the threat posed by next-generation AIP diesel submarines within the littorals, believed to be a major threat for the 2025 time frame.

We define the ASW Search and Engagement mission to be comprised of five phases: Operational Planning, Search Planning, Search Execution, Search Evaluation and Contact Evaluation. The intent of this concept of operations is to accurately represent future ASW operations and standardise analysis efforts. Operations in the 2025 time frame will be centred on dominating the littorals by rapidly achieving area control despite difficult sound propagation profiles and dense surface traffic. The operating environment will be complex. It is assumed adversaries will be operating with significant advances in both stealth technology and weapon lethality (United States Navy, 2005). Therefore, it is essential that a system be developed that can avoid detection and be resistant to attack, as well as to penetrate and function in denied areas for sustained independent operations (Department of the Navy, 2004). Our team considered various SoS architectural alternatives that can achieve these broad objectives.

2.3.6 System requirements

Through extensive research and consultation with our stakeholder population, we determined a set of Littoral ASW requirements for the SoS detailed in Bindi et al. (2005). Requirements were broken down into each of the identified functional areas: Deploy, Prosecute, Defeat and Command. Broadly, our purpose was identified to design a SoS with the capacity to:

1. begin ASW operations in the Operations Area (OA) within 72 hr of tasking, neutralise the threat within 10 days, and sustain that level of denial for 30 days to permit follow-on operations
2. prosecute identified 2025 ASW threats
3. reduce red threat platform performance
4. transmit and receive communications, data and ISR information across a secure and survivable distributed control network.

3 Architecture design and alternatives

Our team developed four viable alternatives for conducting ASW in the littorals. Each of the alternatives is centred on a unique concept, as implied by their respective names. The alternatives can be described as follows:

1. Tripwire
2. Sea Tentacle

3 War of Machines
4 Littoral Action Group (LAG)
5 The four alternatives generated provide a common baseline for simulated operations.

Two aspects important to the scenario are addressed in each alternative. The first is the concept of 'harbour gate'. This concept is built into the alternatives with sensors acting as tripwires for submarines entering and leaving ports. The second issue is the concept of networked sensors and is also incorporated into each of the alternatives, providing for the ability to detect, track and classify any underwater enemy submarine or Unmanned Undersea Vehicle (UUV) present in the AOR.

3.1 Assumptions

3.1.1 Operational scenario

In order to establish a method of comparing and evaluating current and future ASW force structure alternatives, our team developed a series of scenarios that scoped critical aspects of our proposed operating concept. Scenarios focused on capabilities in three functional areas: the ability to form a 'Protected Passage' of the Sea Lines of Communication (SLOCs) and to protect forces during transits, the maintenance of a 'Maritime Shield' that would deny submarine access to operating areas and the ability to 'Hold at Risk' enemy submarines throughout the maritime theatre (United States Navy, 2003). Principal efforts focused on the most challenging of these scenarios – a 'hold at risk' mission conducted in defence of an island nation in a confined littoral environment.

In the selected scenario, a red underwater force is preparing to conduct offensive operations within an island nation strait. The blue force is required to defend this island nation from threatening enemy undersea action and possible invasion. Blue forces will be supported by the deployment of several strike groups into the region to form a sea base, but before they can operate effectively within the region, the red submarine threat must be located and neutralised. The ASW SoS are detached then to the strait operational area in advance of the strike groups. It is assumed one red submarine is operating in the strait while two additional red submarines equipped with UUVs are preparing for offensive patrols. Denial of red underwater force operations is deemed critical. During the SoS transit, the two additional red submarines, previously reported in port, are located getting underway and may have deployed the strait.

3.1.1.1 Specific locale We constructed a simple campaign scenario as a frame of reference to use as a baseline to judge competing system alternatives as they entered into the analysis of littoral ASW. A decision was made to focus on what many subject matter experts consider the most challenging littoral environment – the defence of an island nation in confined waters. This restriction led to the decision to model the environment of the Bass Strait separating Australia and Tasmania, which was chosen as a characteristic representation with oceanographic parameters that well-define littoral operations. Logistical deployment was also based on reaching this region.

The basic campaign scenario calls for blue forces to rapidly respond to aggression against the relatively undefended Tasmania. Specifically for this study, blue forces must deploy into the Bass Strait to neutralise red submarines and their associated UUVs, within three days of notification, and to facilitate follow-on operations designed to deter a complete invasion. This scenario is not intended to serve as a campaign analysis, test future operational plans or suggest any future threat. It was simply chosen based on the unique geography of the strait and the wealth of open access environmental data available.

The various alternatives for the littoral ASW SoS were each evaluated in their conduct of the ASW search and execution mission with the task of neutralising the enemy underwater threat. Specifically, each alternative SoS was to be evaluated on their performance to begin ASW operations in the operating area within 72 hr of tasking, neutralise the threat within 10 days, and sustain that level of denial for 30 days to permit follow-on operations.

3.1.2 Futures analysis and threats

The littoral environment presents a myriad of threats to ASW operations. For example, (Naval Doctrine Command, 1998) stated

> "A submarine force composed of a few relatively unsophisticated submarines is capable of conducting coastal defense or sea denial missions. Such a force can attack merchant and logistics shipping, conduct covert offensive mining, support special operations forces, attack amphibious ships, and hold regional naval forces at risk."

Technology proliferation has broadened the capacity to field a credible submarine force. It is likely that over the next 20 years access to minisubmarines, improved submarines with extended underwater endurance and UUVs will grow significantly. We have identified four specific threat platforms for the purposes of this study:

- *Diesel-powered submarines*: diesel-electric submarines are readily available and easy to acquire, creating a likely threat well into the 2025 time frame. This platform presents smaller space requirements than a nuclear submarine plant. Diesel propulsion submarines provide reduced chances of visual, heat or magnetic counterdetection.
- *Nuclear-powered submarines*: nuclear-powered submarines possess increased range and on station time. This plant provides the most autonomy when patrolling for extended periods of time. Nuclear-powered submarines are susceptible to a high thermal-acoustic signature.
- *AIP submarines*: advances in AIP and associated technologies for use on submarines continue to be made at a rapid pace. Producing no exhaust heat, AIP submarines will be difficult to detect, while fuel cells power undersea operation for weeks without surfacing. Power outputs of AIP technology are significantly less than diesel or nuclear submarines; AIP technology is most valuable in low-speed, long-range submersibles.
- *UUVs*: UUV assets will assume a greater role in operations over the next few decades. These highly versatile vehicles are flexible for launch from a variety of platforms and are capable of operating in autonomous or controlled modes. Individually, the UUV is the least capable of submersibles due to limited range and the automation capabilities it must have, but resources allow for redundancy in deployment.

3.2 Alternatives generation

Alternatives generation portion was completed in two distinct steps. The first step involved detailed research within each top-level system function to determine which entities were capable of accomplishing the ASW SoS associated subfunctions. Specifically, we identified future or existing systems and/or methods capable of performing required functions (command, deploy, prosecute, defeat) in our decomposition and objectives hierarchy to generate effective alternatives to the ASW littoral problem of 2025.

In the second portion of the alternatives generation process, individual components from the generated function-specific lists were combined to create a series of SoS architectures capable of performing the defined ASW mission. Although thousands of architectures could result from the combinations, and numerous SoS were seriously considered, only four were finally determined to be distinct, feasible and useful for follow-on modelling and analysis.

3.3 Alternative architectures

3.3.1 Alternative 1: 'Tripwire'

Summary: the tripwire alternative uses a combination of UUVs and Advanced Seaweb-based sensor components capable of assessing the oceanographic environment, while simultaneously searching, detecting and tracking red submarines throughout the AO. The Advanced Seaweb sensor components work in conjunction with the UUVs to create a complete underwater sensor network.

The initial network will be focused around the 10 NM × 10 NM water space surrounding a red port facility. Any COI that is detected by an undersea sensor or a UUV during the prosecution phase will be communicated through the underwater network and to a Global Information Grid (GIG). The GIG will simultaneously hand off the information to a UUV for the purposes of tracking and classification. This underwater sensor network will generate a comprehensive picture of the AO.

Assets: 50 Seaweb-based sensors and 5 UUVs are air-dropped per harbour.

3.3.2 Alternative II: 'Sea Tentacle'[1]

Summary: the Sea Tentacle alternative combines all assets of the Trip Wire alternative plus a specially designed ship in complementary work by our sister team (Black et al., 2006) accompanied by an MH-60 detachment in order to successfully conduct ASW in the littorals. Once assets are inserted into the AO, the effective utilisation of these assets will be paramount to achieving required sensor coverage. UUV assets will provide multiple capabilities while on station including operating submerged for extended periods collecting, receiving and transmitting data collected by its sensors.

Assets: covering the AOR of a 100 NM × 200 NM box, Sea TENTACLE incorporates 3 Sea TENTACLE ships, 144 large vehicle UUVs, including 144 UUV sleds transported by the large vehicles that detach from the large vehicle to create a stationary bottom sensor, 864 light-weight UUVs that form the communications and 'brains' of the sensors and 2304 man-portable UUVs deployed from the UUV sleds that spread out to form the sensor web.

3.3.3 Alternative III: 'War of Machines'

Summary: in the War of Machines alternative, a combination of sensors, specific to each type of platform, will be utilised to develop a complete and detailed surface and subsurface picture of the AOR. This alternative deploys a series of UUVs and recharging stations designed to provide a real time tactical assessment in the AO. The combination of UUVs and their recharging stations allows for extended presence without personnel risks. This alternative provides for a robust and overlapping sensor suite capable of detecting any enemy submarine whether it is operating underwater or surfaced.

Once a submarine has been detected, assets in this alternative will be capable of accurately tracking an enemy submarine while simultaneously coordinating with other unmanned platforms relaying detection and tracking information to ensure a constant track is maintained. Because of the extended tracking capability, this alternative will also be able to determine with a high level of confidence that the tracked contact is indeed an enemy submarine (higher classification confidence).

Assets: at any given point in time, only 40 operational UUVs will be required to effectively cover the AO. If the UUVs are recovered and maintained, only 60 UUVs along with 12 recharging stations will be required to effectively cover the AO. If the UUVs are not recovered for maintenance, then 160 UUVs and 12 recharging stations will be required to cover the AO.

3.3.4 Alternative IV: 'LAG'

Summary: the LAG, when operating in the AO, will conduct coordinated littoral ASW operations with all available assets and sensors. These operations will be driven largely by the presence of submarines, both organic and inorganic to the LAG, and the endurance and capabilities of onboard unmanned assets to extend the reach of friendly forces as far inside the AO as possible while holding the enemy at risk. Assets in this alternative rely on high speed, manoeuvrability and low detectable signature to attack and withdraw in the shortest amount of time.

Fundamentally, this alternative may be viewed as the closest to current ASW operations, with the addition of new surface platforms which are more aptly suited for the task in the littorals.

Assets: LAG Composition: 2 SSN (on station), plus 1 DD(X) including organic assets and 3 LCS (ASW) including organic assets.

4 Modelling and analysis

A time-dependent process model subsuming the sequence of all system events was developed to analyse each architecture as it related directly to executing desired functions of the system and to analyse the interoperability of all system components within this context. To enable a systematic and comprehensive study on ASW architectures and the factors that affect their performance, this model was built and implemented in a simulation environment. Critical information on each phase of the process for each architecture was gathered and directly incorporated into the model.

The goal of the simulation was to capture the functions, interfaces, delays and systemic characteristics to a desired level of fidelity. The resulting model emulates the processes involved in all phases of Figure 6. It provides a means for full accounting of the transport vehicles, forces, equipment and supplies and their interactions within the system and allows studies of the dependencies of system architecture performance on design and noise factors. Given the breadth of processes involved in our ASW SoS, we used a combination of simulation packages with information transferred between them for each top-level system function.

The specifics of the ASW scenario used for modelling, such as geographic location and number of enemy submarines, were determined by research by our team with extensive stakeholder input. Required model and data preparation followed directly from the team-generated scenario. Data to be used as model inputs included both friendly and hostile (Blue and Red) platform and system characteristics, abilities, vulnerabilities and tactics. A Red force structure was generated with associated doctrine, tactics, operations, schedule and vulnerabilities. This structure was held constant for all alternatives and replications.

4.1 Command/information transfer

Command was the only top-level system function that was not driven by the process timeline. Modelling for the littoral USW C4ISR system was divided between an Excel-based model for use in modelling undersea acoustic data transfer and an EXTEND (discrete event)-based model for modelling above sea data transfer. The two models were constructed in an effort to offer insight into system performance and provide direction for tactical and operational decision-making between various alternatives. Additionally, the two models offered insight into constraints on system performance and utility. The models support previous needs and objectives analysis by quantifying predicted performance that can be compared to the identified metrics and key requirements. Estimated sensor detection ranges, system power constraints and notional nodal spacing, focused model inputs to produce resultant model outputs. Specific models were created for undersea and atmospheric communications. Technical details of the undersea and atmospheric information transfer models used to support the SoS simulation (Bindi et al., 2005).

4.1.1 Undersea information transfer

Extensive modelling based on available data demonstrated environmental ambient noise to have the greatest effect on system performance. The model indicates that as frequency increases, transmission ranges decrease and as transmission power increases, transmission ranges increase. At an acceptable SNR of 100 dB, transmission ranges vary from 1200 to 2200 m depending on frequency and power at 42 dB of average AN. Additionally, when packet size is taken into account, broadband capacities at a 10 kHz carrier frequency and 8-bit digitiser constrain an undersea system by limiting the number of nodes that can make up one network. If 10 nodes were needed in a single network component, then the maximum data rate achievable would be 4000 bps on that 10 kHz carrier frequency.

4.1.2 Atmospheric information transfer

After completing a thorough sensitivity analysis on network performance, based on additional nodes, input and output common operating picture update message sizes, and the frequency update messages were sent, it was found that a relationship exists between the number of participant nodes, node capacities and the update message sent frequency. Specifically, the frequency that update messages were sent has the greatest effect on network system performance.

For a network system with more than 15 participants where limited capacity nodes such as the 0.5 MB-capacity node are present, update messages should be less than 0.12 MB and sent at a frequency that allows for consistent processing to support COP update fusion times of less than 0.5 sec locally and 1 sec for final nodes in a relay. When COP update message sent frequency exceeds the ability of limited capacity nodes, participant nodes with receiving capacities less than 0.5 cannot be expected to perform critical, time-sensitive operations. The relationship between frequency and network participant numbers from this model that was found to optimise system performance was determined to be 4 to 1 for a 5-participant node system and 16 to 1 for a 17-participant node system. As a result of this finding, a determination was made for the message combination and the frequency update messages were sent. The determination made was that the central node fusion of update messages sent should occur at a rate of 1–*N*, *N* for the number of participants to 1 output COP update message. Additionally, COP update message size should increase as the update message sent frequency is reduced.

With respect to bridging undersea and atmospheric battlespace networks, forming a radio frequency gateway between sea sensors and air data networks was represented in this model by the addition of a single, limited-capacity, transmitting node. Analysis of the node indicated that for the node to effectively operate, transmitted packets should be half the node's capacity. For this model, extremely small amounts of data were contributed by the gateway node. Gateway node packets were set at 500 bits for a transmit capacity of 1.0 KB. Data latency due to transmitter capacity that was experienced did not have a significant effect on the overall system performance. Since gateway node update rates followed a triangular distribution between 10 and 20 sec, with a respective mean value of 15 sec, an excessive amount of backlog or node exhaustion did not occur. A 15-sec mean value gateway transmission time was proven by this model as a feasible capability that has a major impact on the reduction of the prosecution timeline.

4.2 Deployment

In an effort to provide a rapid response solution to ASW in the littorals in 2025, the use of subsurface and/or airborne delivery methods of UUV assets appear to be the most viable approach. However, an initial assumption considered for this problem will be the blue force's military's lack of air superiority in the AOR. This assumption places greater emphasis on the use of subsurface deployment vehicles and airborne delivery methods that can be deployed beyond the boundaries of the AOR. Additionally, if surface ships are to play a viable role in the littoral region, it will likely be from a distance outside the AOR unless their operation within the AOR maximises success, while maintaining a minimal risk to Blue forces.

Research was collected on all potential deployment assets: surface, subsurface and air. Quantifiable characteristics such as speed, payload capacity, logistics requirements, logistics capabilities and sustainability were recorded and analysed for potential capabilities in each of the alternatives considered. Data regarding each individual asset, its logical point of origin, transit route and distance to the AOR were evaluated. Collective and exhaustive research was conducted on all assets necessary to deliver SoS components to the AOR. Characteristic data, consisting of performance and design specifications, were utilised in conjunction with statistical data collected from historical performance and operations. This characteristic data was utilised when considering existing deployment assets. When researching programs of record for future systems, analogies between similar existing systems, as well as a review of material concerning these systems, predicted operating characteristics and test and evaluation data were utilised to develop data for implementation in the deployment model. These characteristics were entered into a process-driven deployment model to determine their viability within each alternative and for the overarching SoS.

Modelling each of the four alternatives designed for the SoS required multiple simulation iteration to achieve stability within the data sets and provide an accurate representation of real world possibilities and constraints. Each alternative was subject to identical metrics allowing for uniform, in-depth analysis within and over each alternative. In order to implement the deployment model, several documented assumptions were made. These assumptions were made to reach the proper mix of time, space (distance) and force in deploying the SoS. The deployment model could not be adjusted for the factor of time. The inability to slow or speed up the factor of time forced diverse and wide-ranging force compositions originating from various distances. To evaluate the success of each alternative, each metric used the factor of time as its basis. Once each alternative was evaluated against the same set of metrics, analysis of advantages and disadvantages for each alternative was conducted. The alternatives were then compared to determine which alternative best met the challenge of undersea maritime dominance in the littorals in the 2025 time frame.

All asset research data and assumptions were entered into the deployment model. For example, the input table (Table 1) was used to conduct sensitivity analysis of transit speeds, payload capacities and replenishment thresholds. Each of the possible deployment assets are listed on the far left column, while operating characteristics are listed across the top. Researched data was entered as hard numbers, while assumptions such as payload and replenishment thresholds were entered in yellow for continued sensitivity analysis. Similar inputs were tabulated for sensor (UUV) performance, reliability, tonnage and sustainment to assess the deployment process.

Table 1 Red submarine underway time and mission

Red platform	*U/W hour*	*Mission*
AIP-A2	36	Proceed on track to OPAREA A and commence a random patrol
AIP-C1	53	Proceed on track to OPAREA C and commence a random patrol
AIP-B2	67	Proceed on track to OPAREA B and commence a random patrol
AIP-A1	86	Proceed on track to OPAREA A and commence a random patrol
AIP-C2	103	Proceed on track to OPAREA C and commence a random patrol
AIP-B1	120	Proceed on track to OPAREA B and commence a random patrol
AIP-U1	0	Commence random patrol throughout OPAREAs A, B or C
AIP-U2	0	Commence random patrol throughout OPAREAs A, B or C

Simulation of the deployment process was implemented in discrete increments, with any asset capable of reaching the AOR within the required time constraints considered for the next phase of the deployment model. Those assets unable to meet the time requirements were discarded as viable options. The deployment model performed 115 iterations to produce a sample size that could be considered an approximate representation of a population. This process dictated the arrival time of assets for each alternative architecture. Tables of relevant assets follow as an Appendix.

4.3 Prosecution and defeat

Modelling of the prosecution phase followed the process timeline with the identified functions of assess, search, detect, classify and identify threats. Several means exist to search for, detect, track and classify enemy underwater forces. While the most common method is by intercepting and analysing underwater noise or sounds, other methods also include visual, radar, electromagnetic, infrared, laser and satellite imagery. If properly resourced, new technologies will exist in 2025 that will support friendly forces and provide the ability to quickly detect an underwater enemy asset in the required time.

Shallow water, fixed-path, sound (acoustic) propagation is affected principally by three environmental factors: "tidal effects, water-column sound-speed fluctuations, and scattering from bathymetry and seabed" (Nielsen et al., 2002). Shallow-water sound profiles show that the sound waves refract downward causing 'significant bottom interaction' (Lepage, 2002). Turgut et al. (2002) ascertains that "active and passive sonar systems [are] strongly influenced by [the] interaction of acoustic energy and the seabed" and that proper knowledge of seabed properties (compressional wave speed, attenuation, density structure) is required in order for the sonar systems to perform their predictions accurately.

Rigorous technical details of underwater acoustics is necessary to analyse the prosecution modelling effort, which is not the directed scope of this paper. Etter (1991), Nielsen et al. (2002), Lepage (2002), Turgut et al. (2002) and Ferla and Jenses (2002) provide a short summary of the background leading to models implemented; modelling details may be found in Bindi et al. (2005). For the purposes of analysis of the process model, a summary of the simulation tools used with the results presented here for each architecture.

4.3.1 Prosecution/defeat model

In order to gain the necessary insight and to fully analyse the interaction of the dynamic variables presented by the challenge of littoral ASW, our team utilised Naval Simulation System (NSS). This modelling programme was used specifically to consider interactions between platforms within our scenario. While command, control and logistics were inputs to the model, the metrics and interactions of prosecution were the focus of NSS modelling efforts. These efforts were, therefore, considered under the prosecution phase of operation, with defeat operations following subsequently.

NSS is an object-oriented Monte Carlo modelling and simulation tool that has been developed, validated and verified by Space and Naval Warfare Command (SPAWAR) PD-15. The main goal of this model is to facilitate the analysis of four alternatives by comparing their performance within the given scenario.

The vision of NSS is that of a set of validated low-to-medium resolution warfare entity models, certified data, appropriate simulation services and related user support tools in a framework suitable for modelling multiwarfare scenarios. NSS is less focused on a prediction of an absolute outcome (as traditional discrete models) and more focused on promoting creativity through the visualisation of the battlespace, which allowed the assessment of a range of likely plans, tactics and outcomes, and in doing so, effectively evaluate the strengths and weaknesses of various alternatives.

Representations of SEA-8's proposed alternatives were constructed and tested in a simulated environment with no 'man-in-the-loop'. All commander, platform and system entities were fully simulated. Analysis of these alternatives allowed for a detailed understanding of the capabilities, performance and interaction among forces within our scenario. The result was a better understanding of system interactions and quantitative assessment of forces with their associated ASW systems.

All NSS platforms used in the scenario had specific attributes identifying alliance, asset type and operating medium (air, surface or subsurface). Specifically, all individual platforms are given unique motions or manoeuvring orders, a unique susceptibility to detection, platform specific sensors and system attributes and a unique command structure. Major modelling parameters included.

Platform motion: all NSS platform-level objects have an initial motion plan that is valid for the duration of the scenario (one full replication). This motion plan is subject to change during the simulation, based on the simulated actions of the platform, mission area or on orders of the assigned warfare commander. Ships and submarines are assigned to be stationary, have a track/formation motion, conduct an area/barrier patrol or complete a complex motion, which is a combination of these. Additionally, a transit speed, search speed and tactical response speed is assigned to each platform. The Modelling Team utilised all such motions within the scenario and given alternatives.

Track motion for surface and subsurface assets is conducted by assigning a track of specified waypoints to a specific platform. The platform will start the track on assignment and will maintain that track unless specified to do otherwise.

Area patrol motion for surface and subsurface assets is conducted by assigning a region defined by user imputed data points that are connected to form the region. The platform can start at a specified or random point with the region and/or track to the region before commencing the patrol. Distributions for the time between successive course changes, leg speed and loiter times at the end of each patrol leg are specified or random depending on the scenario. For example, Red AIP submarine patrols were highly randomised, while Blue submarines had a more specified patrol motion.

Barrier patrol motion for surface and subsurface assets starts at the beginning of the replication or when specified by the user. The platform transits back and forth unless vectored elsewhere. For example, a Blue submarine may perform a barrier patrol until a Red asset is detected. The Blue submarine will then commence tracking the enemy platform. If the track is lost, then the friendly asset will return and again commence a barrier search.

Complex motion was the most widely used by the Modelling Team. This motion allows for the combination of various other motions. It employs a series of user defined track, area patrol and/or barrier patrol motion plans for an individual platform. The platform will operate as assigned unless vectored elsewhere to track a detected enemy platform, for example. If track is lost then the platform will resume the motion it was originally assigned.

Susceptibility to detection: in NSS, the ability of a platform to be detected is modelled through the use of conceptual 'detectable signature' objects that are associated with each NSS platform. A detectable signature is specified in terms of its type, the platform properties that can be determined when it is detected, the sensor types that can detect it and its schedule. For example, the Red AIP submarine is a subsurface asset with both active and passive sonar as well as radar that is activated according to a periscope schedule that is user selected. These acoustic and radar signatures indicate an enemy AIP submarine when detected by friendly assets.

Commanders/direction: all NSS force assets are supported by numerous subsystem managers and one or more commanders. Subsystem managers are internal software constructs that provide an interface between the force asset (i.e. submarine or UUV) and its associated subsystem (i.e. passive sonar suite). There are three different types of commanders: Group Commanders, which may be assigned to a specific asset to control a group of assets; Warfare Mission Area (WMA) Commanders, which may be assigned to a specific asset and periodically request control of a Group Commander's assets in order to perform a plan or tactic pertaining to a specific mission area (This would allow the WMA Commander to vector assets to track or utilise platforms' sensors to their benefit. To alleviate competing demands for assets, a WMA prioritisation scheme is employed to determine which allocations are executed) and the Asset Commander, which simply interfaces with and controls all subsystem managers associated with a specific asset.

Communications: we implemented 'Assured Communications' for NSS modelling. Under assured communications, messages and communications plans are represented explicitly by link terminals, communications nodes and networks. However, transmission delays are input by the user to provide time for processing transmissions and reaching posture requirements for transmission.

Assured communications is hence generally applicable to operational situations or analysis in which communications connectivity and availability are not to be modelled in detail.[2] Assured communications was selected for two reasons: firstly, this provided simplification to the model and allowed the team to focus on the ability of our system alternatives to detect and track. Secondly, a detailed, communication-specific model was developed by our team to study this aspect of the system and reached a level of abstraction that surpassed the capabilities of NSS.

The way in which an Assured Communications Plan is used in an NSS simulation is as follows. Whenever a platform in either alliance (Red or Blue) determines the need to send a message, the following communications plan processing steps are triggered:

1 if the message is a command/control message, it is sent to all intended recipients with simulated delays as specified by the user

2 for contact and track reporting, the message is sent to all receivers associated with the send as specified in the connectivity plan, with a specified minimum and maximum transmit delay time declared by the user.

Environmental representation: NSS explicitly represents bathymetric contours and the impact of bathymetry on ocean surface or subsurface platform motion and system level of performance. However, NSS does not explicitly represent other aspects of the ocean environment such as water temperature, thermoclines, etc. To account for this limitation of NSS, we utilised PC IMAT version 3.0 to calculate accurate propagation data that could be accounted for in NSS by altering a specific sensor's ability to detect submarines at given ranges. A detailed explanation of how PC IMAT was used to generate NSS inputs can be found in Bindi et al. (2005).

Metrics: NSS provides a comprehensive set of predefined metrics in the categories of state variables versus time, averaged event values versus time, event counts versus time and event times. State variables versus time measures the instantaneous value of a specific state variable. An example would be the number of detections at a specific hour in the scenario.

Event counts versus time counts monitors the number of occurrences of events of a specific type, such as detections, made for a given calculation time. Event times record the individual times of each occurrence of a specific type.

For each metric type, we were able to specify the calculation times associated with each metric or we could specify the condition under which the metric instance was to be computed. The latter was most beneficial. For example, we were able to record the sum of all tracking times for all Blue forces or a single platform against enemy forces.

Tracking metrics: the primary metrics utilised to fully analyse our four distinct alternatives are outlined below.

Surveillance detections: for the detectable asset (Red AIP submarines), this metric counts the number of detection events simulated to occur during the time interval in question. For tracking sensors, detection events include start/end track and track update events. For non-tracking sensors, detection events are equivalent to sensor detection events.

Tracking sensor events: for the detectable asset, this metric counts the number of track events simulated to occur during the time interval in question.

Tracking sensor status change time: for the detectable asset, this metric records the times of initial detection, time(s) of track updates and loss of track for each track held by the tracking sensor.

Total tracking time: for the detectable asset, this metric records the total time a given track is held by any tracking sensor in each time interval in question. For multiple tracks held simultaneously, the time recorded is the total length of time, there is a track held by any of the selected tracking sensors. The maximum possible time that can be returned by this metric is the length of the interval.

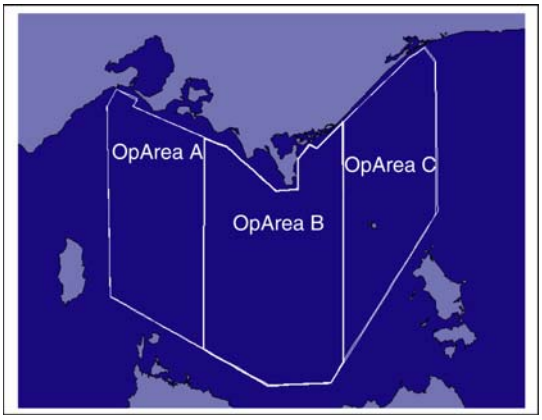
4.3.1.1 NSS simulation plan development The specifics of the ASW scenario used for modelling, (geographic location, number of enemy submarines, etc.) were determined. Required model and data preparation followed directly from the team-generated scenario. Data to be used as model inputs included both friendly and hostile (Blue and Red) platform and system characteristics, abilities, vulnerabilities and tactics. This information was provided as a result of the research done by our team with input from stakeholders.

In addition to our alternative architectures, we constructed a Red force structure with associated doctrine, tactics, operations, schedule and vulnerabilities. This structure was held constant for all alternatives and replications.

The makeup of the Red alliance consisted of two AIP submarines moored in each of three harbours. Additionally, there were two AIP submarines underway within the Red operational area. Each scenario starts with the Red assets in place as described.

When the simulation was commenced, all moored submarines get underway at a specified time and proceed with a 5-knot transit speed until they reach their designated OPAREA. Red submarines from Harbour A were tasked to patrol in OPAREA A, while Red submarines from Harbour B patrolled in OPAREA B and so on. Patrols were conducted with random motion at a speed of 5 knots. The two Red submarines already underway started with a 6-knot, random-motion patrol and maintained this for the duration of the 30-day scenario. Table 1 indicates when each specific Red asset got underway and proceeded with its assigned mission. Details of the operational areas can be seen in the Figure 7.

Figure 7 Bass Strait and Red OPAREAs A, B and C



All Red submarines were vulnerable to passive acoustic sensors, active acoustic sensors and to radar detection when at periscope or snorkel depth. These vulnerabilities were directly linked to a unique signature that will identify them as hostile to Blue forces and a track was initiated.

5 Simulation results

5.1 Deployment

Once all data was recorded and analysed separately for deployment in each individual alternative, the Cumulative Density Function (CDF) for each was then captured, compared and contrasted. A 90% confidence level was constructed about the mean to illustrate variability within each alternative as compared to the other alternatives. Figure 8 depicts the mean CDF for the percentage of critical assets for each alternative deployed versus time. The figure also includes an upper confidence bound, and a lower confidence bound for each alternative.

Figure 8 shows the distinct data output of each alternative when considering their deployment. The greater the area between the closest confidence bound of a competing alternative, the greater the military significance difference between them could be. When an overlap occurs, this may indicate potentially little difference in competing deployment alternatives. The data collected from this model provided a basis for all asset deployment timelines for performance simulation in NSS.

5.2 Prosecution and defeat

5.2.1 Search and detection

With inputs from other model process phases, NSS modelling outputs were imported into an Excel spreadsheet for analysis and graphed to provide a quick glance at the overall results for prosecution and defeat and thus the entire SoS. Three key issues were analysed by exploring the data extracted from the NSS simulations. First was the Probability of detection (Pd) of all Red submarines by Blue assets per time step. This provided a view of how long it would take the assets in that scenario to reach a Pd of

80% (defined based on stakeholder feedback). The second data point extracted looked at the Pd of any Red submarine by Blue assets per time step. In this instance, each scenario's data showed at what time step Blue assets reached the Pd goal for any Red submarine. The third and final point of analysis was taking a look at an instantaneous Pd of Red submarines by Blue assets per time step. This data was more comprehensive and utilised 100 simulation runs in each of the scenarios as opposed to just looking at first detections. All of the three data points analysed are shown in their respective graphs in Figures 8–11.

Figure 8 Alternative confidence intervals

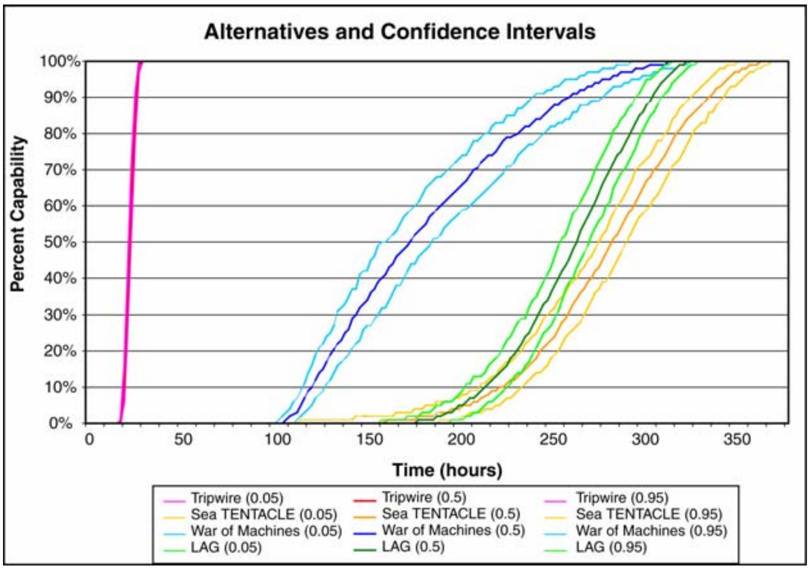


Figure 9 Pd of all Red submarines by Blue assets per time step for each alternative

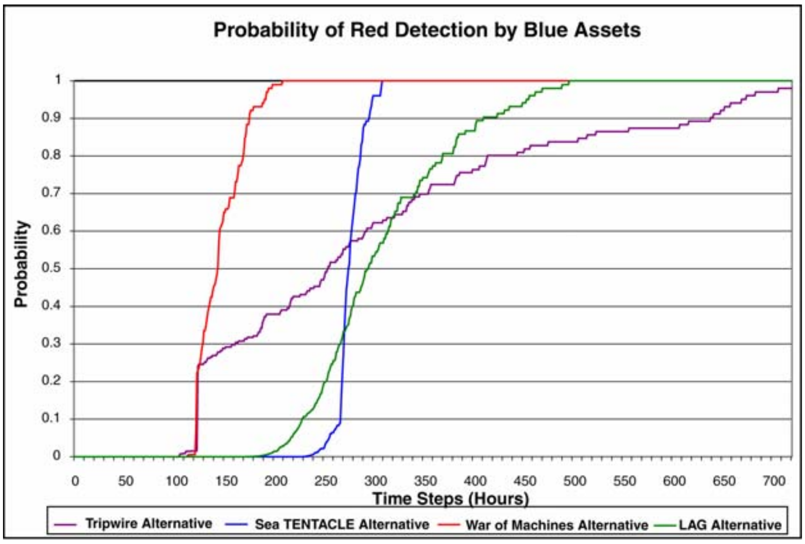


Figure 10 Pd of any Red submarines by Blue assets per time step for each alternative

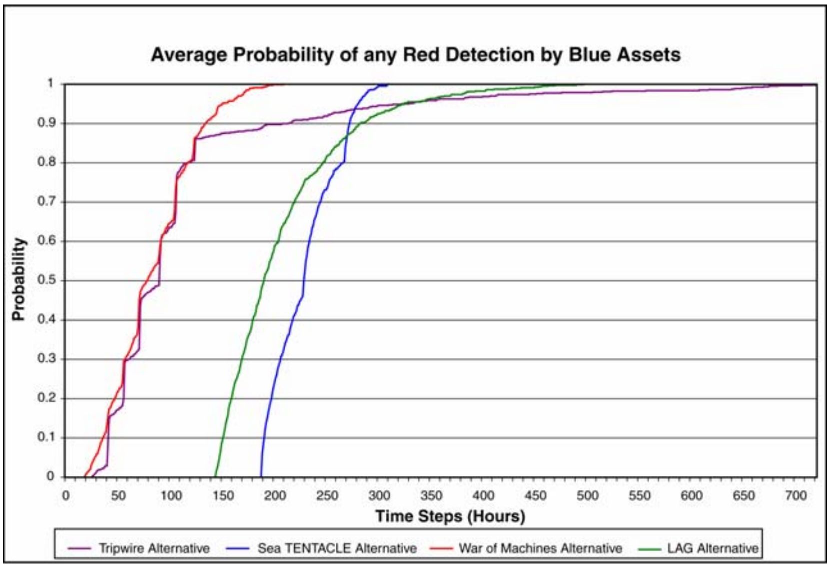
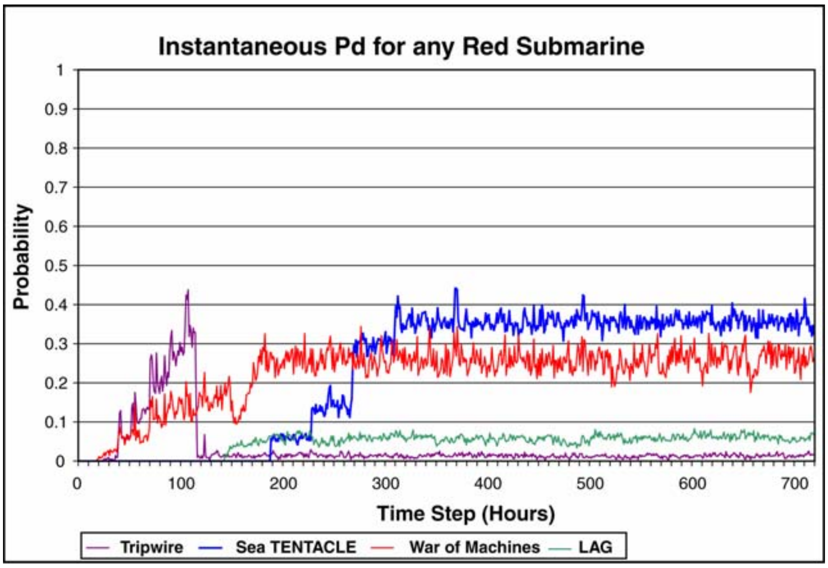


Figure 11 Instantaneous Pd for any Red submarine by Blue assets per time step showing initial Pd as assets enter theatre and the SS Pd with permanence of assets in theatre



The Pd of all eight enemy submarines by each specific scenario hour is shown in Figure 9. The War of Machines alternative provided the best performance, with a Pd of 0.80 by 7 days 1 hr. This means that by 7 days 1 hr, the War of Machines alternative had achieved an 80% probability of detecting all eight Red submarines.

Following the War of Machines alternative was the TSSE alternative, achieving a Pd of 0.80 in 12 days. Third in performance was the LAG alternative at 15 days 11 hr and finally, the Tripwire alternative at 17 days, 8 hr. It is also important to note that the

Tripwire alternative never reached 100% probability of detecting all the eight Red submarines in the 30-day scenario. Figure 10 shows the probability of detecting any one of the eight enemy submarines by the scenario hour listed on the *x*-axis.

Individual alternative Pd of 0.80 for any Red submarine versus Pd of 0.80 for all eight Red submarines is summarised in Table 2.

Table 2 Comparison chart of Pd = 0.80 for any and all Red submarines detected by Blue assets

Alternative	*Pd = 0.80 for ANY one of 8 Red Subs*	*Pd = 0.80 for ALL 8 Red Subs*
Tripwire	4 days 20 hr	17 days 8 hr
Sea TENTACLE	11 days 2 hr	12 days 0 hr
War of Machines	4 days 21 hr	7 days 1 hr
LAG	10 days 7 hr	15 days 11 hr

Of interest was alternative 2, which detected the first Red asset at 11 days 2 hr, and, within the next 22 hr, was able to detect the remaining seven Red submarines.

Figure 11 shows the likelihood of detecting a submarine at any time. All four alternatives are shown in order to compare the probabilities of detection during the initial phases of the scenario and the Steady State (SS) Pd achieved after the sensors are in place and operating continuously.

The Tripwire alternative shows a steadily increasing Pd from 0 to 116 hr and then drops off to near 0. The increased Pd was as a result of Red submarines leaving port at specified intervals and passing through a Seaweb-Based Sensor (SWBS) (grid established at the entrance to these ports. The SWBS system, in conjunction with 15 UUVs, achieved a maximum Pd of 0.4375 at 107 hr. By 116 hr, the SS Pd drops down to 0.013. This is due to the 80 hr battery life limitation of the UUVs. The value of Pd does not drop completely to 0 because the SWBSs are still capable of detecting Red assets, but they are not strong enough to be considered militarily significant.

In the Sea Tentacle alternative, platforms began arriving in theatre at 187 hr with a gradual buildup of sensors throughout the AOR, thus populating the AOR with sensors over time. This led to the stair-stepping Pd witnessed in Figure 11. A SS Pd was finally achieved at hour 309 once all of the sensors were in place and operational. In this alternative, the maximum Pd was 0.4375 with a SS Pd of 0.3569 (27 times improvement over Tripwire alternative).

The War of Machines Alternative consisted of UUVs deployed over time, with recharging stations to ensure that operations remain continuous throughout the scenario. This alternative also demonstrated a gradual increase in Pd that began at scenario hour 0, and continued until all sensors have been deployed, including the recharging stations. The Pd achieves a high of 0.2263 at 123 hr, but drops to 0.1025 at 156 hr (see curve in Figure 11 dip down) due to the UUVs starting to recharge, during which time they are non-operational. The SS Pd was achieved at 0.26, and the maximum Pd for this alternative reaches 0.3263, slightly lower than the TSSE Alternative.

The final alternative, LAG, was based on the conventional approach to ASW. This alternative was slow to start because of the time required for assets to arrive on station. In this alternative, assets arrived on station and began detecting Red submarines by 142 hr (5 days 22 hr). The Pd gradually increased until a SS Pd of 0.057 was reached throughout the scenario.

Data represented in Figure 11 is different than the Pd represented in Figure 11. Figure 11 represents a cumulative Pd over each time step and was based on first or initial detections of each iteration of the scenario (100 total iterations), whereas Figure 11 data represents each alternative's instantaneous ability to detect a submarine at that given time step and was based on the average number of detections for each time step over all iterations in the scenario. In other words, as Blue assets enter the theatre of operations, the Pd was determined not only by their sensor range, but also by their permanence in the AOR.

Table 3 summarises the maximum Pd shown in Figure 11 and explained in the paragraphs following the graph.

Table 3 Summary of Pd for each alternative with the Start Hour, Maximum Pd and SS Pd

Alternative	*Pd start hour*	*Maximum Pd*	*Steady state Pd*
Tripwire	107	0.4375	0.0130
Sea TENTACLE	187	0.4375	0.3569
War of Machines	17	0.3263	0.2600
LAG	142	0.0800	0.0570

If considering Pd as a key metric in determining best alternative, the TSSE and War of Machines alternatives provide the best Pd among all four alternatives, as shown in Table 3.

Table 4 is a spreadsheet of 'best combinations' that can be used to generate a higher Pd. This spreadsheet was created by using the same sensor combination simplistic model as used previously in this section where the P(not d) of each of the alternatives being combined were multiplied together in order to arrive at a P(not d)$_{total}$ and then subtracting this value from 1 to get a Pd of the combination of methods. The data shows that if the maximum achieved Pd was utilised, the best choice is a combination of alternatives 1 and 2 or a combination of all three alternatives together, with alternatives 1, 2 and 3 or alternatives 1, 2 and 4 combined to give a Pd greater than 0.70.

Table 4 Pd of Combined Alternatives using Max Pd and SS Pd to determine the ideal combination of alternatives that provides a higher Pd

Pd Achieved by combining alternatives		
Alternative	*Max Pd*	*SS Pd*
Tripwire and TSSE	0.6836	0.3653
Tripwire and War of Machines	0.6210	0.2696
Tripwire and LAG	0.4825	0.0693
Sea TENTACLE and War of Machines	0.6210	0.5241
Sea TENTACLE and LAG	0.4825	0.3936
War of Machines and LAG	0.3802	0.3022
Tripwire, Sea TENTACLE and War of Machines	0.7868	0.5303
Tripwire, Sea TENTACLE and LAG	0.7089	0.4014
Tripwire, War of Machines and LAG	0.6514	0.3113
Sea TENTACLE, War of Machines and LAG	0.6514	0.5512
Tripwire, Sea TENTACLE, War of Machines and LAG	0.8039	0.5571

Utilising a combination of all four alternatives, the instantaneous Pd was to meet the assigned goal of 0.80. However, the SS Pd produced lower expected Pd values. The combination of alternatives that provided those higher probabilities shows a Pd slightly above 0.50. Using this as a low-end, the conclusion was that a combination of alternatives provided a Pd between 0.50 and 0.80. However, an instantaneous probability of 0.06 (obtained by combining SS or instantaneous Pd for Tripwire and LAG) may be enough to provide a Pd of 0.80 over a specific amount of time steps, a metric not defined within this goal.

5.2.2 Tracking

The data used to analyse each alternative's ability to track was extracted from NSS and evaluated, from which we could then draw conclusions. The metric analysed was the probability that a Blue asset could track a Red submarine long enough to contribute to one or more of the following actions:

- handoff the information to a weapon platform
- generate a fire control solution
- classify the Red submarine
- launch a weapon
- force the Red submarine to leave the OA
- defeat Red submarine.

The amount of time required for tracking, therefore, was dependent on the operational requirements. This time could potentially range from a few seconds to hours or even days. This research investigated the metric of evaluating the probability that a Blue asset can track a Red submarine in 6-min intervals from 6 to 54 min. In the case of tracking, this was simply a confidence level of how probable it was that the assets involved in each alternative will track for the amount of time needed. Tripwire was the first alternative examined and is shown in Figure 11.

This scenario does not provide a good overview of Blue's tracking ability, it shows a very low confidence level. Figure 12 shows the Tripwire alternative's sensors' ability to track all eight Red submarines. Sensors in the Tripwire alternative were designed to detect a Red submarine when it leaves the port. After a Red submarine leaves port, the alternative depends on SWBs and a limited number of UUVs to continue tracking Red submarines. The results shown in Figure 11 indicate this alternative lacks the ability to track with the Sea-web sensors and the UUVs, which have tracking capabilities, have only an 80-hr endurance. If the expected confidence level for this alternative was to provide the operational commander with a 90% confidence level that the sensors will have the ability to track all Red submarines for any period of time, this alternative has clearly failed.

Figure 13, however, represents Tripwire's ability to track any one of Red's eight submarines for each designated period of time.

Figure 12 Probability that Blue assets can successfully track Red submarines per time step in 6-min intervals for alternative 1 – tripwire

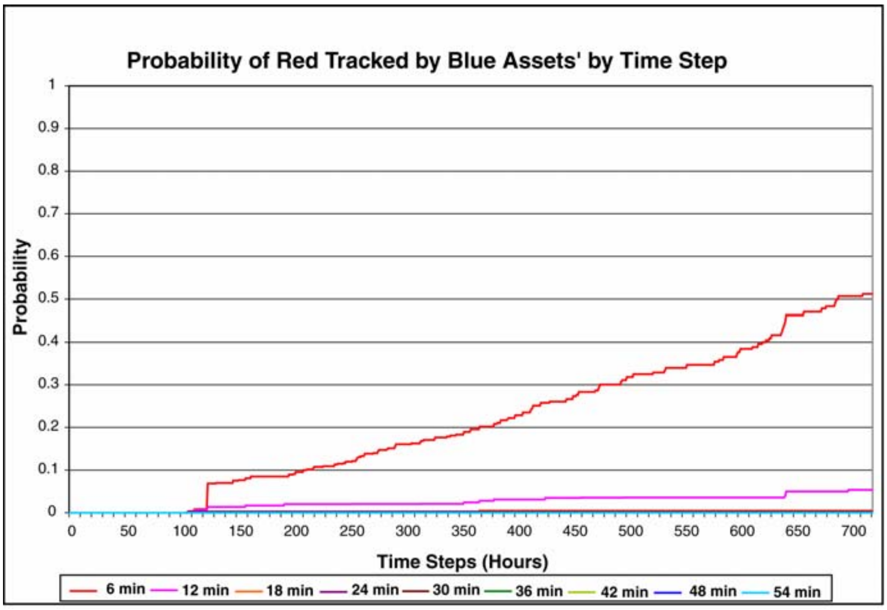
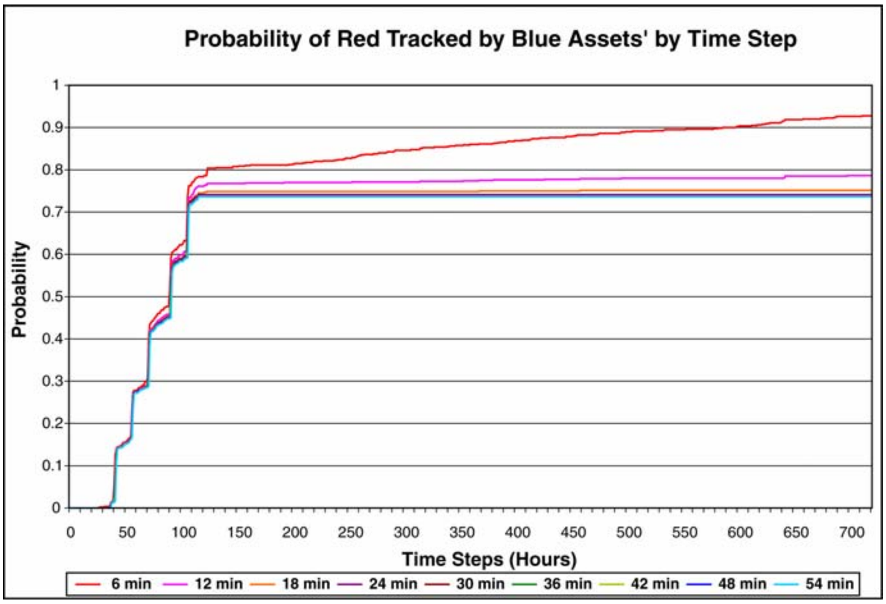


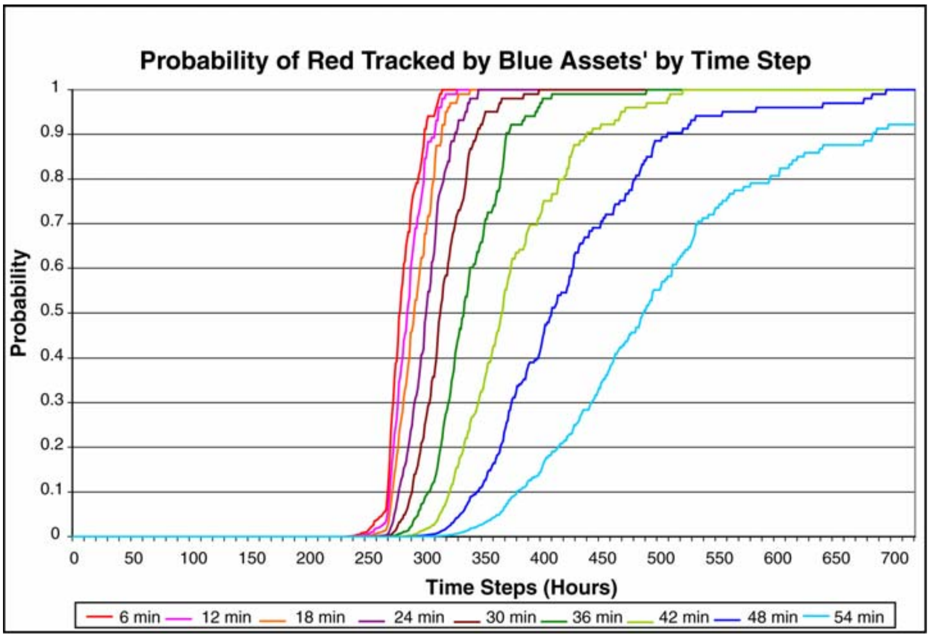
Figure 13 Probability that Blue assets can successfully track any one Red submarine per time step in 6-min intervals for alternative 1 – tripwire



While this data looks more promising than that which is shown in Figure 12, a 90% confidence level was only achieved in the six minute tracking time and only after 598 time steps (24 days 22 hr).

The second alternative examined was TSSE. This scenario shows a significant improvement in the tracking ability over the Tripwire alternative. Figure 14 shows the probability that the sensors in the Sea Tentacle alternative can track all eight Red submarines. After time step 240, the 6-min tracking ability shows an almost vertical probability of tracking capability, with the slope of subsequent time intervals gradually decreasing. As Figure 14 shows, 100% confidence in Blue asset's tracking capability was eventually achieved by all of the time requirements, with the exception of the 54-min tracking requirement.

Figure 14 Probability that Blue assets can successfully track Red submarines per time step in 6-min intervals for alternative 2 – TSSE



While this alternative does not fail in the same sense that the Tripwire alternative fails to provide a high tracking confidence level, the fact that it takes almost 250 time steps to achieve tracking may have a negative impact on operational commitments.

Figure 15 shows the probability that Blue assets can successfully track any one Red submarine per time step for each of the 6-min intervals. Unlike the results shown in Figure 14, when just one Red submarine was tracked, the sensors in this alternative start showing the ability to track at time step 190. By time step 250, the 6-min tracking requirement shows a 70% probability, which may be a high enough confidence for an operational commander.

The third alternative was War of Machines. This alternative produced results that show a significant improvement in Blue's ability to successfully track any (Figure 16) or all (Figure 17) Red submarines over each of the previous two alternatives. In Figure 11, the ability of Blue assets to track Red submarines over the required time period was almost identical for each of the nine time intervals evaluated. A confidence level greater than 90% was achieved within 100 time steps of the first indications that Blue can track all of Red continuously for each time interval studied.

Figure 15 Probability that Blue assets can successfully track any one Red submarine per time step in 6-min intervals for alternative 2 – TSSE

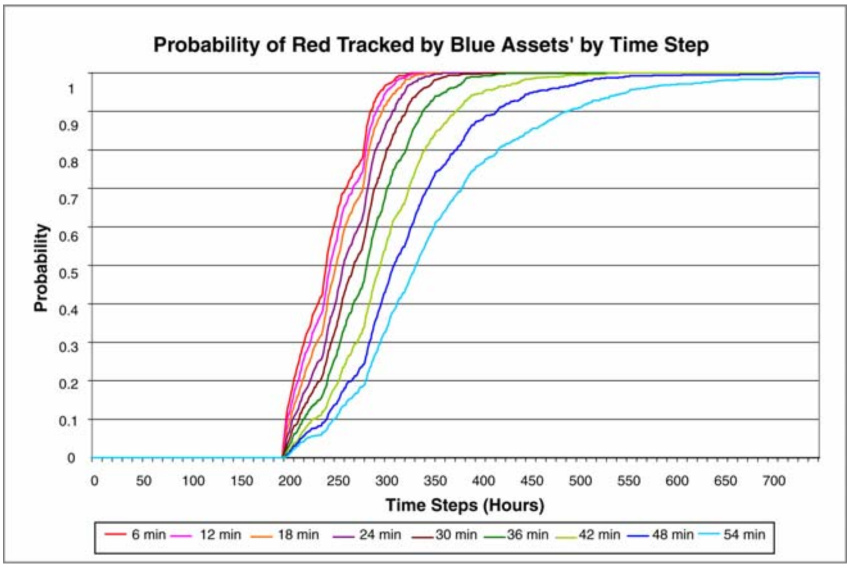
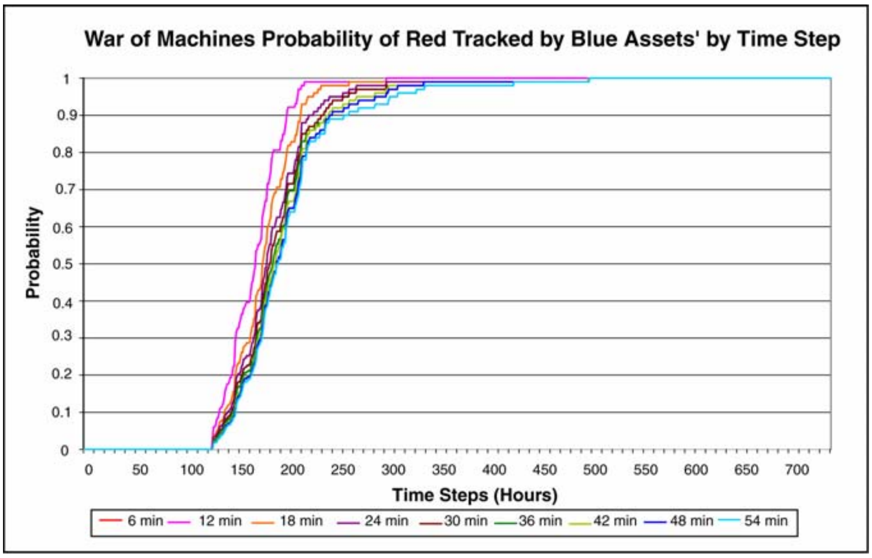


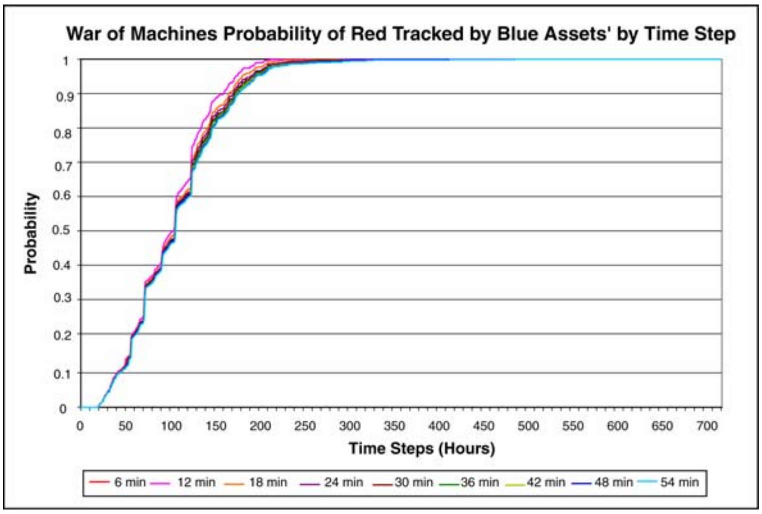
Figure 16 Probability that Blue assets can successfully track Red submarines per time step in 6-min intervals for alternative 3 – War of Machines



While the TSSE alternative showed that the tracking probability starts to increase at time step 250, this alternative demonstrated that, by time step 250, all of the evaluated time intervals reach a 100% confidence level in Blue's tracking ability.

Figure 17 shows that Blue assets have a constantly increasing ability to track any one Red submarine. In addition, the probabilities of Blue successfully tracking Red for each time interval studied are almost identical. By time step 160, the confidence level reaches 90% on all nine time intervals. At a quick glance, the conclusion could be made that if the time to achieve the required confidence level was in line with the time steps represented by this scenario, this alternative succeeds in providing that required tracking capability.

Figure 17 Probability that Blue assets can successfully track any one Red submarines per time step in 6-min intervals for alternative 3 – War of Machines



The LAG alternative tracking capability confidence levels are represented in Figures 18 and 19. Figure 18 shows Blue assets' ability to track all of Red's submarines over the time steps and in the tracking time intervals needed for the kill chain to take place. This alternative was probably the second weakest alternative in that it never reaches a 100% confidence in Blue's tracking ability for all eight enemy submarines. The increase in confidence level was gradual and takes dozens of time steps for small improvements in performance.

Figure 18 Probability that Blue assets can successfully track Red submarines per time step in 6-min intervals for alternative 4 – LAG

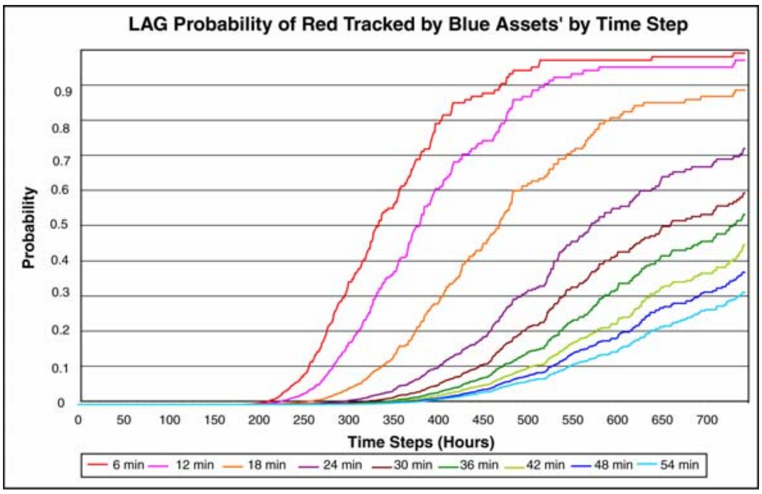


Figure 19 Probability that Blue assets can successfully track any one Red submarine per time step in 6-min intervals for alternative 4 – LAG

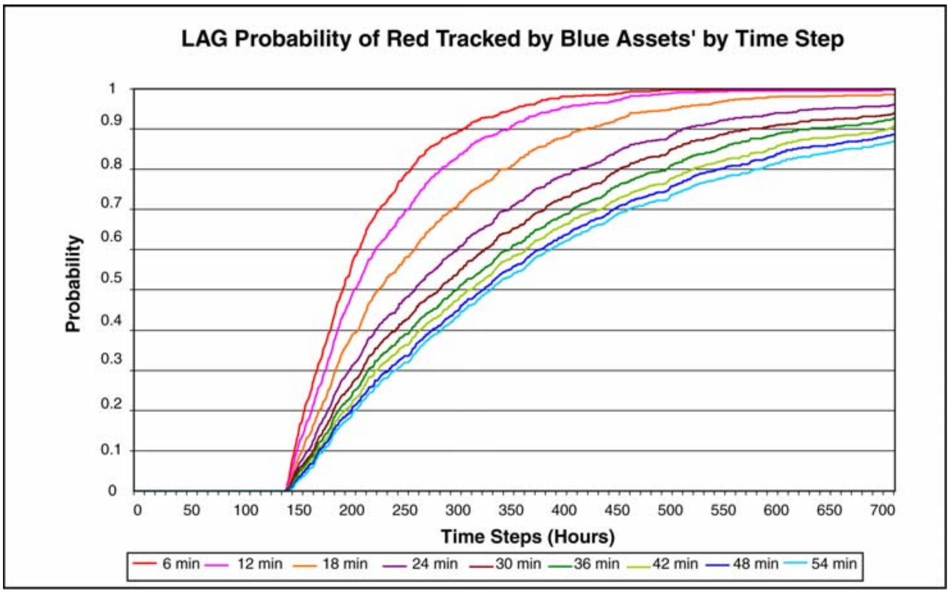


Figure 19 shows the probability that Blue can track any one of Red's submarines at each of the time intervals. As the graph shows, the increase in probability was sharp at first, but as time progresses, the confidence levels take longer time to reach, with only the 6-min tracking time reaching 100% in the scenario.

General conclusions can be drawn from all of the data analysed above. The best way to evaluate which alternative succeeds over other alternatives was to take a look at which alternative impacts the kill chain more than the others.

By taking a snapshot of a specific time step, and by putting all of those data points on the same graph, one can see which alternative provided the strongest and weakest link in the kill chain. Figure 20 shows that specific snapshot at time step 240 (10 days into the scenario) for Blue's ability to track all eight Red submarines for the time intervals that were evaluated in the graphs above. As the graph clearly shows, the War of Machines alternative has the ability to track all eight Red submarines for any of the nine time intervals evaluated. Although the confidence level slowly decreases, the change does not exceed 10%. In the other three alternatives, the tracking confidence level remains slightly below 10% and quickly drops to 0 as the time interval increases.

Figure 21 shows Blue's ability to track any of Red's eight submarines. The War of Machines alternative shows an unhindered ability to track in either of the nine time intervals with a slight, but insignificant, decrease in the confidence level. The second best alternative is Tripwire, which plateaus at 75% confidence by the 24-min time interval. LAG and TSSE alternatives both show a gradually decreasing ability to continuously track a Red submarine at greater time intervals. The lowest confidence is 10% at the 54-min interval for TSSE and 25% confidence at the same time interval for the LAG alternative.

Figure 20 Snapshot of the probability of Blue assets being able to track all Red submarines by 240 time steps

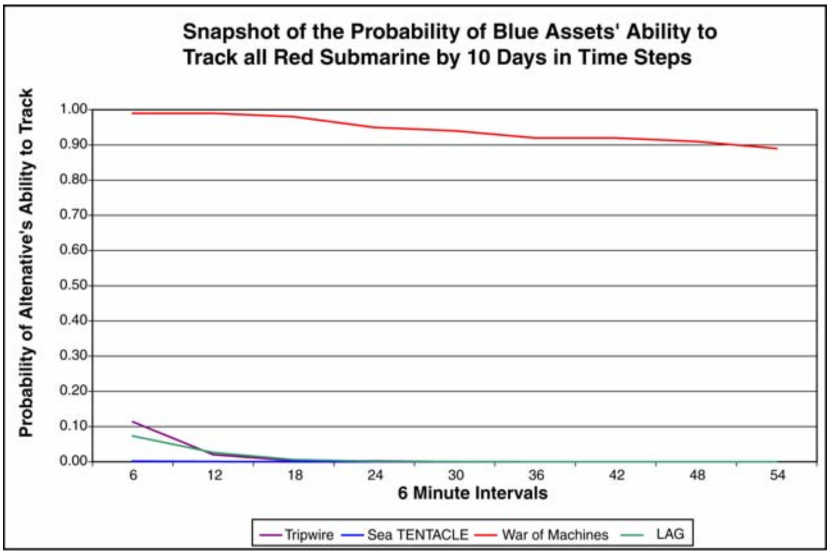
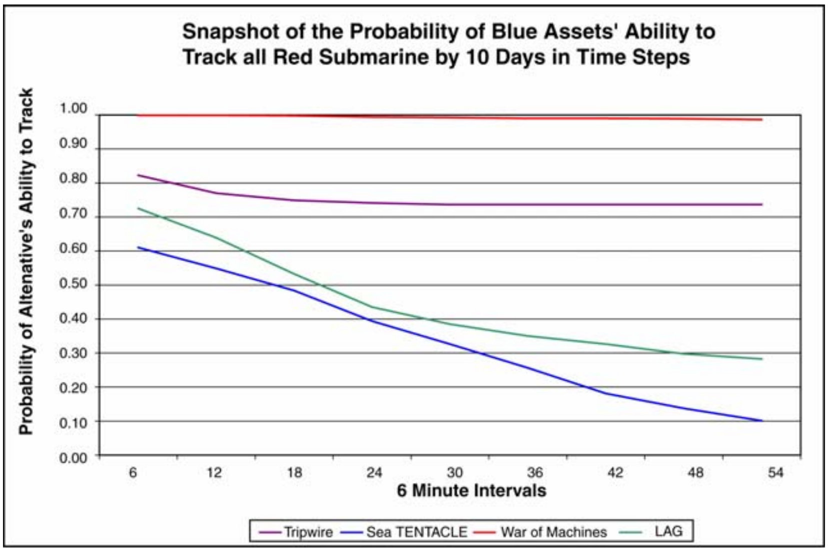


Figure 21 Snapshot of the probability of Blue assets being able to track any one of Red's 8 submarines by 240 time steps



6 Conclusions

6.1 ASW analysis and conclusions

This work has generated insights into the future of littoral ASW during the problem definition, modelling and analysis phases of the systems engineering design. By comparing distinct alternative architectures, we have been able to identify which aspects of each alternative are critical to its success as well as to quantify the value of each solution's strength and weakness. From our analysis, we have drawn the following conclusions:

There are no perfect systems: no single alternative was the best solution for all ASW scenarios. Theatre specific variables such as threat, geography, remoteness of location, ambiguous warning periods, Red-force timelines and differing Blue-force readiness profiles prevented the determination of a single dominant solution. While each competing alternative ASW force structure had strengths, each also had weaknesses. Some alternatives were logistically burdensome, others could not respond quickly when warning timelines were short, and those that could be rapidly deployed tended to lack pervasive endurance. Pronounced differences in detection and tracking capabilities exist between alternatives, but even the worst performer could be effective if the Blue timeline was flexible. The best solution may be a combination of system architectures that could be tailored to suit specific theatre scenario needs.

Reaction time is the key driver to seizing the initiative: our process modelling demonstrated that red submarines was most vulnerable entering and exiting their home ports, due primarily to restricted waterways, where position and movements were predictable. Therefore, detecting and tracking these submarines as they were leaving port became an important part of the research study. However, red force actions were uncertain and (without any future intelligence-gathering advantage) attempting to determine when and from where they were to deploy their submarines was difficult. Warning timelines were often ambiguous and unpredictable. During modelling and simulation, blue forces were unable to begin ASW operations within three days or to seize the initiative within 10 days without leveraging the delivery, flexibility and speed associated strategic air assets got non-traditional ASW assets such as UUVs and netted sensor grids.

Persistent systems are required to sustain ASW denial: constant presence of detection systems was required to effectively sustain ASW for 30 days. Ability to achieve undersea control was dependent on employing systems that were persistent in both time and space. Traditional methods used relatively small numbers of sensing platforms over large areas. These assets were persistent in time, but due to their limited number were not persistent in space. Non-traditional methods (such as rapidly deployed sensor grids and UUVs) proved to be persistent in space, but without improvements in system recharging, tending and/or replacement they lacked the staying power of more traditional manned assets.

Defeat timeline trade-offs exist between traditional and non-traditional ASW methods: traditional manned trailing assets require short defeat timelines because of the need for manned systems to operate from a safe trailing distance in order to prevent counterdetection and countertargeting. While maintaining safe standoff, a quieter red force will further complicate the problem for manned platforms. Traditional ASW forces, using traditional ASW methods, have to make rapid choices concerning whether or not to engage or else risk losing contact with a perspective target. By comparison, invasive non-traditional unmanned trailing systems that are capable of tracking at a closer range, decreased their probability of lost track and allowed for the use of longer timeline attack systems.

Undersea Joint Engagement Zones (UJEZ) are the key to unlocking the power of future ASW technology: finding that no single ASW alternative was the best solution for our littoral ASW scenario, and after gaining insight on the preceding themes of Reaction Time, Presence and Kill-Chain Timeline (KCT) tradeoffs, we have concluded that a dramatic shift in ASW doctrine and methodology was required to unleash the power of future ASW technologies. The waterspace management and Prevention of Mutual Interference (PMI) techniques employed during the late 20th century are akin to stove-pipe engineering; they prevent complementary platforms and sensors from operating together to fill other systems' weaknesses in deployment timelines, endurance, prosecution and engagement capabilities. This study shows that future littoral ASW requires a scenario-specific mix of sensors, UUVs and manned platforms that will operate with one another in the same waterspace. It is imperative that these forces be designed to operate cooperatively, with low false positive and fratricide rates, in a manner that more accurately resembles the Joint Engagement Zone (JEZ) currently used by air warfare systems.

6.2 Contributions

The goal of this work was to demonstrate the application of a process modelling approach to develop and analyse a SoS capable of conducting ASW operations projecting to the year 2025, with specific focus on system performance and interoperability. ASW is a unique problem with a level of complexity beyond conventional analysis techniques. Despite wide recognition of this issue, no available work today has addressed high-level architectural issues of ASW operations on this level of abstraction. New contributions in this paper include:

- the successful development of a process modelling approach to map operations for an ASW SoS
- the successful simulation of a large-scale high-level set of processes using a range of platform characteristics, data and constraint parameters
- the integration of numerous high-fidelity models representing a very diverse range of events, phenomenon and platforms into one cohesive system whose overall performance could be assessed
- the successful simulation of the interaction of these models (whose fidelity precluded combination in any single software system) to provide an understanding of the interoperability of the overall system
- the first cohesive set of results analysing the overall operation of an ASW SoS as a series of processes with future projections to the year 2025.

We believe this work may serve as a foundation for future systems engineering research addressing the interoperability and performance of complex systems of systems whose function is closely tied to time-dependent processes with particular application for military and security systems.

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Notes

[1]Note that we also refer to this option as 'Total Ship Systems Engineering', TSSE, named for the curriculum that generated the future ship design.

[2]METRON Incorporated (2002).

Appendix

Relevant platform and sensor assets modelled for deployment and prosecution

Figure A1 Modelling input data for potential asset deployment

AIR	Endurance	Transit Speed	Max Speed	Max Payload capacity (tons)	Working Payload	Max Range (NM)	Organic sensor assets (number and type)	Max Endurance (hours)	Payload Threshold Ratio	Utilized Asset Speed	Total Max Operating hours (fuel)	Total Max distance traveled due to logistics re-supply	Refueling Threshhold	Fuel Threshold Ratio
B-2	300	400	550	20	18	10000	Web-sensors, UUV, Mines, (to be tailored dependent on mission assigned)	36.00	0.90	400	25.00	N/A	21.25	0.85
B-52 (G)	352	442	516	35	31.5	6513	Web-sensors, UUV, Mines, (to be tailored dependent on mission assigned)	18.50		442	14.74	N/A	12.53	
B-52 (H)	352	442	516	35	31.5	8685	Web-sensors, UUV, Mines, (to be tailored dependent on mission assigned)	24.67		442	19.65	N/A	16.70	
P-8 (MMA)	300	440	490	29	26.1	1400	Web-sensors, UUV, Mines, Torpedoes (to be tailored dependent on mission assigned)	4.00		440	3.18	N/A	2.70	
C-5	465	489	541	145.5	130.95	2960	N/A	6.37		489	6.05	N/A	5.15	
F-18 E/F	275	420	960	2	1.8	1200	Torpedos, Mines, UUVs	2.25		420	2.86	N/A	2.43	
F-35 JSF	275	420	1080	2	1.8	1200	Torpedos, Mines, UUVs	1.80		420	2.86	N/A	2.43	

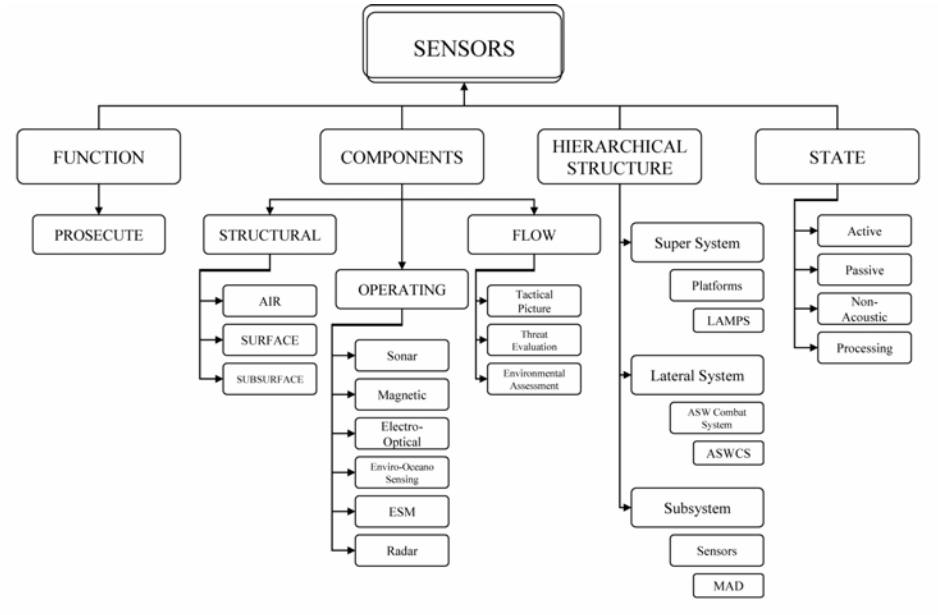
SURFACE	Transit Speed	Range (NM)	Max Speed	Payload capacity (tons)		Max Range (NM)	Organic sensor assets (number and type)	Logistics Provisions limitations (hrs)	Utilized Asset Speed	Total Max Operating hours (fuel)	Total Max distance traveled due to logistics re-supply	Refueling Threshhold
DD(X)	16	44000	30	6	[redacted]	44000	2 SH60R LAMPS Helos, 3 RQ-8A Fire Scout VTUAV, Acoustic Sensor Suite	720	23	1913.04	16560	1626.09
DDG	16	44000	31	6	[redacted]	44000	2 SH60R LAMPS Helos, 3 RQ-8A Fire Scout VTUAV, AN/SQS 53C(V) Sonar AN/SQR 19(V) TACTAS Sonar	720	23.5	1872.34	16920	1591.49
LCS	20	4300	50	40	[redacted]	4300	1 MH-60R/S/UAVsNTUAVs	504	35	122.86	17640	104.43
T-AOE(X)	20	10000	26	1800	[redacted]	10000	N/A	720	23	434.78	16560	369.57
TSSE SHIP	25	4500	45	0	[redacted]	4500	TBD	504	25	180.00	12600	153.00

SUB SURFACE	Notional Transit speed (kts)	Range (NM)	Max Speed	Payload capacity (tons)		Max Range (NM)	Organic sensor assets (number and type)	Logistics Provisions limitations (hrs)	Utilized Asset Speed	Total Max Operating hours (fuel)	Total Max distance traveled due to logistics re-supply	Refueling Threshhold
SSN	20	Indef	25	6	[redacted]	Indef	ANBSY Active passive sonar, AN/WLQ-4(V)1 ES receiver, TB-23 Towed array	2160	22.5	N/A	48600	N/A
SSGN	15	Indef	25	6	[redacted]	Indef	BQS-13 Active Sonar, TB-16 Towed Array	2160	20	N/A	43200	N/A

Figure A2 Payload data for modelling input sensor asset deployment

Sensor Components	Number of Sensors Required	FMC (.96)	Number of Sensors to be deployed	Displacement (tons)	Shape Tonnage	Endurance (High Hotel Load) Hrs	Edurance (Low Hotel Load) Hrs	Recharge Required (hrs)	Repair Required (hrs)	Replacement Required (hrs)	Total Tons
UUV (Man Portable)	0	0.96	0	0.005	0.005	10	20	20	120	240	0.00
UUV (LWV)	0	0.96	0	0.25	0.25	20	40	40	240	480	0.00
UUV (HWV)	51	0.96	53	1.5	1.5	50	80	80	480	960	159.12
UUV (Large)	0	0.96	0	10	10	300	400	400	2400	4800	0.00
Recharging Station	12	0.96	12	1	1	360	720	720	4320	8640	24.96
Floating Sensor (sonbuoys)	0	0.96	0	0.015	0.015	120	240	240	1440	2880	0.00
Sea-Web Component (Medium)	0	0.96	0	0.055	0.055	120	240	240	1440	2880	0.00
Sea-Web Component (Large)	0	0.96	0	0.075	0.075	120	240	240	1440	2880	0.00
										Total Tonnage req for deployment	184.08
										Payload tonnage Available	229.50
										Remaining/ Needed	45.42

Figure A3 Sensor hierarchy breakdown and all-inclusive list of sensor systems



Advanced Distributed System	ADS			X	
Advanced Extended Echo Ranging	AEER		X		
Airborne Radar Periscope Detection & Discrimination	ARPDD		X		
Deployable Autonomous Distributed System	DADS		X	X	X
Dipping Sonar			X		
Electro-Magnetic	EM		X		
Electronic Warfare	EW			X	X
Electro-Optic Passive ASW Sensor	EPAS		X		
European Synthetic Radar Satellites	ERS	X			
High Gain Volumetric Array	HGVA			X	
Improved Extended Echo Ranging	IEER		X		
Infrared	IR		X		
Infrared Mode W	IR Mode W		X		
Large Wide Aperture Array	LWAA				X
Light Detection and Ranging	LIDAR		X		
Lightweight Broadband Variable Depth Sonar	LBVDS				X
Littoral Volumetric Acoustic Array	LVAA		X	X	X
Low Frequency Active Sonar	LFAS			X	
Magnetic Anomaly Detector	MAD		X		
Medium N Sensors	Medium N			X	
Mobile Off-Board Source	MOBS			X	
Multi-Function Towed Array	MFTA			X	
Near Term Multi-Line Towed Array	NTMLTA				X
Network Enabled Anti-Submarine Warfare	NEASW		X		
Parametric Sonar				X	
RADAR	Radar		X	X	X
Radar Augmentation for Periscope Identification	RAPID			X	
Receive While Transmit	RWT			X	
Reliable Acoustic Path Vertical Line Array	RAP VLA		X	X	X
Remotely Operated Mobile Ambient Noise Imaging System	ROMANIS			X	
Scalable Improved Processing Sonar	SIPS			X	
SONAR	Sonar			X	X
Sonobuoys			X		
Sound Surveillance System	SOSUS				X
Surface Towed Array Sonar System	SURTASS			X	
Unmanned Lightweight Towed Arrays	UTAS			X	
Visual			X	X	X
Visual Electro-Magnetic	Visual EM		X		