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SYSTEMS ENGINEERING CAPSTONE REPORT

**DATA FUSION ARCHITECTURES FOR UNDERSEA
WARFARE WITH AUTONOMOUS UNDERWATER
VEHICLES**

by

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June 2018

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AUTONOMOUS UNDERWATER VEHICLES**

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ABSTRACT

This capstone report examines the concept of combining mobile and stationary underwater sensors into a coherent, distributive network. This project presents a baseline architecture for a data fusion system that facilitates the near real-time exchange of information from disparate sources. This architecture, in turn, provides a basis for further system development, and guides future studies of relevant data/information fusion concepts and technologies for applications to anti-submarine warfare (ASW) and mine warfare.

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The resulting architecture facilitates the successful integration of passive acoustic sensor information with intelligence products and timely distribution of fused data across manned and unmanned platforms. The architecture also allows for future growth into active acoustic sources, environmental data sources, non-traditional ASW sources such as radar, and ESM.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACINT	acoustic intelligence
AOU	area of uncertainty
ASW	anti-submarine warfare
AUV	autonomous underwater vehicle
AW	air warfare
C2	command and control
CERTSUB	certain submarine
CSG	carrier strike group
DF-NTC	data-focused naval tactical cloud
DOD	Department of Defense
ESM	electronic support measures
F2T2	find, fix, track, target
F2T2EA	find, fix, track, target, engage, assess
FFBD	functional flow block diagram
HVT	high value target
JDL	Joint Data Laboratories
KPP	key performance parameter
LAN	local area network
MFTA	multi-function towed array
MOE	measure of effectiveness
MOP	measure of performance
MTBF	mean time between failures
MTTR	meant time to recovery
MW	mine warfare
NONSUB	non-submarine
NPS	Naval Postgraduate School
NR	net ready
POSSUB	possible submarine
PROBSUB	probable submarine
SNR	signal-to-noise ratio

SUW	surface warfare
USN	United States Navy
USW	undersea warfare
UUV	unmanned undersea vehicle

EXECUTIVE SUMMARY

Currently, no system exists for combining mobile and stationary underwater sensors into a coherent, distributive network. The absence of an anti-submarine warfare (ASW) data fusion system prevents strategic/theater planners and tactical operators from accurately identifying undersea threats/targets, maintaining maritime superiority, and efficiently allocating resources. This project developed a baseline architecture for a data fusion system that facilitates the near real-time exchange of information from disparate sources into a cohesive, distributed network. This architecture will, in turn, provide a basis for further system development and guide future studies of relevant fusion concepts and technologies for applications to ASW and mine warfare.

Figure 1 depicts the scope of the project. The ASW data fusion system architecture is encapsulated in the green box. The black box depicts the systems that are impacted by the architecture while those outside impact the architecture. The team determined that passive acoustic sensors would be the only sensors included in this iteration of the architecture. The diagram also shows non-passive sensor capabilities, those marked in grey. The team recommends these sensors be incorporated in future iterations of the architecture. The addition of the non-passive sensors in the diagram illustrates the true scope of the ASW data fusion problem and influences the system design anticipating future growth (i.e., not build a system so restrictive as to only be able to function with passive acoustic sensors).

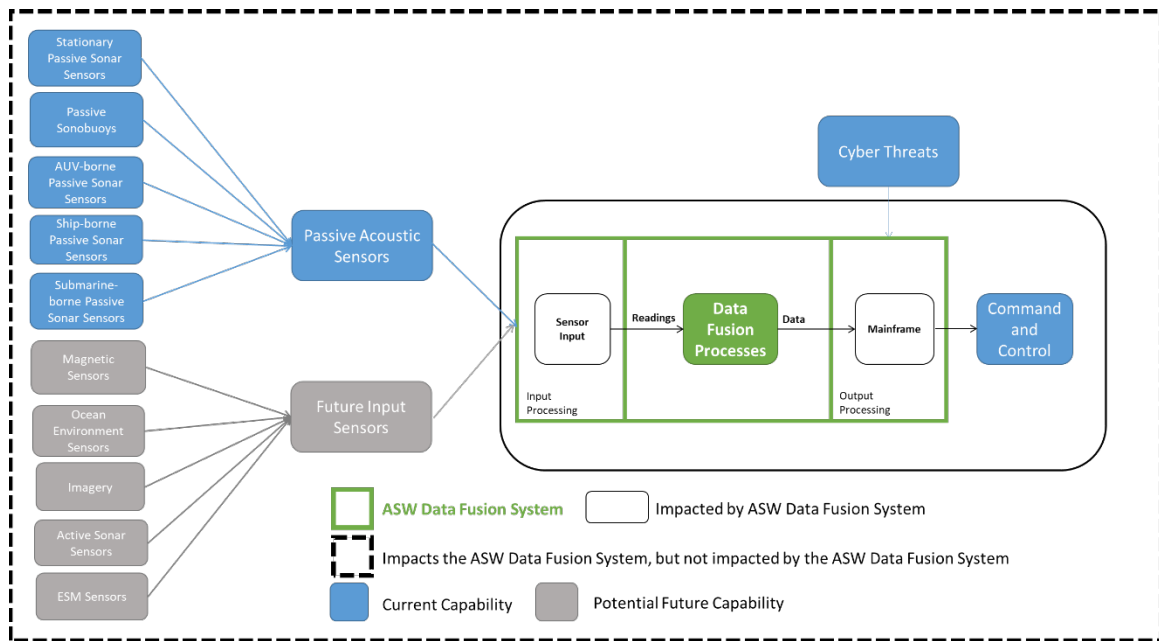


Figure 1. ASW Data Fusion System Context Diagram

The team used the standard kill chain paradigm to conceptualize the success of the ASW data fusion system. The serial nature of the kill chain supports the application of Lusser's Law. Lusser's Law, as is commonly understood, states the reliability of a series system is equal to the product of the reliability of its component subsystem (Myers 2010). In the case of the ASW data fusion system, the system is the ASW mission represented using the kill chain, with each step of the kill chain represented by ASW data fusion system functions. Applying Lusser's Law to the kill chain, the probability of success of the ASW mission can be characterized using the probability of success of each link in the kill chain. Specifically, the probability of success of the ASW data fusion system is equal to the product of the probabilities of detection (find), classify (fix), localize (track), engage (target), and kill (engage). Figure 2 depicts Lusser's Law for the ASW kill chain.

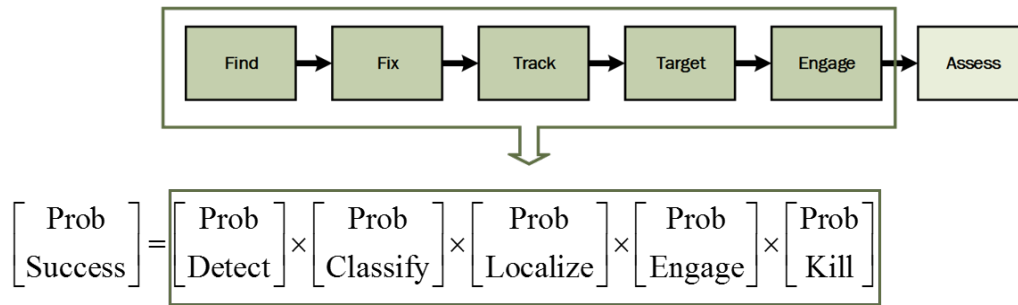


Figure 2. Lusser's Law for the ASW Kill Chain

The current state of ASW relies heavily on human operators. In essence, the human operator acts as a data fusion system. With limited processing capacity today, operators are unable to assess all incoming information, and potentially relevant data is lost. Additionally, in every step of the kill-chain process, human error can be unknowingly injected into the solution. The ASW data fusion architecture seeks to automate the fusion process to increase efficiency and remove human subjectivity and associated error from the equation in order to improve performance and increase the effectiveness of the ASW mission. The success of the ASW data fusion system is dependent on the system performing at least as well a human operator.

The team utilized a top-down systems engineering to define the success criteria for the ASW data fusion architecture. The first step of the process is establishing success trees. Success trees are similar to commonly used fault trees except, instead of quantifying failure modes, the success tree aims to quantify elements that contribute to the success of a mission. A black box model then fulfills each branch of the success tree. John Green, a professor at the Naval Postgraduate School, presented a lecture titled “Capability-Based Assessment and System Effectiveness” in November of 2017 to the Systems Architecting and Design class where he discussed the black box model. The black box model allows the team to quantify the performance and behavior between modules without having to define the processes resident in each module (Figure 3) In essence, it allows the team to start in the ideal plane then incrementally and recursively define processes to adjust the system to handle real-world stimuli. In Professor Green’s presentation he describes how each

iteration in the system engineering process seeks to move black boxes into clear boxes (i.e., modules with processes defined).

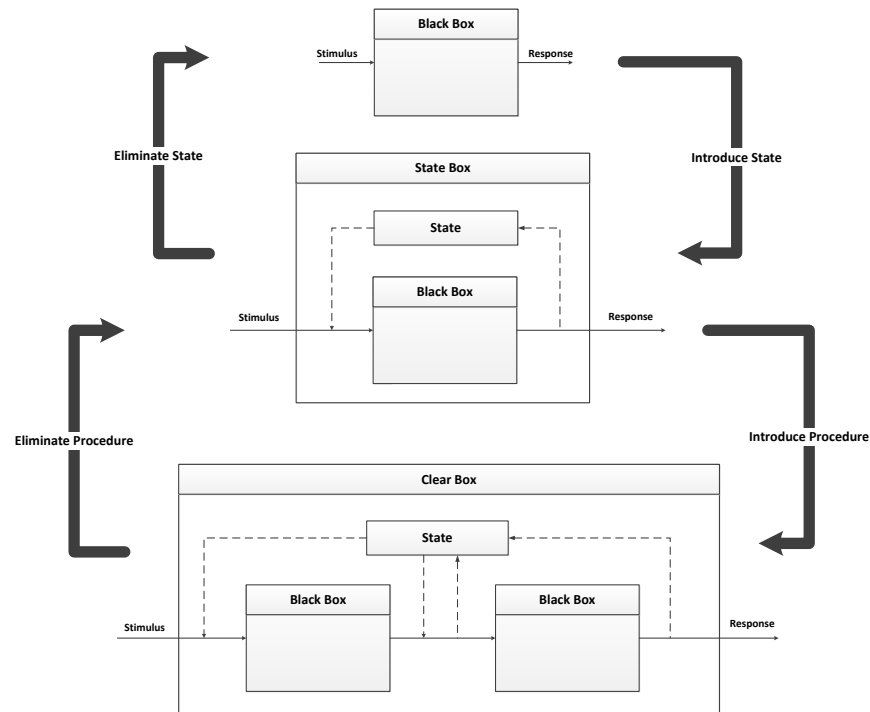


Figure 3. Box Structure Expansion/Reduction. Source: Mills, Linger, and Hevner (1986).

Using information from Professor Green’s presentation, the team opted to engineer the mission, instead of the system, in a top-down system engineering approach. This allowed the team to ensure the success of the system architecture while enabling a direct comparison of the ASW data fusion system performance against the data fusion performance of human operators. To start the definition of the success trees, the team first establishes the capability need as a black box with a target performance value. Shifting the viewpoint of the ASW data fusion system to the mission, one can view the capability and performance goal provided by the data fusion system is to “prosecute submerged, man-made objects with a probability of success of 0.x.” The performance goal for the system is not defined at this point nor will it be in this paper. The actual number is not needed for the further development of the system. The architecture is deemed successful if it meets or

exceeds the capabilities of the human operator which is determined during the simulation stage. Further decomposition of the mission will identify the components that facilitate the overall success of the system.

Continuing with the systems engineering design model, each of the top-level system activities is decomposed further. The second level decomposition of system activities includes: Receive Sensor Data, Create Cluster, Create Contact, Identify Threat, Refine Process, Provide Fusion Database, and Distribute Data. The team allocated each of these activities to its own system function. Just like the overall system performance, the nominal probability of success for each of the functions is not needed; the decomposition categorizes the factors affecting the overall success of the system to enable decision makers to determine the required level of performance.

The primary purpose of the ASW data fusion system is to provide accurate, time-sensitive data to the warfighter. The system must be capable of receiving data from various sources, determining the accuracy of the data, combining that data into accurate solutions, and distributing those solutions to the fleet for optimal situational awareness. Figure 4 depicts the capability diagram representing the capability hierarchy of the ASW data fusion system. Figure 5 maps the capabilities back to the F2T2EA process. The correlations shown in Figure 5 display the relationships between the capabilities and the success trees.

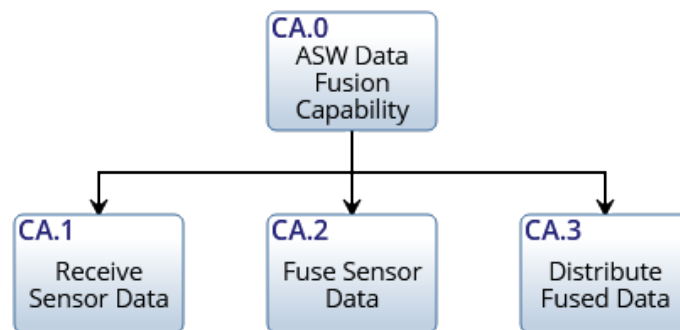


Figure 4. Capability Diagram

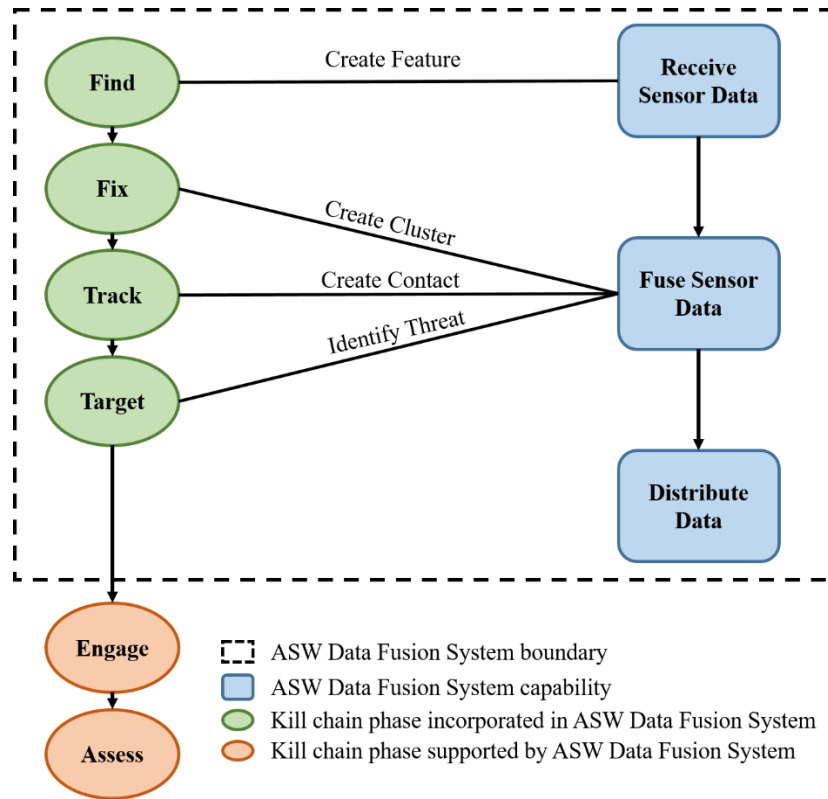


Figure 5. Kill Chain to Capability Map

The functional architecture of the system establishes the sequential flow of operations within the system and the dependencies between each of the system functions. The team utilized Innoslate to build multi-tiered functional flow block diagrams (FFBDs), establishing the functional architecture of the ASW data fusion system. Figure 6, the top-level FFBD, depicts the three top-level functionality groupings of the ASW data fusion system: Receive Sensor Data, Fuse Sensor Data, and Distribute Fused Data. The Receive Sensor Data function serves as the system’s interface to the acoustic sensor network, receiving all passive acoustic data along with the locations of the providing sensors. The Receive Sensor Data Function detects signals within the passive acoustic data and sends those signals along with the sensor provider positions to the Fuse Sensor Data function group as “Feature Data.” The Fuse Data Function aggregates the received feature data and, through its fusion processes, develops Fused Contacts, Sensor Performance Feedback Data, Sensor Tasking Suggestions, and Situational Awareness Data. These outputs of the Fuse Data Function are sent to the Distribute Data Function where they can be distributed

to external systems. The Distribute Data Function operates in parallel with the Receive Data and Fuse Data functions because it also receives externally generated Feature, Cluster, and Contact Data information for inclusion in the fusion processes.

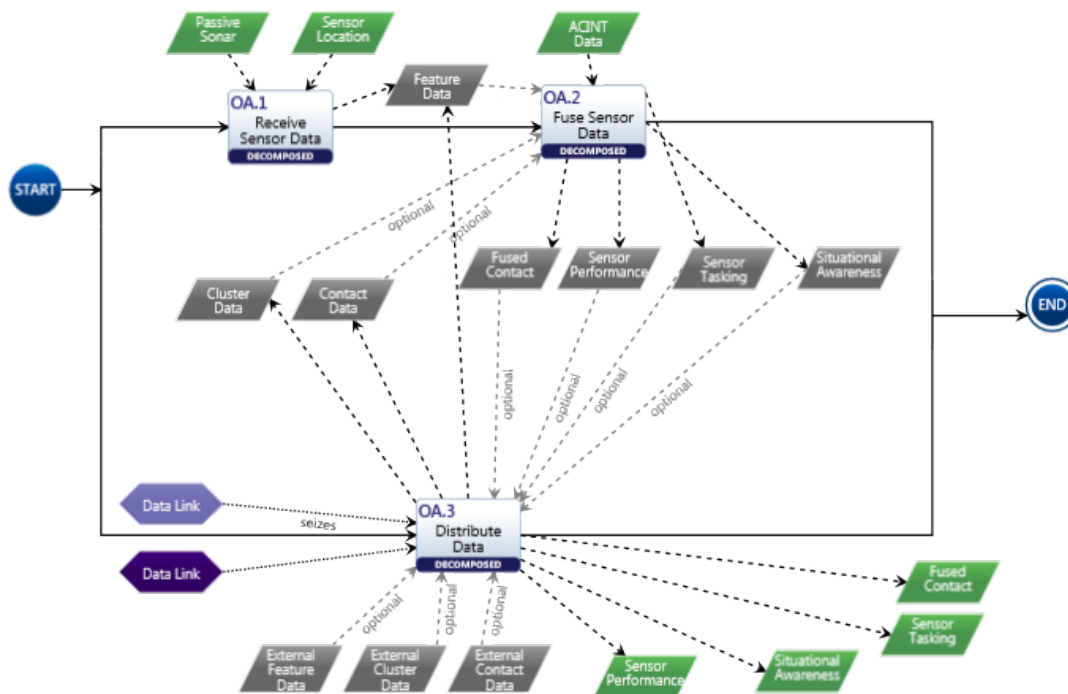


Figure 6. Top-Level FFBD

The Fuse Sensor Data function group is where the majority of the work of the ASW data fusion system takes place. Figure 7, the decomposed Fuse Sensor Data functionality, depicts the existence of three parallel streams of functionality within the Fuse Sensor Data function group. Within the top stream of functionality, the Create Cluster, Create Contact, and Identify Threat functions operate in series, with the Create Contact function dependent on the Create Cluster function and the Identify Threat function dependent on the create Contact Function. Feature Data generated from the Receive Sensor Data function and external systems is received by the Create Cluster function. The Create Cluster Function determines the relationships between the elements of Feature Data, aggregates related

Feature Data elements into Cluster Data, and sends Cluster Data to the Create Contact function. Cluster Data contains a detected entity's signal frequency, its bearing from a known location, and a high-level entity classification. The Create Contact function receives Cluster Data, aggregates it based on frequency and time, and creates Contact Data. Contact Data contains the tracked entity's location, along with a calculated AOU, and course and speed information.

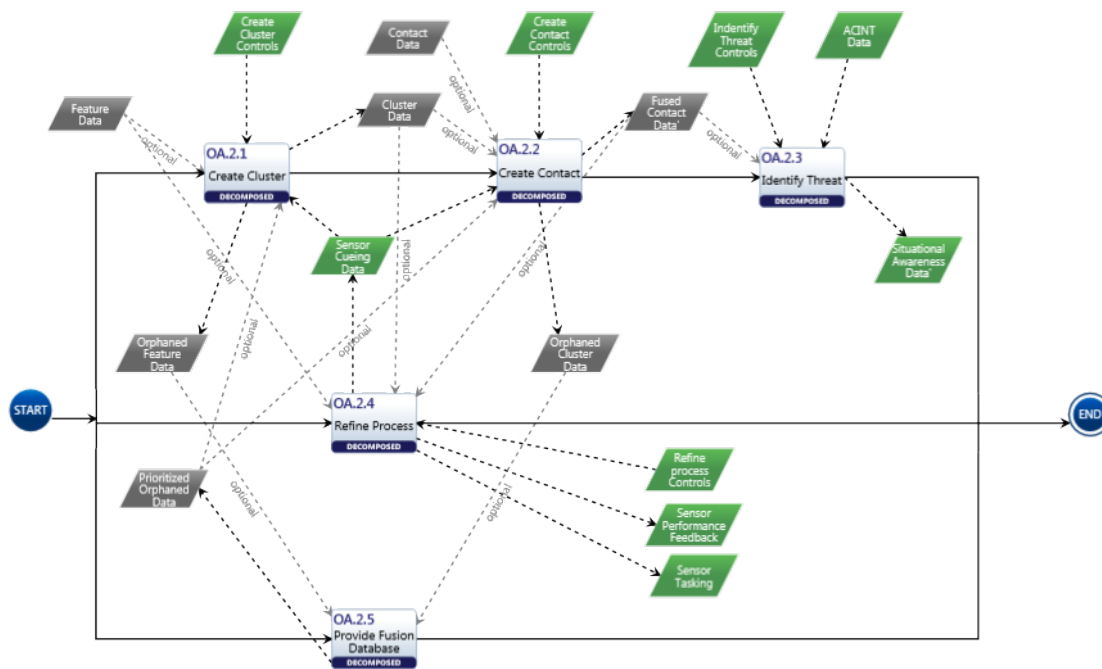


Figure 7. FFBD of the Decomposed Fuse Sensor Data Functionality Group

The team evaluated decentralized, centralized, and distributed physical architectures for feasibility, timeliness, maintainability, adaptability, and scalability. The analysis eliminated the decentralized option, as it was determined to be infeasible given the capabilities of some of the C2 platforms and determined the distributed physical architecture is superior to the centralized architecture in all but one category: maintainability. Though the centralized architecture is far more maintainable than the distributed architecture, the advantages afforded by the distributed system in terms of

timeliness, adaptability, and scalability far outweigh its reduced maintainability. Therefore, the distributed system architecture is selected for the ASW data fusion system. Figure 8 depicts the distributed architecture.

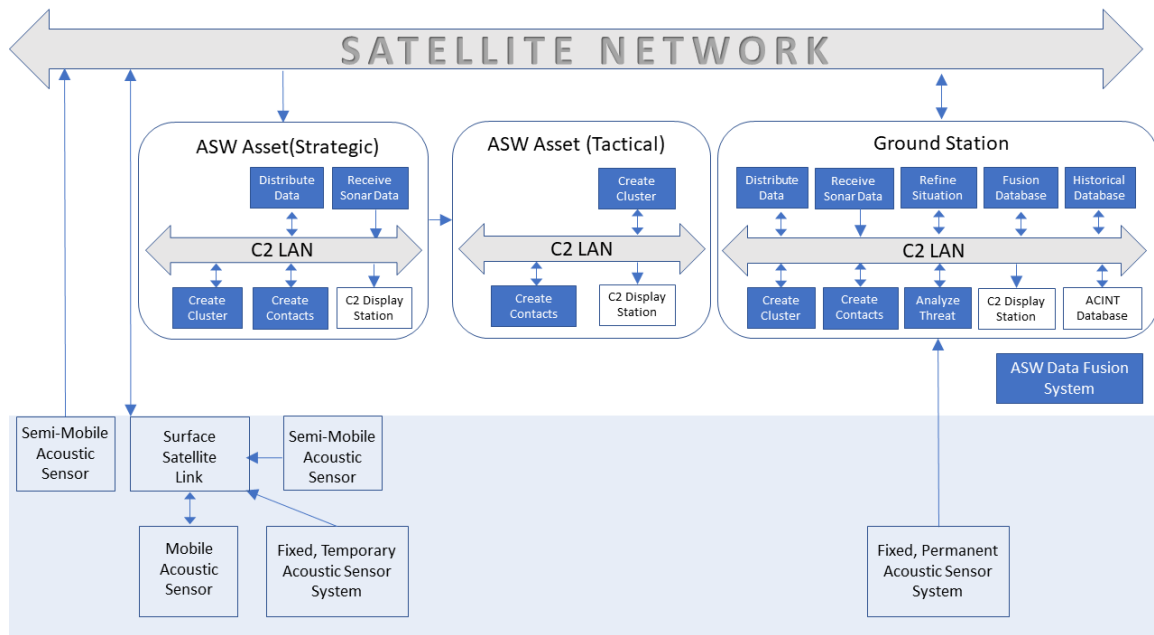


Figure 8. Distributed Architecture

The team performed modeling and simulation to characterize the performance of the ASW data fusion architecture. The nature of the top-down system engineering process permitted the team to model the system as a Markov Chain. Figure 9 depicts the Markov chain for the ASW data fusion system with the states remaining the same as the human model marked in blue. The primary difference between the human operator and the ASW data fusion system occurs during Target Detection. The human operator receives information from multiple sources simultaneously, determines the presence of usable data, and forwards that data to the next step of the chain. All information rejected by the operator, whether correctly rejected or not, is lost. By comparison, rather than discarding unused data, the ASW data fusion system retains it and reprocesses it, providing multiple opportunities to refine the fused data solutions with the incorporation of data that had previously been unused.

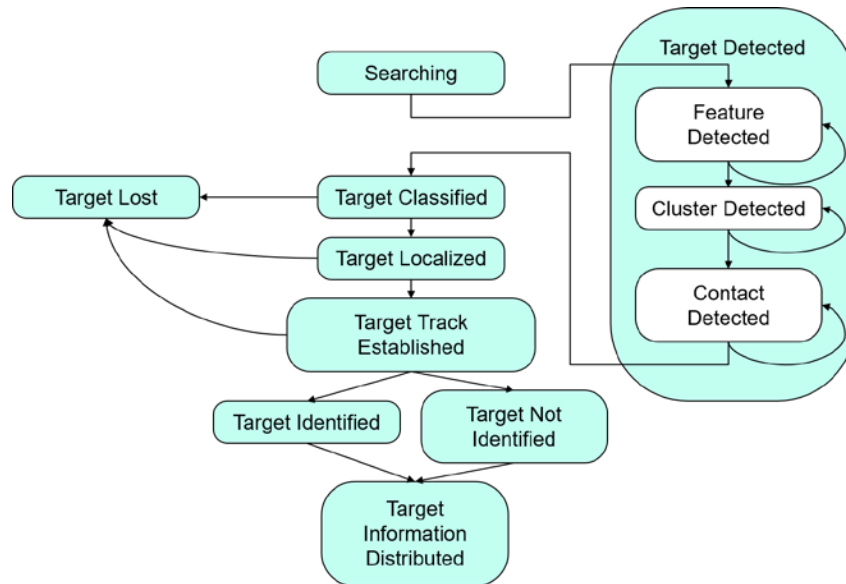


Figure 9. ASW Data Fusion Markov Chain

The team characterized the ASW data fusion system by comparing it to the performance of the human system. Applying the modeling paradigm of comparative analysis and the Markov process, the team characterized the current, human system first. The team utilized the Markov chains as the basis for a simulation model in ExtendSim. The simulation model remains the same between the human system and the ASW data fusion system with the only differences being the probabilities and resource numbers provided as inputs to the simulation. The team utilized a two-fold approach to fully characterize the performance of the ASW data fusion system over that of the human system. The first analysis run compared the performance of the human system to the ASW data fusion system without the augmentation of the probability of detection gained from enhanced processing. This run characterized the performance of the ASW data fusion system solely with respect to time. The second run of the simulation utilized enhancements to signal processing enabled by the ASW data fusion system. This run characterized the expected performance increase of ASW prosecutions with the implementation of the ASW data fusion system. The data from modeling and simulation demonstrates the ASW data fusion system outperforms the human operator by a factor of 20.

Through design and analysis, the team has determined a distributed architecture configuration will meet all of the system performance requirements. Using the Markov model for comparative analysis, the proposed Data Fusion architecture consistently exceeds the performance standards of a human ASW operator. As such, the team has determined the proposed ASW data fusion architecture is suitable for further development.

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I. INTRODUCTION

World War I saw the first effective tactical and strategic implementation of the submarine with the German U-boats devastating Allied shipping. Virtually undetectable until it was too late, enemy submarines could sneak up on their target, employ ordnance, and leave the area without being detected by U.S surface ships. The Allied navies gave top priority to the need to detect this new threat, and the field of underwater acoustics was born. WWI ended before any breakthroughs in the field could be applied to a submarine detecting system. With the break out of World War II, the German Navy immediately fell back on the effectiveness of their U-boats, and the USN again prioritized underwater detection. This time an effective detection system, sonar, was employed; signaling the start of the cat and mouse game between quieter submarines and more sensitive sensors.

Russian submarine activity is at one of its highest levels since the Cold War. “Russia has begun to reestablish a sea denial strategy using a layered defense approach through increased operations of surface ships and submarines in the North Atlantic and moving steadily closer to Russia’s territorial waters through the Barents, the Arctic, and the Baltic Seas. This is reflected in the estimate that Russia has increased its submarine patrols by 50 percent in the past year alone” (Hicks, Metrick, Samp, and Weinberger 2016, 6). China has followed suit with recent developments in submarine technology and increased subsurface activity inside the first and second island chains. China is expected to double its defense budget over the next decade to over \$260 billion (CNBC 2015). The increased budget will allow for the rollout of new surface and subsurface assets and technology.

With the increased focus from near-peer adversaries in the undersea domain, coupled with increasing financial constraints and operational commitments, the U.S. Navy (USN) has focused on submarine detection systems and unmanned underwater vehicles to increase the efficiency of its current undersea warfare (USW) systems. This refocusing of USW has the desired effect of boosting the Navy’s detection capabilities while limiting the enemy’s ability to use their submarine force.

As warfare technology continues to advance, autonomous vehicles are seeing more time in the field and are increasingly relied upon for the information they collect. In 2004, the Navy developed a master plan for the future of the unmanned undersea vehicle (UUV): “nine sub-pillar capabilities were identified and prioritized: Intelligence, Surveillance, and Reconnaissance, Mine Countermeasures, Anti-Submarine Warfare, Inspection / Identification, Oceanography, Communication / Navigation Network Node, Payload Delivery, Information Operations, Time Critical Strike” (Department of the Navy 2004, abstract). Many of these capabilities require a large amount of data collection, storage, transmission, and organization. Technology advancements and increased data demands require an advanced architecture to handle the increased data load. With the increased data load comes a corresponding increase in potential data fragmentation or loss. The shift to net-centric warfare has the Navy becoming more reliant on data for tactical decision making. Therefore, it becomes critical to ensure data collected from assets are accurately transmitted to decision makers in a timely manner. As the data volume from USW increases, there is the potential for more erroneous data and increased data processing times, resulting in a longer delay in the presentation of accurate data to the end user. To address some of these issues, the Navy is implementing new technology; the data-focused naval tactical cloud (DF-NTC) (Office of Naval Research 2014). The DF-NTC is similar to its civilian cloud counterpart in that it will store, process, and transmit information. The major difference is the DF-NTC will provide this information in a near real-time fashion to deployed assets. While this helps to alleviate the congestion involved with the transmission of data, it does not address the architecture required to handle raw data streams from external assets.

Today’s deployed assets utilize a distributed network to pass vital contact and target information in the air warfare (AW) and surface warfare (SUW) domain to other units and decision makers. Onboard systems process large amounts of data then transmit the important information needed to execute the mission to other assets within range. Those assets can then transmit the data via satellite over the horizon. This distributed network allows for a near real-time data assessment and distribution to surface, ground, and air assets. As the subsurface environment continues to grow and advance, so does the need for

such a distributed network to transmit USW data between surface and subsurface assets to include static, semi-mobile, and mobile sensor sources. This distributed network would need to include tenets from the Joint Data Laboratories (JDL) Data Fusion Model to integrate the output from all these sources into coherent information.

In a paper released in May of 1997 titled “Concept for Future Joint Operations,” there is an early discussion of information superiority. The paper defines information superiority as an unprecedented new capability that surpasses the incremental improvement of previous capabilities (Joint Chiefs of Staff 1997). The information superiority concept is to design systems that encourage the implementation of the three information superiority components: information systems, information operations, and relevant information. Figure 1 depicts the three components and how they relate to one another.

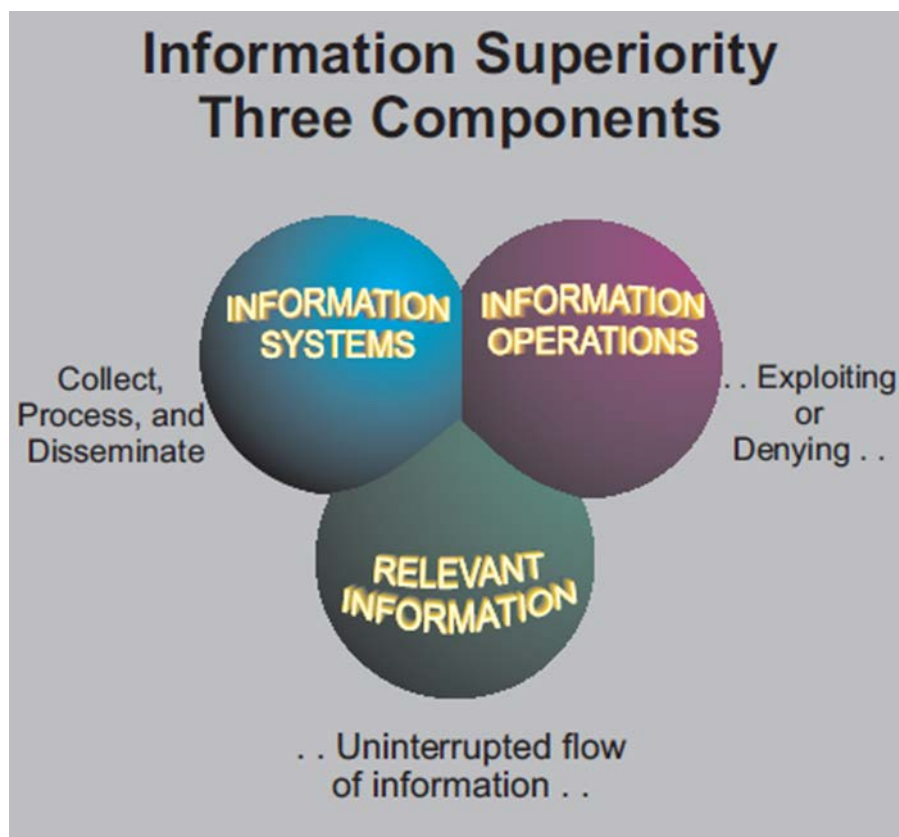


Figure 1. Three Components of Information Superiority. Source: Joint Chiefs of Staff (1997).

The concept of constant collection and dissemination of information is the foundation of the modern distributed networks. These networks allow for near real-time distribution of information to and from deployed forces and decision makers. To attain and maintain a strategic advantage, USN must ensure the sorting, prioritization, and distribution of the massive amount of information generated by current and future technologies. The information must be prioritized and distributed in the time required by modern warfighting assets.

As the USN continues to advance the capabilities of its military personnel and equipment, it must also advance the way information is collected and disseminated. Since the turn of the century, the military has shifted away from a central processing hub and toward a distributed network force structure to achieve quick, uninterrupted flow of information: “the primary advantage in distributed, network forces arises from the networked effects that are distributed in many dimensions throughout a force that can be summoned for use in the manner of advantage chosen by clever commanders based on evolving conditions” (Cares, Christian, and Manke 2002, 1). A distributed network is composed of two major components: elements and connections. Elements are the sensors providing the information to the network. The connections are the methods by which the information is transferred from sensor to sensor (Cares, Christian, and Manke 2002). An example of a distributed network currently in use by the military is Link 16. Link 16 is a multi-national, joint distributed network utilized by air and surface assets that allow for near-real-time distribution of a tactical picture to assets connected to the network. The architecture of Link 16 has some major limitations. Link 16 treats each platform as a single sensor; relying upon the platform’s data fusion to create a single track and grade the track’s quality before reporting the information to the network. In this architecture, any data collected by a platform not able to be resolved into a track (i.e., at least contact location resolved) will not be entered into the network. This paradigm works fine in an AW or SUW domain where a majority of the sensors which cannot immediately determine a location (e.g., ESM) are paired with “active” sensors (e.g., radar) that can. This architecture does not work in the USW domain where a majority of the USW sensors are passive because active sonar sensors that are capable of location determination have a very limited range

due to attenuation. Due to this limitation, Link 16 is limited in its USW ability; relying on only manual track reporting. Additionally, the tracks which are reported are created by a single platform with multiple sensors in contact, which represents a major time and personnel investment into a single track.

Undersea Warfare, by its nature, is a large area problem, in contrast to the relatively small battlespace of AW and SUW. In some cases, contact can be gained by a sensor, hundreds of miles from the target, by utilizing the phenomena of convergence zones. From these distances, it is nearly impossible to determine position; the operator can resolve bearing, but range, thereby position, would need a second sensor in contact. Complicating the solution is signal attenuation affecting each frequency band differently. Lower frequencies can travel farther but typically have less resolution (broadband signal versus the preferred narrowband tracking signal). Higher frequencies have greater resolution and direction determination but, are absorbed more easily by the surface and seabed or may penetrate the surface entirely. In other words, the lower the frequency, the longer the distance it can travel but, with less information available to the sensor. In one location, a sensor could be tracking one frequency while another sensor is tracking a harmonic of the first frequency. Without being able to share this data among assets, a majority of USW information fails proper integration into contact solutions.

A. PROBLEM STATEMENT AND OBJECTIVES

Currently, no system exists for combining mobile and stationary underwater sensors into a coherent, distributive network. Without this system, strategic/theater planners and tactical operators cannot accurately identify undersea threats/targets, maintain maritime superiority, and efficiently allocate resources.

The goal of this project is to provide an architecture for a data fusion system that facilitates the near real-time exchange of information from disparate sources into a cohesive, distributed network. This architecture will, in turn, provide a basis for the further system development, and guide future studies of relevant data/information fusion concepts and technologies for applications to Anti-Submarine Warfare (ASW) and Mine Warfare (MW).

B. TECHNICAL APPROACH

This section describes the team organization and the systems engineering process. Team organization and systems engineering process are provided herein.

1. Team Organization

The following personnel comprises the team. Figure 2 depicts the organization structure and roles and responsibilities summarized in Table 1.

- Michelle Bones, supervisory engineer, Naval Undersea Warfare Center, Newport, Rhode Island
- CDR Leonard Bunch, USN, assistant reactor officer, USS George Washington (CVN 73)
- LT Kenneth Fisher, USN, helicopter instructor pilot, HELTRARON EIGHT
- Stephanie Mara, computer scientist, Naval Undersea Warfare Center, Newport, Rhode Island
- LT Alex Stone, USN, operational test director, COMOPTEVFOR

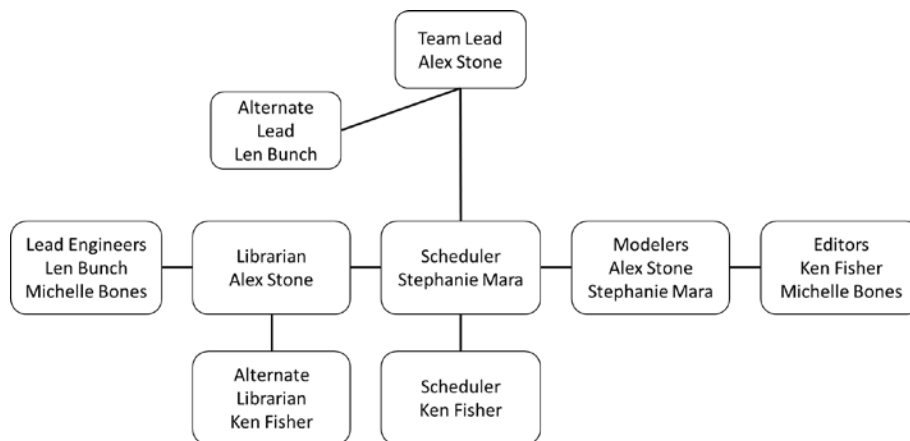


Figure 2. Team Data Fusion Project Organization

Table 1. Team Data Fusion Project Roles and Responsibilities

Team Member	Roles and Responsibilities
Team Lead	Responsible for planning, monitoring, and coordinating activities of the project.
Scheduler	Responsible for developing a plan of action and milestones.
Librarian	Responsible for ensuring the most accurate versions of project materials are available for use.
Modelers	Responsible for developing models of project alternatives.
Lead Engineers	Responsible for elicitation, documentation, and organization of the stakeholder requirements.
Editors	Responsible for review and consolidation of all project team member inputs.

2. Systems Engineering Process

The team opted to utilize a top-down system engineering process to develop a recommended architecture for the ASW data fusion system. The systems engineering plan from *Modeling the Ship as a Weapon System* (Green, 2001) was tailored utilizing top-down engineering principles (explained in detail in Chapter III) to fit the ASW data fusion architecture project. Figure 3 illustrates this modified version.

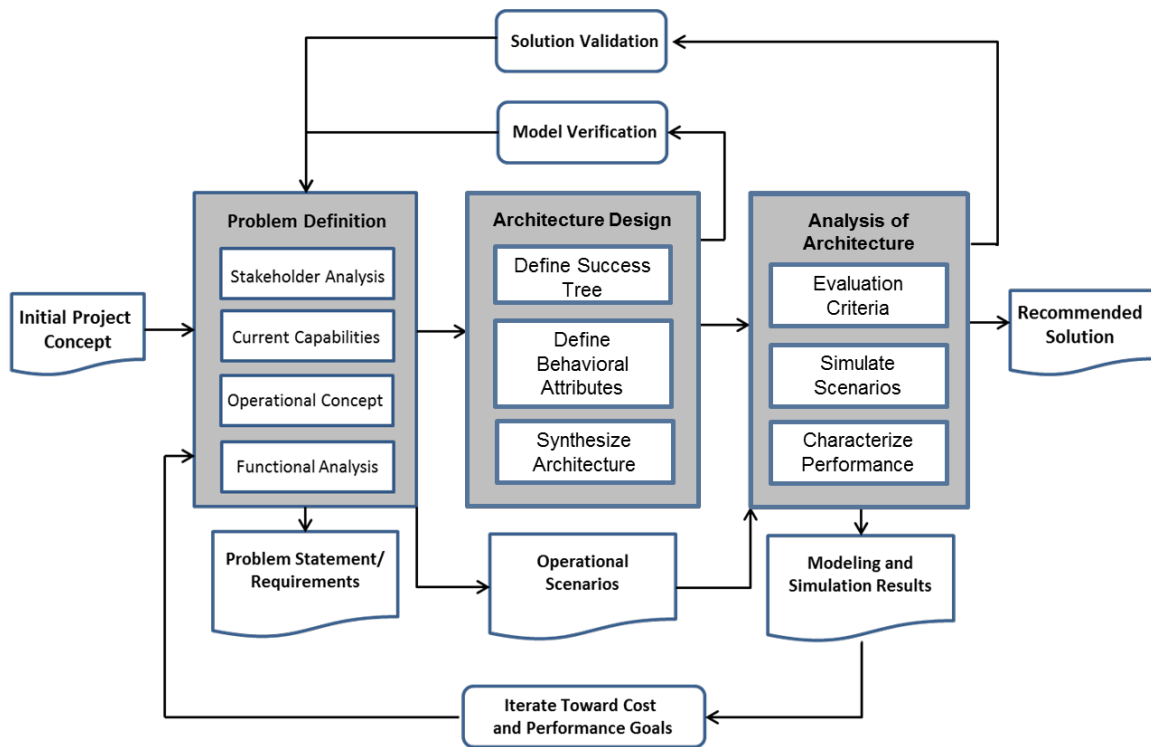


Figure 3. Modified 3-Phase Systems Engineering Process. Adapted from Green (2001).

Each of the three “phases” in the Modified 3-phase Systems Engineering Process contains multiple tasks, and the iteration and feedback mechanisms are embedded within the process.

a. Problem Definition

The stakeholders defined the initial problem. A detailed analysis of stakeholder requirements is conducted to define the scope, limitations, and boundaries of the problem. Outputs of this phase include a detailed, refined problem statement, detailed system requirements, primary stakeholders, and the boundaries and constraints within which the team will conduct our analysis.

(1) Stakeholder Identification and Analysis

This task provides insight into the entities controlling the project, including primary decision makers and financial interests. It also allows the team to elucidate the needs of the

stakeholders from which requirements, limitations, and system boundaries will be determined.

(2) Current Capabilities

It is imperative, extensive research is conducted into current capabilities in order to prevent duplication of effort of other research teams. This research provides a solid foundation upon which to conduct research, ensuring the advancement of current technology. This task ultimately produces an OV-1 diagram of the current situation.

(3) Operational Concept

This task produces the overall intent of the project, and assists in defining the scope, constraints, limitations, and boundaries of the problem. This helps the team to focus on those tasks and items pertinent to the Data Fusion project. This task produces an OV-1 diagram of the desired end state.

(4) Functional Analysis

This task defines the functions required by the data fusion system, along with the key performance parameters (KPPs) that are used to assess the quality of the system. The output of this task is the functional and non-functional requirements of the Data Fusion System.

b. *Architecture Design*

This phase builds upon the output of the Problem Definition Phase, including the system requirements, KPPs, and measures of performance (MOPs) to determine several viable architecture alternatives. These alternatives are analyzed and compared to the Problem Definition phase for suitability. Those determined to be acceptable are modeled for additional analysis and comparison.

(1) Define Success Tree

This task defines the success trees for the 1st and 2nd level behavior. Success trees are similar to commonly used fault trees except, instead of quantifying failure modes, the

success tree aims to quantify elements that contribute to the success of a mission. The success trees allow the team to start in the ideal plane then incrementally and recursively define processes to adjust the system to handle real-world stimuli.

(2) Define Behavioral Attributes

In this task, the team identifies system behavior and evaluates it against established parameters.

(3) Synthesize Architecture

During this task, established requisite activities for ASW data fusion are allocated to system functions. Next, the functional architecture of the system is defined. The functional architecture establishes the processes through which the system functions exchange information and it defines the specific data to be exchanged. This functional architecture along with the non-functional requirements drive the physical architecture of the ASW data fusion system, which the team also establishes as part of the architecture synthesis.

c. Analysis of Alternatives

The team conducts the analysis of alternatives in three phases: establish evaluation criteria, simulate scenarios, and characterize performance. The evaluation criteria phase converts the MOPs, KPPS, and measures of effectiveness (MOEs) to mathematical equivalents. The team then utilizes these measures to evaluate the architectures. The simulation phase simulates each architecture alternative against discrete scenarios. The performance analysis phase utilizes data from the previous phase and analyzes the performance of each alternative.

d. Recommended Solutions

The team uses a top-down system engineering process to identify the best architecture. The team then promotes the candidate architecture to the stakeholders for their consideration.

C. SCOPE

Figure 4 depicts the scope of the project. The green box encapsulates the Data Fusion system. The black box depicts the systems that are impacted by the architecture while those outside impact the architecture. While scoping the project, the team determined that passive acoustic sensors would be the only sensors included in this iteration of the architecture. Other sensor capabilities, those marked in grey, are recommendations for future iterations of the architecture. They are included in this diagram to illustrate the true scope of the ASW data fusion problem and to design a system with an eye towards future growth (i.e., not build a system so restrictive as to only be able to function with passive acoustic sensors). The team makes the following assumptions and identifies the following constraints regarding the Data Fusion System Architecture.

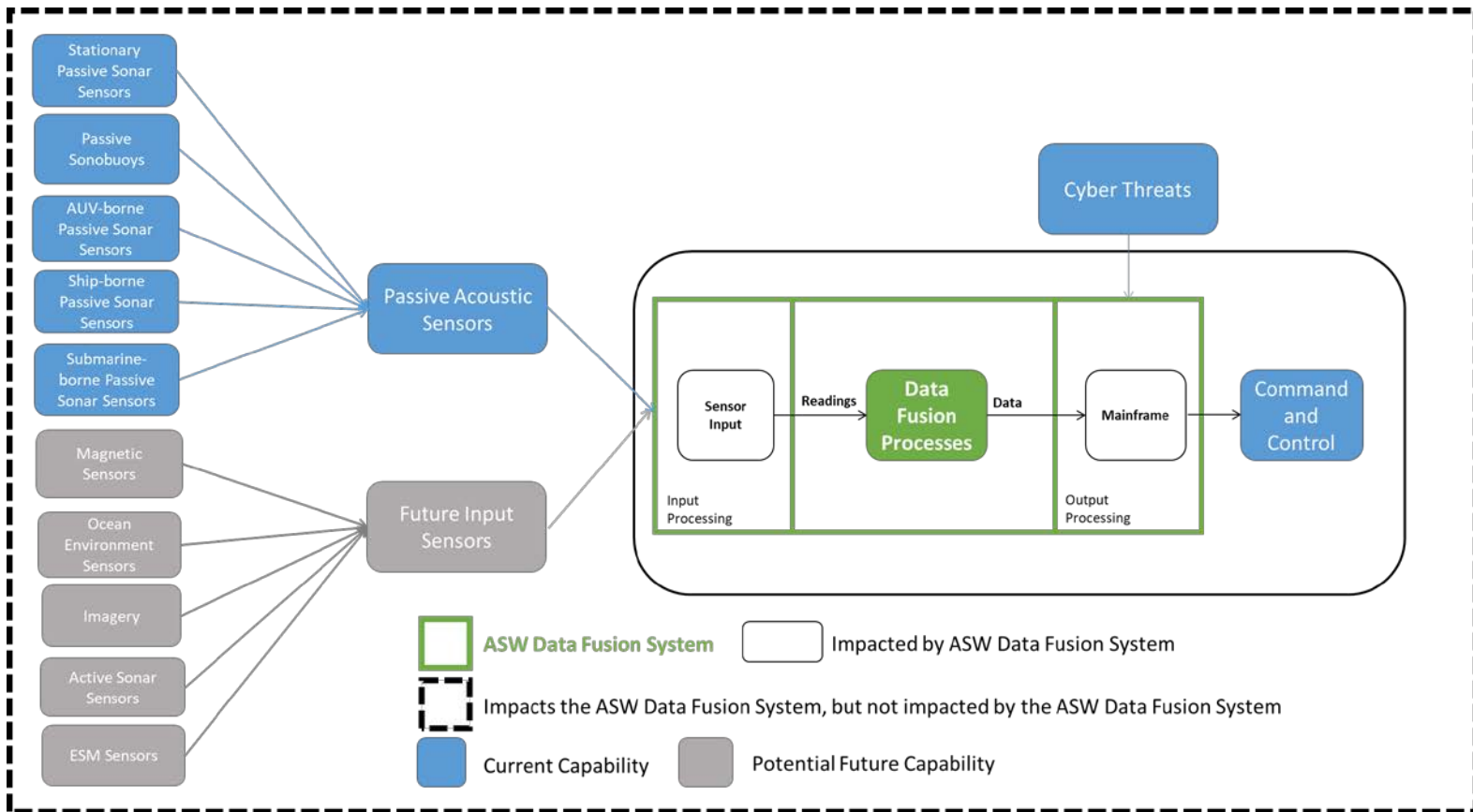


Figure 4. ASW Data Fusion Context Diagram

1. Initial Requirements

To scope the Data Fusion System Architecture, the team utilizes the following initial requirements. Further requirement definition is discussed in Chapter IV.

a. Initial Requirement 1

This project shall build upon the principles of the JDL model and the wide database of data fusion research. The intent of the project is to further research and serve as a basis for future data fusion efforts.

b. Initial Requirement 2

Given the rapid changes in data fusion technology and the wide variety of potential applications, this project shall utilize a product-line, open architectural approach to the data fusion problem. A product-line approach recognizes that the goal is to provide a specific capability for use by many different customers. It strives to provide an architecture flexible enough to accommodate customers with varying needs, platforms, sensors, and maintenance schedules. Similarly, an open architecture approach recognizes the need to make adding, upgrading, and swapping components easy. Open architectures allow potential users to access to the architecture and interfaces without imposing proprietary constraints. A product-line, open architectural approach will provide a framework for the integration of technology advances as they occur, as well as the integration of future platforms, sensors, and customers.

2. Constraints

The team identified the following constraints for the Data Fusion System.

a. Constraint 1

The accuracy of the data from individual reporting sensors constrains the total accuracy of the Data Fusion System. The Data Fusion System utilizes all data, regardless of accuracy, until the system can reject invalid data.

b. Constraint 2

The accuracy and availability of the sound velocity profile data of the ocean at the pertinent location and time constrain the Data Fusion System's accuracy.

c. Constraint 3

The time delay of the reporting sensors constrains the Data Fusion System's time to acquire a track solution.

d. Constraint 4

The use of deployed, legacy sensors constrains the Data Fusion System by preventing alterations to the legacy sensor data output format.

e. Constraint 5

The capabilities of current satellite communication systems constrain the Data Fusion System's distribution capability.

D. DELIVERABLES

The main output of the project is a reference architecture, based on product line principles, which integrates the tenets of the JDL data fusion model for undersea applications, including fixed and autonomous vehicle sensors. This architecture will provide a basis for further study of relevant data/information fusion concepts and technologies for future applications to ASW and MW. The product line approach to the architecture captures the current state of the art technology and provides a reference architecture for the integration of technology advances as they occur.

The deliverables for this project are the following:

- Capstone project report: "Data Fusion Architectures for Undersea Warfare with Autonomous Underwater Vehicles."
- A systems engineering model of the architecture developed in Innoslate and held at Naval Postgraduate School (NPS) by the project advisors.

E. SUMMARY OF CHAPTERS

(1) Chapter I: Introduction

Chapter I includes the introduction to the project, problem statement, team organization, system engineering process, scope, and deliverables.

(2) Chapter II: Problem Definition

Chapter II includes an in-depth explanation of the project problem definition, stakeholder analysis, an assessment of current capabilities, the project operational scenarios, requirements definition, objectives hierarchy and the functional analysis.

(3) Chapter III: Architecture Success Criteria

Chapter III includes a discussion of the systems engineering process and the development of success criteria for the architecture.

(4) Chapter IV: Candidate Architecture

Chapter IV delves into the design of alternatives. It includes the identification of the alternatives, functional architectures, physical architectures, process/operational architectures, interface architectures, the project qualification methodology, and finally the models of the alternative architectures. Additionally, Chapter IV contains the evaluation of the candidate architecture utilizing the success criteria described in Chapter III.

(5) Chapter V: Recommendation/Conclusion

Chapter V contains the conclusion and recommendations of this report.

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II. PROBLEM DEFINITION

The team performed a requirements analysis by transforming the statement of need into verifiable functional requirements. The requirements analysis included a stakeholder analysis, assessment of current capabilities, operational concept development, functional analysis, and objectives analysis. The following sections include details of each of these steps.

A. STAKEHOLDER ANALYSIS

With help from the project advisors, the team identified the stakeholders for the ASW data fusion architecture. The stakeholders are those individuals, roles, or organizations having a vested interest in the results of this project. A thorough analysis conducted by the team resulted in a detailed list of stakeholders. A determination of needs for each of the stakeholders provided a list of primary needs. A needs analysis further refines the primary needs into effective needs. The team condensed the list of stakeholders into two primary roles. The roles, needs, and concerns of the primary stakeholders are identified and documented in Table 2. Appendix A contains the full list of stakeholders.

Table 2. List of ASW Data Fusion Architecture Stakeholders

Stakeholder	Role	Primitive Needs	Effective Needs / Goals / Objectives	Concerns
NPS Department of Systems Engineering, John M. Green	Customer / Decision Maker	• Reference Architecture • Inclusion of AUVs	• Framework for the study of information fusion concepts for future applications • Adaptability for future technologies • A state-of-the-art, flexible, and expandable product.	• Timeline • Technological advances
N97	Customer / Decision Maker	• N/A	• Effective architecture	• Cost • Maintainability • Scalability • Upgradability • Cybersecurity

B. ASSESSMENT OF CURRENT CAPABILITIES

This section includes an assessment of current capabilities relating to the Data Fusion architecture. The JDL Model for Data Fusion provides a framework for the ASW data fusion architecture. The team provides previous work in this section, including multiple articles and publications relating to data fusion in various fields of study. The team provides Link 16, a distributive data exchange system, as an example of a system in use by international military forces. These current capabilities provide insight into the planned ASW data fusion architecture.

1. JDL Process Model for Data Fusion

In 1986, the JDL Data Fusion Working Group established a high-level system architecture for multi-sensor data fusion. Figure 5 depicts The JDL process model for data fusion (Liggins II, Hall, and Llinas 2001).

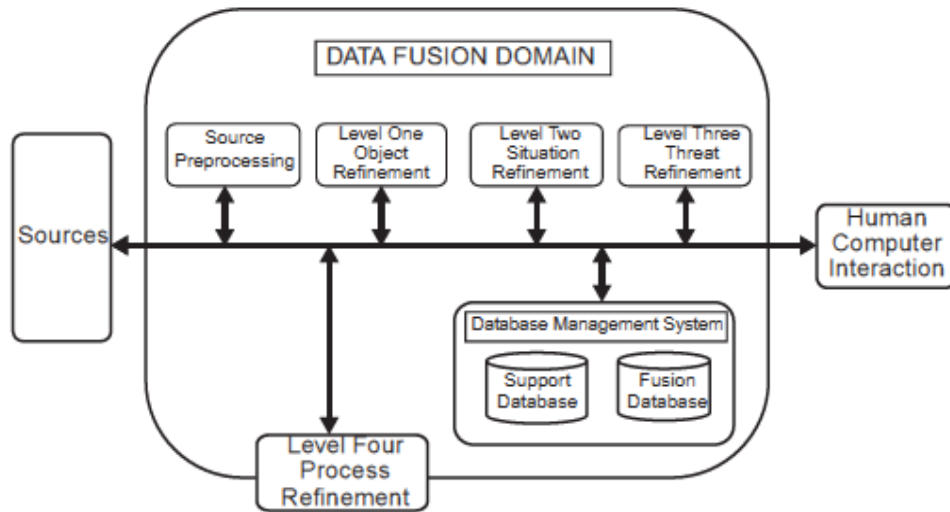


Figure 5. JDL Process Model for Data Fusion. Source: Liggins II, Hall, and Llanas (2001).

The JDL Data fusion process includes sensor inputs, human-computer interaction, database management, source preprocessing, and four key sub-processes (Liggins II, Hall and Llinas 2001).

a. Level 1 Object Refinement

Determine entity's position, velocity, attributes, and identity.

b. Level 2 Situation Refinement

Develop a description of current relationships among entities and events in the context of their environment.

c. Level 3 Threat Refinement

Project current situation into the future.

d. Level 4 Process Refinement

Assess and improve real-time system performance.

At this time, no current capability utilizes the JDL data fusion architecture in a near real-time ASW environment. The ASW data fusion architecture builds upon the JDL

model; refining the data fusion concept with the specific context of ASW data fusion utilizing current and future ASW platforms and sensors.

2. Current Concepts for Data Fusion Architecture

The team utilized *The Handbook of Multisensor Data Fusion* by Liggins, Hall, and Llinas as the main resource for previous work. Liggins, Hall, and Llinas provide an excellent primer on multisensor data fusion architecture. In particular, the handbook addresses the systems engineering concerns and process for developing a data fusion architecture. The text generalizes all data fusion systems and does not specify the constraints and requirements for undersea sensor fusion.

Additionally, the team reviewed the following articles:

“An Approach for Near-Optimal Distributed Data Fusion in Wireless Sensor Networks.” It is an article in *Wireless Networks* · July 2010, by Damianos Gavalas, Aristides Mpitzopoulos, Grammati Pantziou, Charalampos Konstantopoulos; Published by Springer Science Business Media, LLC

“Task-Oriented Distributed Data Fusion in Autonomous Wireless Sensor Networks.” It is an article in *Soft Computing* Volume 500 August 2014, by Hongmei He, Zhenhuan Zhu, and Erkki Makinen; Editor-in-Chief: Antonio Di Nola, Published by Springer Berlin Heidelberg

“A Review of Data Fusion Models and Architectures: Towards Engineering Guidelines.” Authors are Jaime Esteban, Andrew Starr, Robert Willetts, Paul Hannah, Peter Bryanston-Cross; The University of Manchester School of Mechanical, Aerospace and Civil Engineering, Sackville Street, Manchester, M60 1QD, UK; <http://www.manchester.ac.uk>

“Underwater Sensor Networks: Applications, Advances, and Challenges” By John Heidemann, Milicia Stojanovic, and Michelle Zorzi; Published by Philosophical Transactions of the Royal Society; <http://rsta.royalsocietypublishing.org>

3. Link 16

Link 16 provides a militarized, distributive data exchange network connecting ground, surface, subsurface, and air assets. Link 16 enables forces to exchange tactical information in near real-time; enabling accurate and comprehensive situational awareness information distribution to warfighters and decision makers. The level of information given to the warfighter by Link 16 and, to an extent, its distributive network architecture serves as a starting point for the ASW data fusion architecture. The DOD built Link 16 around active sensor systems with good signal-to-noise ratios (SNR) (e.g., radar); however, it has major limitations in ASW. The Link 16 architecture does not fuse sensor information. Instead, the architecture relegates sensor fusing to each platform's sensor fusion paradigm before being distributed.

4. Human-System Data Fusion

As it currently stands, the human operator solely provides the data fusion capability for the ASW environment. A console operator analyzes the output from multiple sensors, determines the relevant information, and combines that information to create a contact in the digital environment. The digital nature of the contact allows the operator to share the contact with other networked systems. The contact must be frequently updated using information from the sensors to ensure that system portrays accurate information. Since the input from the sensors must be manually integrated and the contact frequently updated, oversaturation of information to the user may occur. This oversaturation may result in the expiration of the relevant information due to the lack of timely integration into the contact. The current system is bottlenecked by the human operator. Replacing the human operator with an autonomous system allows for increased efficiency and a resultant increase in accuracy due to a reduction in the delay associated with the implementation of sensor information. The automated system also allows for the utilization of more sensor data. Since the human operator can only look at one sensor at a time, it acts as a system in series while the autonomous system can implement information from multiple sources at once and thus acts as a system in parallel.

C. OPERATIONAL CONCEPT / SCENARIOS

Figure 6 depicts the operational concept diagram for the ASW data fusion system. The ASW data fusion architecture receives inputs from the underwater sensor network, which may include static, semi-mobile, and mobile sensor sources. Static sensors may include bottom mounted sensor arrays, anchored buoys, and sensors affixed to docks and other static structures. Semi-mobile systems include temporary sensor systems suspended from buoys (e.g., sonobuoys). Mobile sensors include those attached to autonomous underwater vehicles (AUVs), low power gliders, and unpowered drifters. The ASW data fusion architecture provides a framework that fuses sensor data to detect and track undersea entities, determine their threat potential and distribute this situational awareness data to aviation, surface, and subsurface assets promptly.

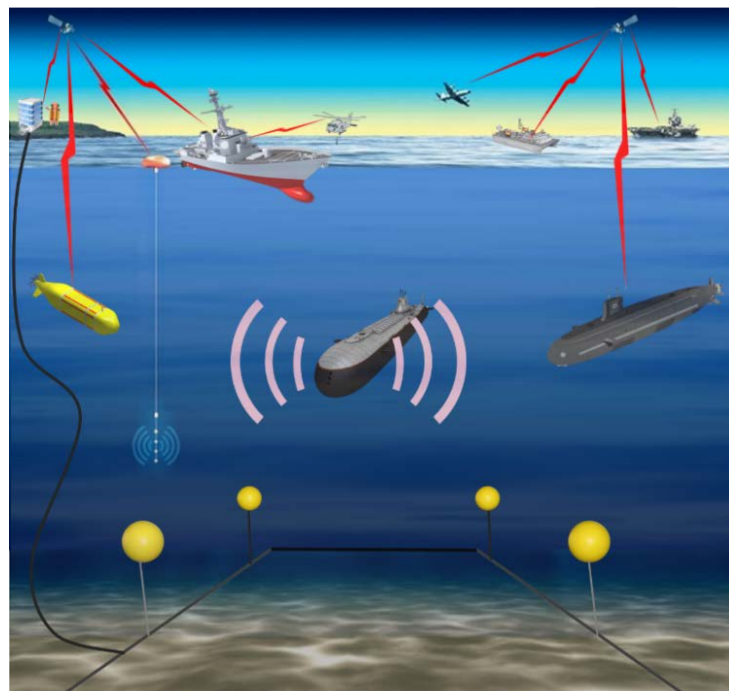


Figure 6. OV-1

The following operational scenarios of the ASW data fusion system are presented to provide examples of the ASW data fusion system potential capabilities.

1. Scenario 1: Tactical Employment

A carrier strike group (CSG) transitions to an operational area of interest. Sea-floor, stationary acoustic sensors and UUV mounted passive acoustic sensors detect noise features in the vicinity of the CSG planned path. Without operator interaction, the ASW data fusion system correlates the noise feature from the stationary sensors and aggregates it with the feature from the UUV. The system distributes the created track to decision-makers in the CSG along with contact classification information, accuracy probability, area of uncertainty (AOU), and sensor placement recommendations. The strike group commander elects to reroute the carrier away from the potential undersea contact while dispatching the escort destroyers, and their embarked ASW helicopters, to prosecute the contact. The destroyers, working off the track started and maintained by the UUV and sea-floor sensors, deploy towed sonar arrays while helicopters deploy sonobuoys. The ASW data fusion system receives the information from the sensors where more noise features are detected, correlated, and aggregated with the current track. The increased information allows the system to confirm the track as a submarine and, by linking with intelligence databases, can determine the submarine as hostile. The system changes the contacts display information to signify it is hostile and provides situational awareness information to decision makers concerning the contacts weapon employment capabilities. The strike group commander decides to continue monitoring the submarine and avoid entering the submarine's weapon engagement zone. The commander also requests the assistance from the theater commander to redirect assets (e.g., surveillance towed array sonar system, maritime patrol and reconnaissance aircraft) to aid in the long-term monitoring of the hostile submarine.

2. Scenario 2: Strategic Employment

While patrolling in an area of interest, the tactical action officer onboard a U.S. Naval vessel receives an alert on his or her screen of a potential subsurface contact 100 nautical miles to the North. The ship selects the new contact where the ASW data fusion system supplies amplifying information. The ASW data fusion system informs the crew the contact of interest is passing through a field of fixed passive acoustic sensors.

Additionally, the system provides course and speed information, initial contact identification, and probability information (such as contact confidence and AOU). The AOU for the contact shrinks as the system receives more information. The system then suggests the deployment of organic assets to continue the prosecution of the contact. The Captain orders the deployment of the multi-function towed array (MFTA) and the launch of the MH-60R. Shortly after the ship picks up contact on the MFTA and information feeds into the ASW data fusion system, the system determines the type and country of origin of the contact to be a ballistic nuclear submarine which was known to have left port two days prior. The Captain then passes the information obtained to the force commander who redirects the destroyer to continue monitoring and prosecuting the contact as well as a CSG transiting through the area.

3. Scenario 3: Intelligence, Surveillance, and Reconnaissance Employment

A CSG receives orders to perform intelligence, surveillance, and reconnaissance operations off the coast of an unfriendly nation. The naval commander of the CSG needs to make appropriate and timely decisions with available data to predict the potential actions of other nations in the maritime domain, whether friendly or unfriendly. To provide the naval commander with a continuous assessment of the operating area to detect suspicious behavior that may correlate to potential threats, the ASW data fusion system provides the CSG with relevant outputted information. The CSG requests ASW aircraft assets deploy semi-mobile sonar systems (i.e., sonobuoys) into the area of interest. CSG surface vessel assets maneuver along the perimeter of the areas of interest collecting data with their passive acoustic sonar devices. Swarms of UUVs outfitted with acoustic receive sensor payloads deploy to gather and collect data. Fixed bottom-mounted sources also collect passive acoustics in the area. The data exchange network receives all acoustic data, where available, for input into the data ASW data fusion system. The ASW data fusion system utilizes the sensor inputs to process, exploit, and transform the data to deliver information back to command and control (C2). CSG analysts evaluate and transform the output data into the intelligence required to support decision-making and operational planning and execution.

D. PROBABILITY OF SUCCESS DEFINITION

Figure 7 depicts the standard kill chain paradigm derived from the ASW mission.

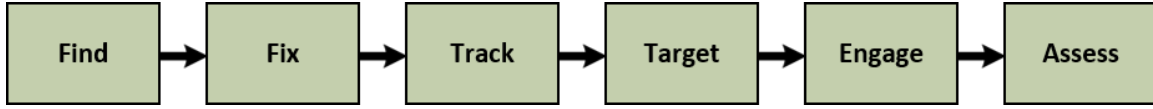


Figure 7. ASW Kill Chain

The serial nature of the kill chain supports the application of Lusser's Law. Lusser's Law states the reliability of a series system equals the product of the reliability of its component subsystem (Myers 2010). In this case, the system is the ASW mission defined by the kill chain, and the subsystems are the steps of the kill chain.

Lusser's Law, equation (1), states the reliability, or, in this case, success, of a system in series equals the product of each subsystem's probability of success.

$$R_t = R_1 * R_2 * R_3 * R_4 * R_5 * ... * R_n \quad (1)$$

The impact of Lusser's Law is the system is weaker than its weakest link. For example, a simplification of the kill chain can be defined as sense, decide, and then act. In this example, the probability of success (P_s) of the system equals the product of the probabilities of sensing an object (P_{sense}), making the correct decision about the object (P_{decide}), the action on the object being successful (P_{act}). The serial nature of the kill chain allows the application of Lusser's law as demonstrated in equation (2).

$$P_s = P_{sense} * P_{decide} * P_{act} \quad (2)$$

For example, if you assume an equal value of 0.9 for the three factors, the overall probability of success would be 0.73, significantly lower than each factor.

With the application of Lusser's Law to the kill chain, the probability of success of each link in the kill chain characterizes the probability of success of the ASW mission (Figure 8). The probability of success of the kill chain equals the product of the

probabilities of detection (find), classify (fix), localize (track), engage (target), and kill (engage).

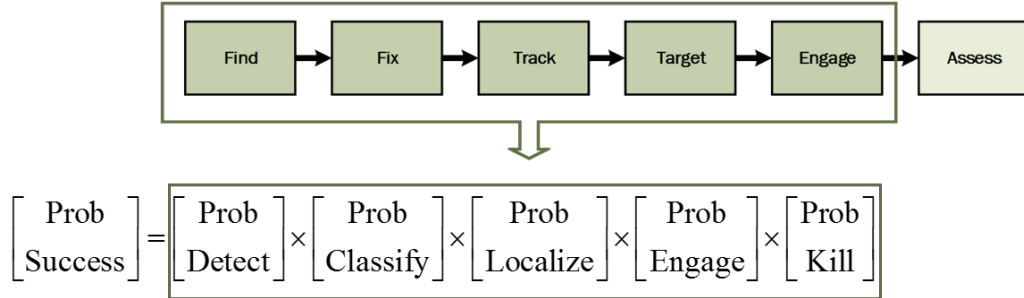


Figure 8. Lusser's Law for the ASW Kill Chain

E. CHAPTER SUMMARY

This chapter provided insight as to the framework of the system, the boundaries of the system, and introduced the find, fix, track, target, engage, and assess (F2T2EA) methodology which is the bedrock of the architecture discussed in the next chapter. Chapter III describes the development of the actual architecture of the system to include the top-level and second-level behavior definitions, the objectives hierarchy, a capabilities analysis, and defines the functional and nonfunctional requirements for the system.

III. ARCHITECTURE SUCCESS CRITERIA

The current state of ASW relies heavily on human operators. In essence, the human operator acts as a data fusion system. The operator receives acoustic information, of different stages of processing, from a variety of sensors. The operator, relying on experiential training, filters out acoustic “noise” and extracts signals that are deemed worthy of elevating in classification. The extracted signals are combined with additional sensor geometries (e.g., target motion analysis, additional sensors in contact) to support fixing the target location. Operators are limited in their ability to fix target locations since they only correlate the same sound frequency across sensors. After fixing location, the operator either manually tracks the signal or has a computer assist in tracking. Additionally, the operator attempts to identify the target based on comparing intelligence data to observed information such as tonals, target speed profile, and operating depths. This human-operated data fusion system is subjective and has a wide range of performance. In every step of the process, human error may affect the solution. The ASW data fusion architecture seeks to remove human subjectivity and associated error from the equation to improve performance and increase the effectiveness of the ASW mission. The success of the ASW data fusion system is dependent on the system performing at least as well a human operator.

Top-down systems engineering was utilized to define the success criteria for the ASW data fusion architecture. The cost and complexity of system of systems design significantly hamper the effectiveness of bottom-up design approaches. Top-down design approaches are better in this application; however prior knowledge of system behavior is needed to seed the solution. Therefore, as the architecture reaches maturity, there exists a need to design out a solution bias associated with top-down modeling. The ASW data fusion system is further limited in a top-down approach due to its nascent nature; previously developed data fusion system models (e.g., JDL data fusion model) serve as a guideline for the ASW data fusion system development but are unable to encapsulate the problem of ASW data fusion fully.

Data fusion systems currently in operational use primarily utilize active sensors (e.g., radar), and none of them are used in an undersea environment. ASW data fusion significantly differs from other data fusion systems due to the use of passive sensors to monitor very dynamic events, the constraints posed by the undersea environment, the very short useful life of ASW data, and the limited bandwidth available to ASW assets. No data fusion architecture in use today can handle the issues presented by the ASW mission.

The first step of the top-down engineering process is establishing success trees. Success trees are similar to commonly used fault trees except, instead of quantifying failure modes, the success tree aims to quantify elements that contribute to the success of a mission. A black box model then fulfills each branch of the success tree. The black box model allowed the team to quantify the performance and behavior of modules without having to define the processes resident in each module (Figure 9). In essence, it allowed the team to start in the ideal plane then incrementally and recursively define processes to adjust the system to handle real-world stimuli. John Green, a professor at the Naval Postgraduate School, presented a lecture titled “Capability-Based Assessment and System Effectiveness” in November of 2017 to the Systems Architecting and Design class where he discussed the black box model. Each iteration of the system engineering process seeks to move black boxes into clear boxes (i.e., modules with processes defined).

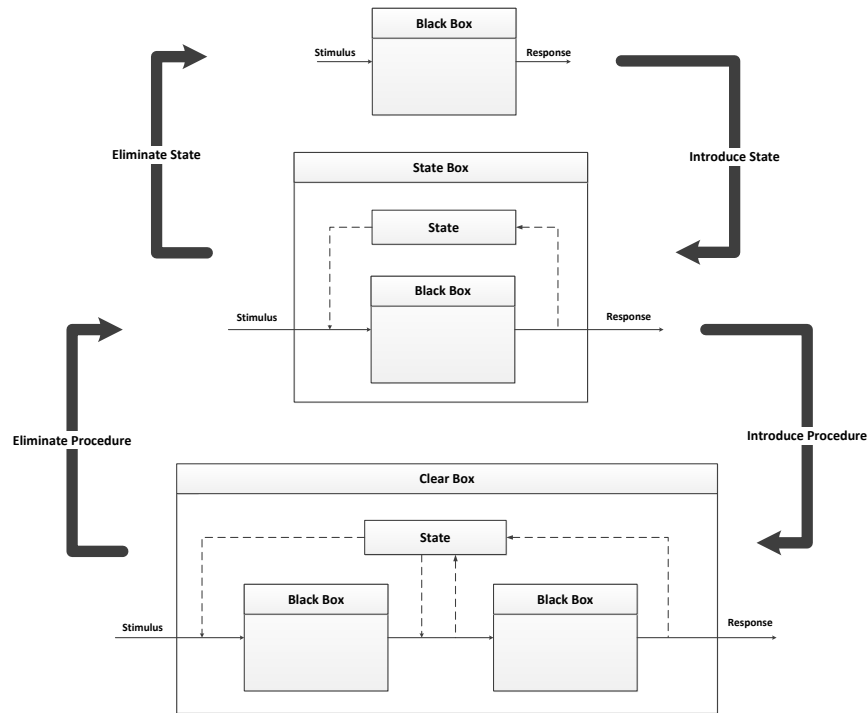


Figure 9. Box Structure Expansion/Reduction. Source: Mills, Linger, and Hevner (1986).

Using information from Professor Green’s presentation, the team opted to engineer the mission, instead of the system, in a top-down system engineering approach. This allowed the team to ensure the success of the system architecture while enabling a direct comparison of the ASW data fusion system performance against the data fusion performance of human operators.

A. TOP LEVEL BEHAVIOR DEFINITION

The team first established the capability need as a black box with a target performance value. Shifting the viewpoint of the ASW data fusion system to the mission, one can view the capability, and performance goal provided by the data fusion system as to “prosecute submerged, man-made objects with a probability of success of 0.x.” The performance goal for the system is not defined at this point nor will it be in this paper. The actual number is not needed for the further development of the system. Further decomposition of the mission will identify the components that facilitate the overall success of the system.

It is important to distinguish the success of the system architecture from mission success of the system. The ultimate goal of this investigation is to provide the framework by which decisions can be made to determine the overall required probability of mission success. The ability of the system to perform at least as well or better than the human operator under the same circumstances defines the success of the system. Chapter IV includes a detailed discussion of the evaluation of the architecture's success.

1. Top-Level Success Tree

At this point in the design of the system architecture the mission is still examined as the system. In later steps, functions of the system architecture tie in mission success.

The ASW data fusion architecture supports the detect-to-engage phases of the mission represented by the functions: find, fix, track, and target (F2T2). The actual engagement and assessment of the engagement's effects are outside the data fusion system boundary. Therefore, the probability of success for the architecture becomes the product of the probabilities of success for F2T2. Figure 10 depicts the top-level success tree.

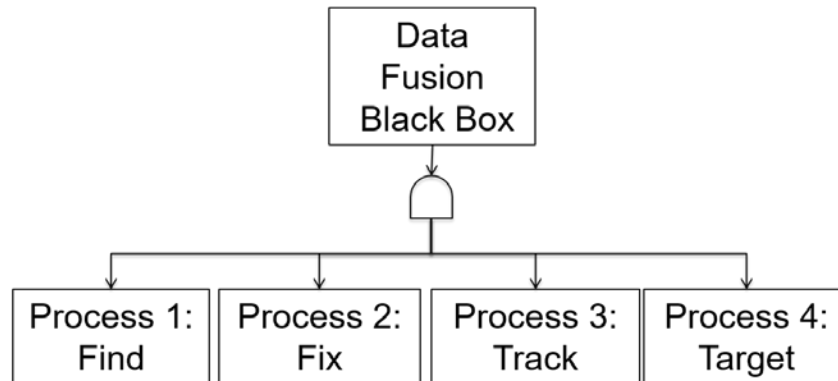


Figure 10. Top-Level Success Tree

2. Top-Level Functional Behavior

The kill chain, by design, is a series evolution. The output of the data fusion system, information to engage a target, only occurs if all subsequent steps (find, fix, track, target) are performed, and are independent. Figure 11 depicts the top-level functional behavior.

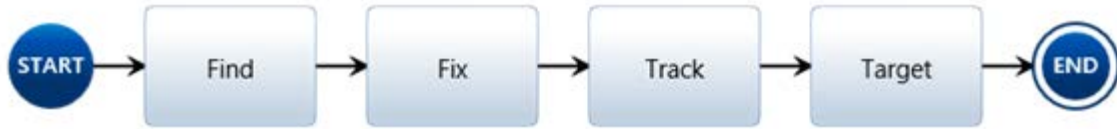


Figure 11. Top-Level Functional Behavior

B. SECOND LEVEL BEHAVIOR DEFINITION

Continuing with the top-down engineering design model, each of the top-level functions is decomposed further. Each function is assumed to be fulfilled by its own system. Under this assumption, each function becomes a black box with its own measure of performance and probability of success. Just like the overall system performance, the engineering process can continue without the nominal probability of success for each of the top-level functions. Rather, the decomposition categorizes the factors affecting the overall success of the system to enable decision makers to determine the required level of performance.

1. Find Function's Success Tree and Functional Behavior

The Find function of the ASW data fusion kill chain is responsible for detecting undersea entities. These entities can be natural, biologic or man-made. The sole responsibility of the Find function is to distinguish ASW data from noise. Therefore, to state the measure of performance, “detect undersea entities with a probability of detection of 0.x.”

As the entry point for all data entering the system, the Find function is comprised of the undersea sensors. The actual type of sensor is unimportant. As such, we can treat any sensor as a generic sensor. The Find function is also agnostic to the number of sensors utilized. It only takes one sensor to detect a sound for the kill chain to proceed to the next function. Multiple sensors present more opportunities to detect a sound; increasing the probability of detection. Figure 12 is the success tree for the Find function.

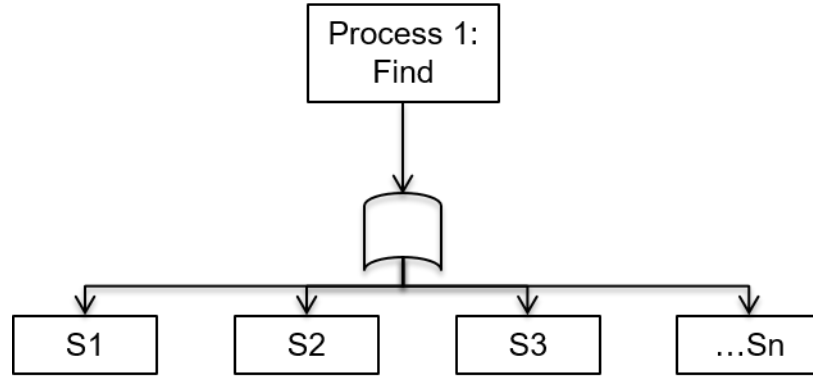


Figure 12. Find Function Success Tree

Each sensor in the Find process will have a probability of detection, varying based on a variety of factors including sensor type and location. The detection of a passive sensor, as defined by Urick, is provided in equation (3) and the definitions of the variables are provided in (Table 3).

$$DT = SL - TL - NL + DI \quad (3)$$

Table 3. Detection for a Passive Sensor Variable Definition

DT: Detection
SL: Target Source Level
TL: Transmission Loss
NL: Self Noise Level
DI: Receiving Directivity Index
<i>All variable units in dB</i>

Since only one sensor needs to detect for the find function to be successful, and the success of one sensor does not affect the success of another sensor, the sensors all operate in parallel (Figure 13).

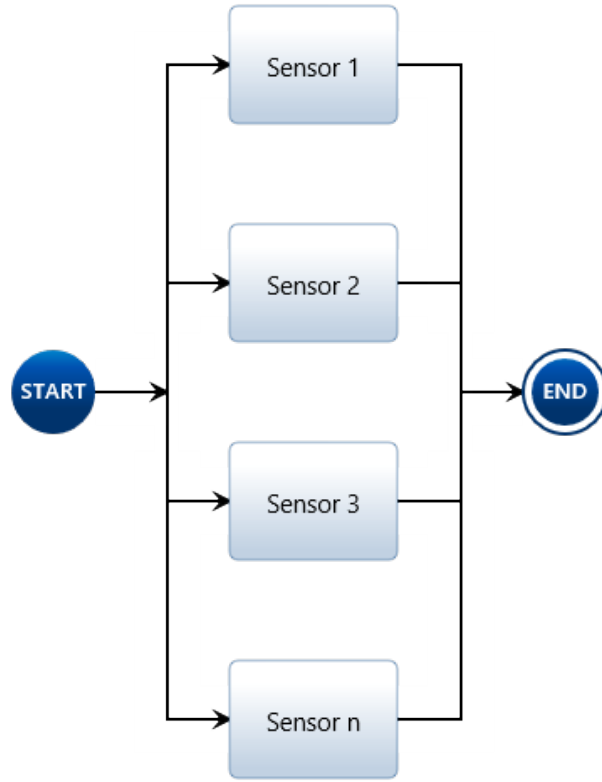


Figure 13. Parallel Sensors

The overall success of the Find function is highly sensitive to the type and number of sensors used. Higher quality sensors (with a greater probability of detection), additional sensors, or a combination of both, will increase the overall probability of detection.

To calculate the success of the Find function, enter the sensor probability of detection into equation (4).

$$P_{\text{detection}} = 1 - [(1 - P_{S1}) * (1 - P_{S2}) * (1 - P_{S3}) * \dots * (1 - P_{Sn})] \quad (4)$$

For example, assume the required probability of detection is 0.99. There are two sensors to choose from: Sensor A with probability of detection of 0.99 and Sensor B with probability of detection of 0.70. Sensor A costs four times as much as Sensor B. One of Sensor A will provide the required performance but at a high cost. However, we can buy four of Sensor B for the same cost. Utilizing equation (4), the probability of detection of

four of Sensor B in parallel is 0.992, which represents a .002 increase in performance over one Sensor A. Although the difference of 0.002 does not seem significant, when entered into the series system of the kill chain, that very small difference can have a significant effect on the overall performance.

2. Fix Function's Success Tree and Functional Behavior

The Fix function of the ASW data fusion kill chain is responsible for classifying all entities detected by the Find function. A statement for the measure of performance of the Fix function is “classify undersea entities with a probability of classification of 0.x.”

Currently, the human operators use classification categories based on the likelihood of the entity being a submarine. Entities are binned into four categories: NONSUB (non-submarine), POSSUB (possible submarine), PROBSUB (probable submarine), and CERTSUB (certain submarine). The human operator utilizes established criteria for each of the categories; however, there is still a significant amount of subjectivity. The ASW data fusion system does not have the capability to apply subjective judgment nor will it need to. The purpose of the classification system is to manage task loading of a human operator; the dedication of more human resources increases to further the kill chain for CERTSUB entities than lower classifications, with NONSUB getting no further resources. Misclassification can lead to a significant amount of data rejection with a high probability the rejected data contains information relatable to a submarine. The ASW data fusion system is not as limited in processing power and data retention as its human operator counterparts. Therefore, eliminating the need for subjective classification categories and the resulting loss of potentially valuable information.

The first step in classifying an entity is to determine a preliminary location. The success of the preliminary location is contingent on the sensor geometry as well as the bearing and range accuracy, as illustrated in Figure 14.

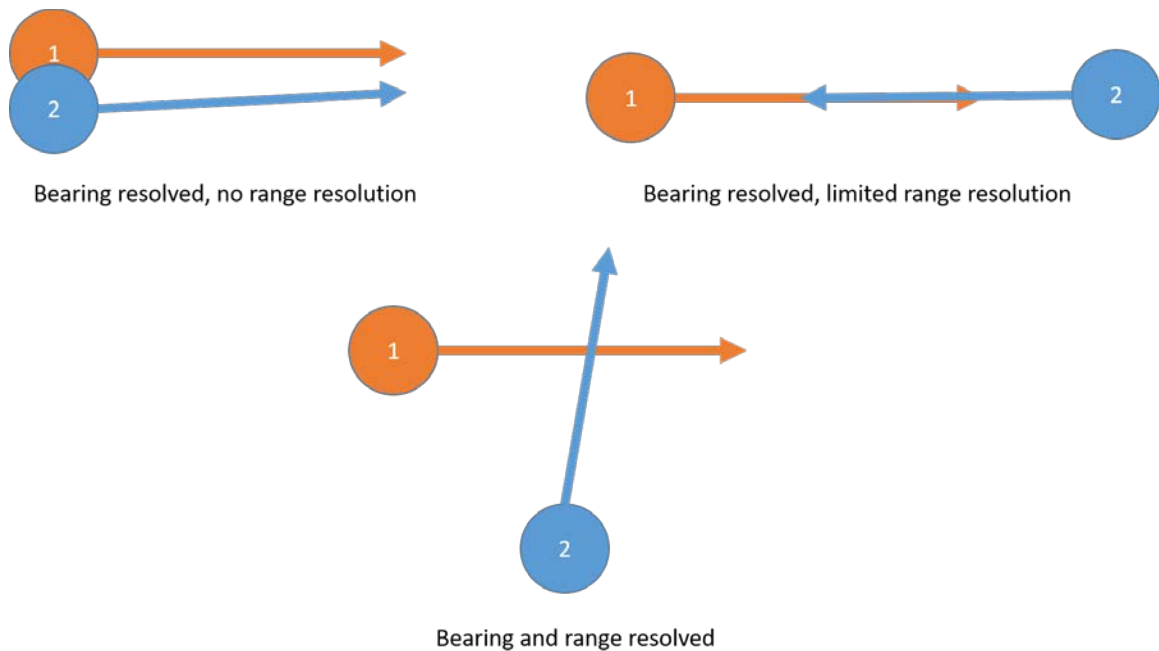


Figure 14. Sensor Geometry

Upon the establishment of a preliminary location, objects will be extracted and classified for further processes down the kill chain. Anti-Submarine Warfare is a time sensitive evolution; getting information in time is as important as getting the right information. The success of the Fix function is directly dependent on both its timeliness and accuracy. Figure 15 shows the success tree for the Fix function, and Figure 16 shows its functional behavior.

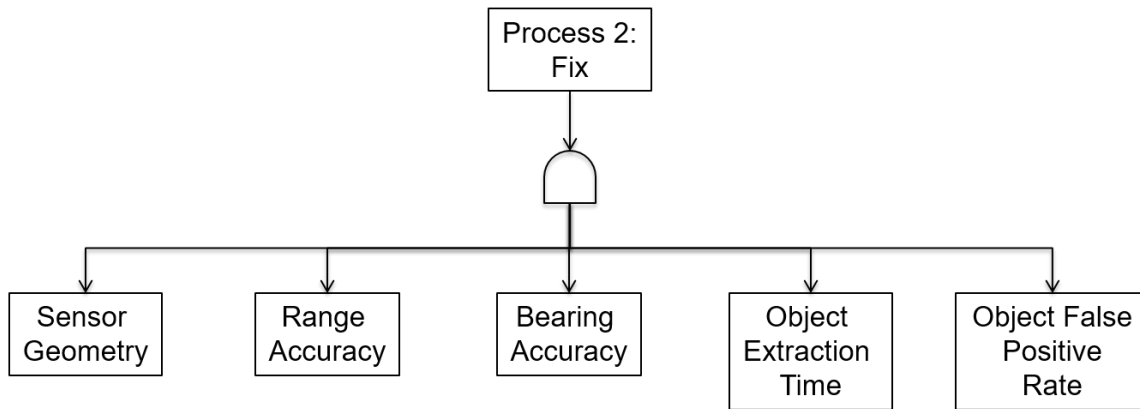


Figure 15. Fix Function

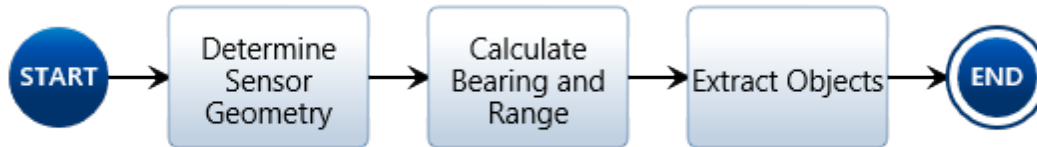


Figure 16. Fix Function Behavior

3. Track Function's Success Tree and Functional Behavior

The Track function of the ASW data fusion kill chain is responsible for localizing all entities classified by the Fix function. A statement for the measure of performance of the track function is “localize undersea entities with a probability of localization of 0.x.”

The Track function of the kill chain includes the calculation of contact dynamics. A contact's course and speed information are necessary for the success of the remaining portion of the kill chain. A track is essentially a collection of locations over time. This historical collection is then processed to determine trends in motion. The processing can be as simple as calculating the velocity vector using the contact's last two positions, or it can employ more complicated methods which utilize multiple positions and least square regressions to determine the contact's velocity vector.

In a theoretically perfect world, the two-point tracking method would suffice. Passive sonar sensors would not have to contend with signal propagation loss, attenuation, refraction, reflection, and other signal degrading phenomena. As such, the sensor would have no bearing error and would always point directly at the sound source. With multiple sensors pointing at a sound source, the collective bearing lines would always intersect at a single point directly over the source. Since there would be no ambiguity of the location of the sound source, the most recent two of the intersections tracked over time will give the exact course and speed.

Unfortunately, this theoretical, perfect world does not exist. Signal degradations that cause bearing errors are commonplace; so, when three or more sensors are in contact with a sound source, the intersecting bearing lines form a polygon rather than a single point (Figure 17).

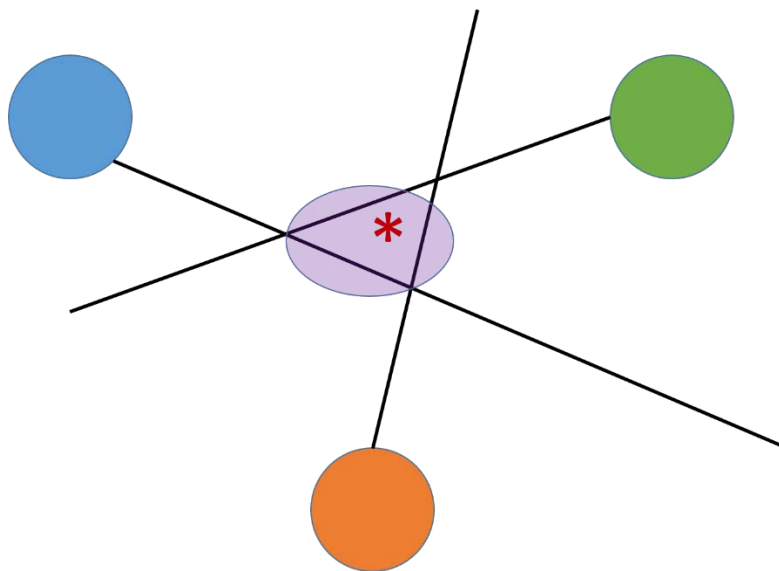


Figure 17. Area of Uncertainty

The sound source, shown as a red asterisk, can be anywhere inside the polygon. The shaded oval represents the area of the polygon where the sound source can exist, shown in purple and termed the AOU. This calculation is similar in function to the Global Positioning System calculation of accuracy.

The AOU is critical to track accuracy and the ability to localize an undersea entity. A large AOU leads to a complex probabilistic calculation to determine a contact's course and speed. As the AOU shrinks in size (representing an increase in accuracy), the number of possible routes the contact could take decreases. If the AOU is small enough, the margin of error will be small enough to be able to treat the AOU as a perfect intersection, thus the reliable utilization of the two-point method. Shrinking the AOU can be accomplished either through increasing the accuracy of the sensors through post-processing or increasing the number of sensors in contact.

The AOU is the primary driver of the Track function's success. Just like the Fix function before it, the Track function is also sensitive to the time required to extract a contact for localization, and the potential misclassification of a contact (Figure 18).

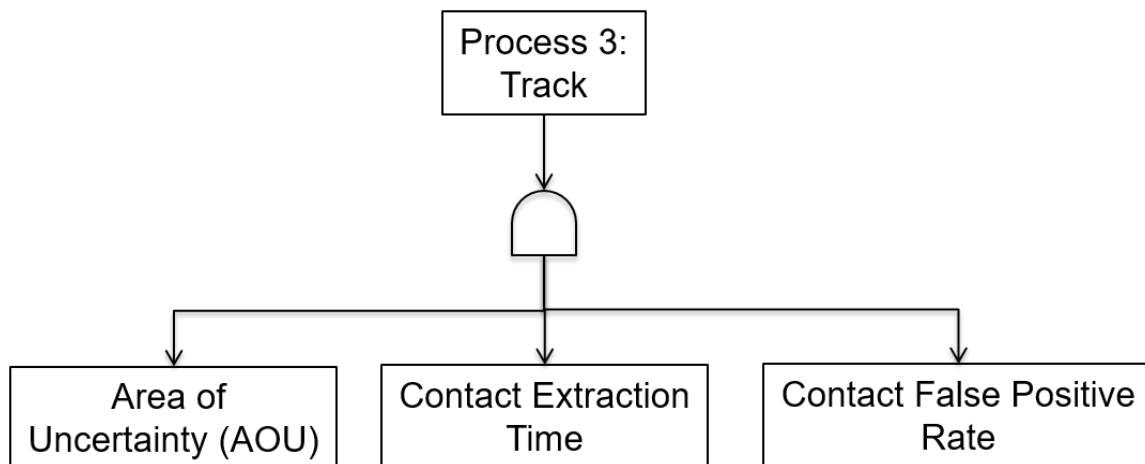


Figure 18. Track Function Success Tree

Figure 19 depicts the functional behavior for the Track function derived from the success tree.

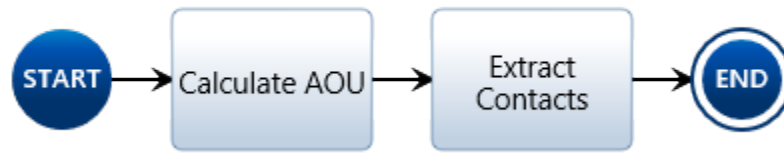


Figure 19. Track Functional Behavior

4. Target Function's Success Tree and Functional Behavior

The Target function of the ASW data fusion kill chain is responsible for identifying all contacts localized by the Track function. The statement for the measure of performance of the Target function is “identify undersea entities with a probability of identification of 0.x.”

Identifying an undersea contact can be a difficult process. The amount of effort required to identify a contact is dependent on the level of fidelity required in the situation. In some cases, a refined classification is sufficient for targeting. Proceeding with a refined classification, vice positive identification, is typical for situations where other intelligence information precludes the possibility of contact other than the target contact from existing in the area. Therefore, targeting success only requires an identification of a contact as a submarine.

If the requirement exists for a higher fidelity of identification, the solution must refer to outside information. The Acoustic Intelligence (ACINT) database contains information that can be used to correlate a noise signature with a particular class and in some cases an individual, submarine. The database also contains additional information on submarine capabilities including dimensions, speed, endurance, weapons, and tactics. To identify a submarine, an operator must compare the tonals (specific frequencies produced by the contact) to the signatures listed in the ACINT database. The success of identification through ACINT data is dependent on having the particular contact sound signature in the database, and the time it takes to access and correlate the information.

The combination of the two approaches provides the success tree (Figure 20) and the functional behavior (Figure 21).

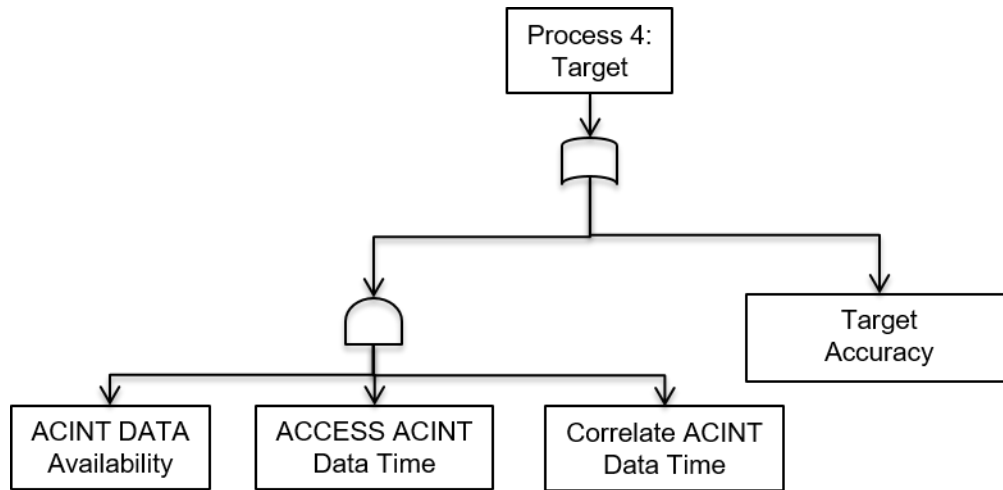


Figure 20. Target Function Success Tree

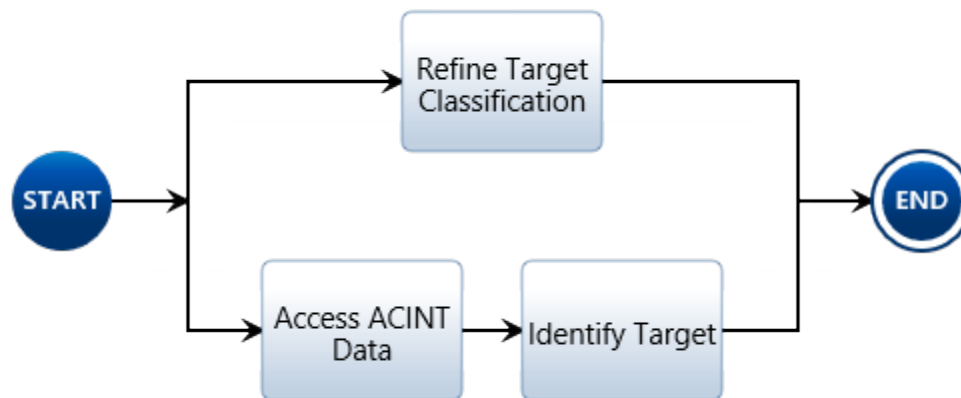


Figure 21. Target Functional Behavior

C. CAPABILITY ANALYSIS

The primary purpose of the ASW data fusion system is to provide accurate, time-sensitive data to the warfighter. The system must be capable of receiving data from various sources, determining the accuracy of the data, combining that data, and redistributing the data to the fleet. Figure 22 depicts the capability hierarchy.

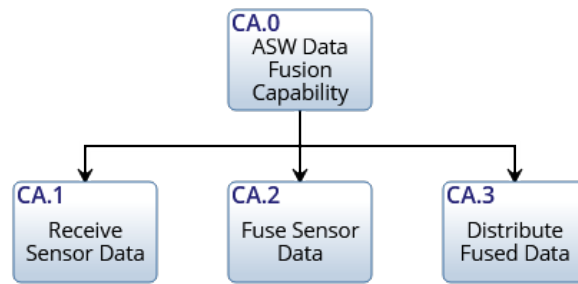


Figure 22. Capability Diagram

The primary capability of the ASW data fusion system is broken down into three sub-capabilities: receive sensor data, fuse sensor data, and distribute fused data. The receive capability is the system's ability to receive data from multiple different sensors simultaneously. Along with passive acoustic data, those sensors must provide their locations, accurate times, and any other relevant sensor data for accurate fusion with information from other sensors.

The capabilities are mapped back to the F2T2EA process in Figure 23. The Find function relates to receive sensor data capability through feature data. Feature data contains sound detected by the sensors. The Fix, Track and Target functions relate to the fuse sensor data capability through cluster data, contact data, and situational awareness data, respectively. Cluster data is the aggregation of feature data stemming from a single sensor source. Contact data is the aggregation of cluster data from multiple sensors. Situational awareness data contains the contact identification and performance information derived by the correlation of contact data with acoustic intelligence data. Feature, cluster, contact, and situational awareness data are further defined in Chapter IV.

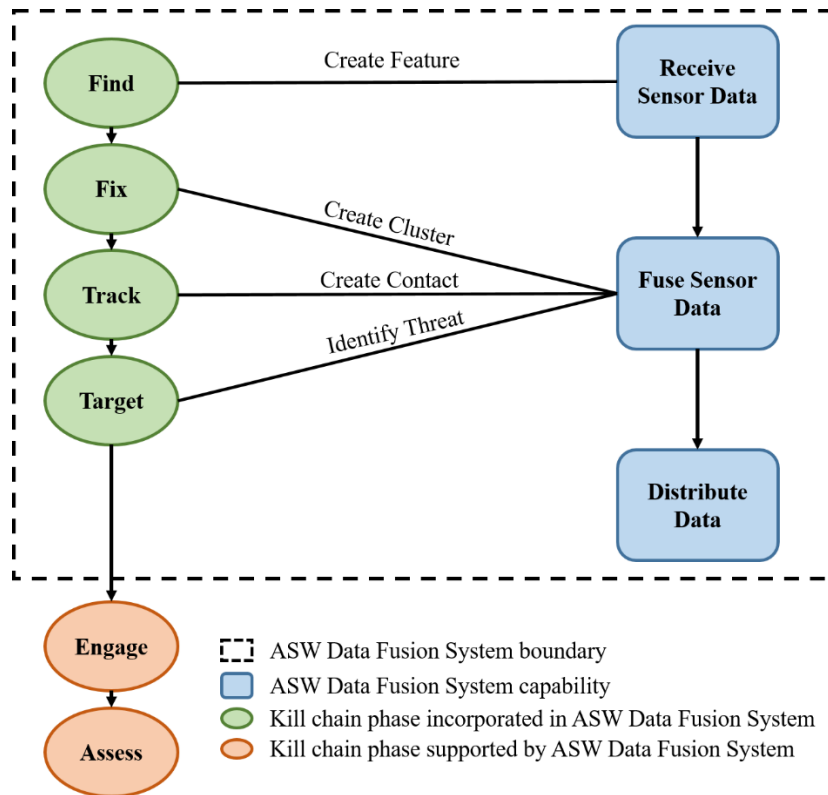


Figure 23. Kill Chain to Capability Map

The fuse sensor data capability is heavily reliant on the system's ability to extract feature data from the received sensor data and determine if it matches other data from other sensors. The system compares the feature data, determines which features match, and fuses those features to create a cluster. As more clusters are created, they are then fused to create contacts. Contacts provide more detailed information, including position, course, and speed. Established network infrastructures distribute the newly created contact to the warfighter.

D. OPERATIONAL ACTIVITIES

The capabilities described in Section C were used to establish the Operational Activities Model (OV-5a). The decomposition of each capability established the required functions. Figure 24 presents the OV-5a Hierarchy for the ASW data fusion system. The OV-5a diagram is located in Appendix B.

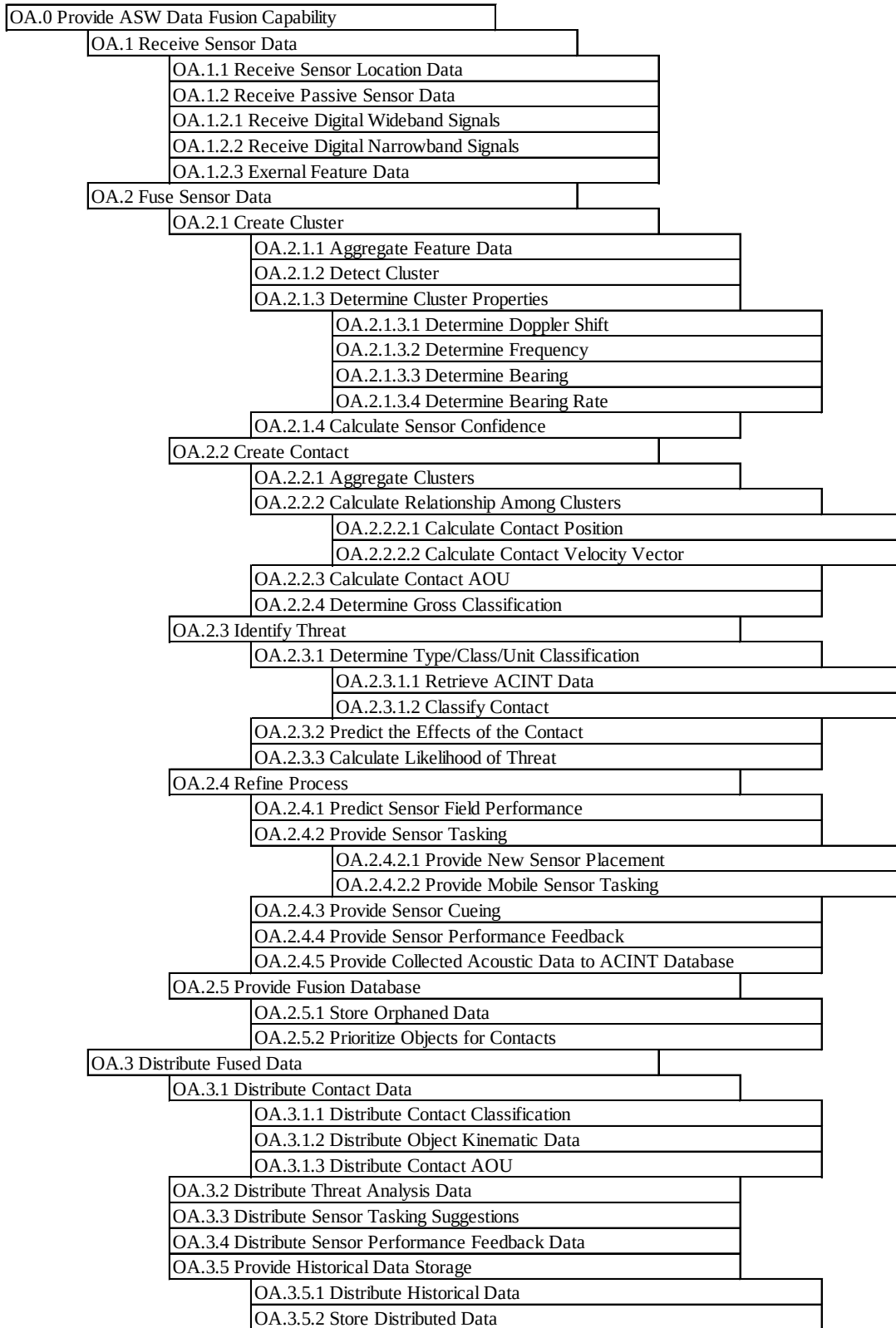


Figure 24. OV-5A Hierarchy

E. OBJECTIVES HIERARCHY

KPPs are the foundation of the objectives hierarchy. The *Manual for Operations of JCIDS Systems* regulates the creation of KPPs for the DOD. The following is directly from the manual:

Key Performance Parameters (KPPs) are performance attributes of a system considered critical or essential to the development of an effective military capability. Failure of a system to meet a validated KPP threshold value triggers a review by the validation authority and evaluation of operational risk and/or military utility of the associated system(s). The review may result in validation of an updated KPP threshold value, modification of production increments, or recommendation for program cancellation.

DOD Components must develop, acquire, test, deploy, and maintain IS that:

1. Meet the essential operational needs of U.S. forces.
2. Use architecture data and associated artifacts/views to develop the NR KPP that is
 - a. Certified in capability requirement documents in accordance with this manual.
 - b. Reviewed in Information Support Plans (ISPs) in accordance with reference DODI 8330.01, 21 May 2014, "Interoperability of Information Technology (IT), Including National Security Systems (NSS)".
3. Are interoperable and supportable with previously fielded, developing, and proposed (pre-MS A) IS through architecture, standards, defined interfaces, modular design, and reuse of previously fielded IS solutions.
4. Are supportable over the DODIN in accordance with reference DODI 8320.02, 5 August 2013, "Sharing Data, Information, and Information Technology (IT) Services in the Department of Defense" and DODI 2010.06, 29 July 2009, "Materiel Interoperability and Standardization with Allies and Coalition Partners".
5. Are interoperable with host nation, multinational coalition, and federal, state, local, and tribal agency partners.
6. Provide global authentication, access control, and enterprise directory services; provide information and services to the edge; utilize joint information environment operational reference architecture (JIE ORA); provide unity of command; and comply with common policies and standards in accordance with reference JROCM 095-09, 1 June 2009,

“Global Information Grid 2.0 Initial Capabilities Document” and DOD 4650.1-R1, 26 April 2005, "Link 16 Electromagnetic Compatibility (EMC) Features Certification Process and Requirements".

7. Leverage emerging capability-based references and methods, including JCAs as described in this manual and references CJCSI 3170.01I, 23 January 2015, “Joint Capabilities Integration and Development System” and VCJCS and PDDNI Memorandum, 30 July 2013, “Guidelines for Interaction between the Intelligence Community Capability Requirements (ICCR) Process and Joint Capabilities Integration and Development System (JCIDS)”, JMTs as described in reference Joint Mission Threads. On NIPRNET – <https://wmaafip.csd.disa.mil/Home/Index/?aId=26>, and the Joint Common System Function List (JCSFL) as described in reference Joint Common System Function List. On NIPRNET – https://www.intelink.gov/wiki/Joint_Common_System_Function_List. On SIPRNET

http://www.intelink.sgov.gov/wiki/Joint_Common_System_Function_List

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8. Comply with spectrum requirements throughout the capability solution’s life cycle.

9. CCMDs, Services, and other DOD Components ensure capability solutions are aligned and interoperable during the development cycle.

10. Comply with DOD Interoperability and Supportability (I&S) policy and instruction in accordance with reference DODI 8330.01, 21 May 2014, “Interoperability of Information Technology (IT), Including National Security Systems (NSS)”.

11. Complies with DOD Cybersecurity policy in accordance with reference DODI 8500.01, 14 March 2014, “Cybersecurity”.

...The net ready (NR) KPP identifies operational, net-centric requirements in terms of threshold and objective values for MOEs and MOPs. The NR KPP covers all communication, computing, and EM spectrum requirements involving information elements among producer, sender, receiver, and consumer. Information elements include the information, product, and service exchanges. These exchanges enable successful completion of the warfighter mission or joint business processes.

The NR KPP includes three attributes derived through a three-step process of mission analysis, information analysis, and systems engineering. These attributes are then documented in solution architectures developed according to the current DODAF standard in reference DOD CIO, August

2010, “DOD Architecture Framework (DODAF), Version 2.02,” On NIPRNET
<http://dodcio.defense.gov/TodayinCIO/DoDArchitectureFramework.aspx>.

(a) Attribute 1: Supports military operations.

(b) Attribute 2: Is entered and managed on the network.

(c) Attribute 3: Effectively exchanges information. (Department of Defense 2015, B-A-1 – B-A-3)

The net ready (NR) KPP for the ASW data fusion system can be found in Table 4.

Table 4. ASW Data Fusion NR KPP

NR Attribute	Mission	MOE	KPP	Threshold	Objective
Support Military Operations	Find High Value Targets (HVT)	Maximize ability to find HVT	Measure: Time to locate of HVT	TBD (minimize)	TBD (minimize)
			Measure: Probability of false HVT detection	TBD (minimize)	TBD (minimize)
	Fix and Track HVT	Maximize ability to Fix and Track HVT	Measure: Size of AOU for HVT location	TBD (minimize)	TBD (minimize)
	Target HVT	Maximize ability to target HVT	Measure: Probability of HVT misidentification	TBD (minimize)	TBD (minimize)
			Measure: Time to provide targeting information	TBD (minimize)	TBD (minimize)
Is entered and managed on a network	Provide data distribution capability	Maximize availability of distribution capability	Measure: Time to connect to an operational network from power up	TBD (minimize)	TBD (minimize)
			Measure: Operational Availability (Ao)	TBD (maximize)	TBD (maximize)
Effectively exchanges information		Maximize timeliness of data exchanged	Measure: Latency of distribution of data on to the network	TBD (minimize)	TBD (minimize)

This effort does not require the definition of the threshold and objective. For this investigation, only the knowledge of maximizing or minimizing a KPP is sufficient. The proposed architecture is validated utilizing the generalized KPPs in conjunction with the distributed error allocations defined by the team later in this report.

The KPPs seed the non-functional requirements definition for the system. The functional analysis section in Chapter IV defines the functional requirements. Both functional and non-functional requirements are contained in Appendix C.

F. CHAPTER SUMMARY

Chapter III established the process for defining and building the architecture. The use of the find, fix, track, and target processes mimic the human operator, which is the current system. The current, human system provides a starting point for the architecture development. The top-down systems engineering process provides the means of how to design the system. The process effectively works backward from an optimal state. Finally, both processes are utilized to derive the top-level and second-level functional behaviors. Chapter IV introduces the finalized architecture and models both the human and computer systems to demonstrate the optimal choice.

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IV. CANDIDATE ARCHITECTURE

The team identified the operational activities necessary to accomplish ASW Data Fusion. The next step of the engineering process is establishing the method for the definition of the operational activities. First the operational activities are allocated to system functions, then the behaviors of the functions are defined, and lastly, the optimal configuration is determined. Chapter IV defines the behavioral allocation, functional architecture, and physical architecture of the ASW data fusion system, along with the performance characterization of the system.

A. FUNCTIONAL ANALYSIS

The functional analysis includes the Behavioral Allocation and the mapping of operational activities to system functions. The analysis also includes the establishment of the functional requirements from the operational activity model.

1. Behavioral Allocation

This section will discuss the allocation of ASW data fusion system operational activities to system functions. The goal of the allocation process is to minimize the number of functions to reduce the complexity of the system. The team considers this goal along with the goal of maximizing the system's scalability and adaptability during this allocation process. Table 5 contains the functional allocation of the ASW data fusion system.

Table 5. Functional Allocation of the ASW Data Fusion System

Activity	Function	Reason
Receive Sensor Location Data	Receive Sensor Data Function	The team could not identify a reason to separate the Receive Sensor Location Data and Create Feature Data activities. The Receive Sensor Data Function is separated from the other system functions to allow the possibility of distributing it to maximize the scalability of the system. Distributing this function would reduce the potential “bottleneck” effect of increasing the amount of incoming sensor data, thereby increasing the scalability of the system.
Create Feature Data		
Create Cluster	Create Cluster Function	The Create Cluster activity is allocated to its own system function because it is expected to be process intensive and separating it allows the possibility of distributing it to scale the workload. Further, its mission is singular, and separating it enhances the adaptability of the system. Separating it from the Create Features Function supports the possibility that feature data input may be externally generated, thereby enhancing system adaptability.
Create Contact	Create Contact Function	The Create Contact activity is allocated to its own function to enhance the adaptability of the system. Separating it from the Create Cluster activity allows for the potential usage of externally generated cluster data objects.
Identify Threat	Identify Threat Function	The Identify Threat activity is allocated to its own function because it requires input from the ACINT Database, which may constrain its physical location. Further, calculated contact data should be sent to decision makers as soon as it is available. While the Identify threat function is essential, it should not hinder the timely distribution of pertinent situational awareness data.

Activity	Function	Reason
Refine Process	Refine Process Function	The Refine Process activity is allocated to its own function to enhance the adaptability of the system. Separating the Refine Process from the functions allows for greater flexibility of integration on legacy platforms.
Provide Fusion Database	Support Database Function	The Provide Fusion Database activity is allocated to its own function because it is expected to have a unique set of hardware requirements based on its storage capability.
Distribute Contact Data	Distribution Function	The team allocated the Distribute activities to a single function due to the similar requirements of each activity. To allow dissimilar platform integration, the team separated from the Create Contact, Identify Threat and Refine Process functions from the Distribute Function.
Distribute Threat Analysis		
Distribute Sensor Tasking Suggestions		
Distribute Sensor Performance Feedback Data		
Provide Historical Data Storage	Historical Database Function	The Provide Fusion Database activity is allocated to its own function because it is expected to have a unique set of hardware requirements based on its storage capability. It is separated from the Support Database Function because it contains different data and will require an external interface.

2. Functional Requirements

The ASW data fusion functions identified in the ASW data fusion OV-5a are further derived into the functional requirements. The high-level functional requirements are listed below with the full list in Appendix C.

a. 1.0 Process Sensor Data Function

The purpose of the Process Data function is to receive signal data from passive acoustic sensors, extract feature data from the received signals, and provide the feature data to the data fusion process.

b. 2.0 Create Cluster Function

The purpose of the Create Cluster function is to receive feature data, aggregate feature data into detected clusters and provide detected cluster data to the Create Contact Function.

c. 3.0 Create Contact Function

The purpose of the Create Contact function is to receive cluster objects, aggregate those clusters into a single, fused contact solution, and provide that contact to the Identify Threat Function, Refine Process Function, and Distribution Function.

d. 4.0 Identify Threat Function

The purpose of the Identify Threat function is to receive fused contact data, classify the contacts using retrieved ACINT data, assess the potential threat of the contacts, and provide the relevant situational awareness data (classification, threat, and threat likelihood) to the distribution function.

e. 5.0 Refine Process Function

The purpose of the Refine Process function is to continuously assess the results of the fusion processes and provide feedback to those processes in order to improve their performance. Additionally, the Refine Process function will identify areas of poor performance and provide suggestions for sensor placement/tasking to C2 via the Distribution function.

6.0 Data Fusion Storage Function

The purpose of the Data Fusion Storage function is to store feature and cluster data, not associated with an aggregation, for future use (solution refinement) by the relevant functions.

7.0 Distribute Fused Data Function

The purpose of the Distribute Fused Data function is to distribute the Data Fusion results to all interested C2 stations.

Table 6 shows the mapping of the capabilities to the functional requirements.

Table 6. Capabilities Matrix

		Capabilities	Receive Sensor Data	Fuse Sensor Data	Distribute Fused Data
	Functional Requirements		CA.1	CA.2	CA.3
1	Receive Sensor Data Function		X		
1.1	Receive Sensor Location Data		X		
1.2	Receive Digital Wide-band Signals		X		
1.3	Receive Digital Narrow-band Signals		X		
1.4	Extract Feature Data		X		
1.5	Provide Feature Data		X		
2	Create Cluster Function			X	
2.1	Aggregate Feature Data			X	
2.2	Detect a Cluster			X	
2.4	Determine the Doppler Shift of the Detected Cluster			X	
2.4	Determine the Frequency of the Detected Cluster			X	
2.5	Determine the Bearing of the Detected Cluster			X	
2.6	Determine the Bearing Rate of the Detected Cluster			X	

		Capabilities	Receive Sensor Data	Fuse Sensor Data	Distribute Fused Data
	Functional Requirements		CA.1	CA.2	CA.3
2.7	Calculate Sensor Confidence			X	
3	Create Contact Function			X	
3.1	Aggregate Clusters			X	
3.2	Create a Contact			X	
3.3	Calculate Contact Position			X	
3.4	Calculate Contact Velocity Vector			X	
3.5	Calculate Area of Uncertainty for a Contact			X	
3.6	Determine Gross Classification of a Contact			X	
4	Identify Threat Function			X	
4.1	Receive ACINT Data			X	
4.2	Classify Contact			X	
4.3	Predict Contact Effects			X	
4.4	Calculate Likelihood of Threat			X	
5	Refine Process Function			X	
5.1	Predict Sensor Field Performance			X	
5.2	Provide New Sensor Placement Suggestions			X	
5.3	Provide Mobile Sensor Tasking Suggestions			X	
5.4	Provide Sensor Cueing			X	
5.5	Provide Sensor Performance Feedback			X	
5.6	Provide Collected ACINT Data to ACINT Database			X	
6	Data Fusion Storage Function			X	
6.1	Store Orphaned Feature Data			X	
6.2	Store Orphaned Cluster Data			X	
6.3	Prioritized Stored Data			X	
7	Distribute Fused Data Function				X
7.1	Distribute Fused Contact Message				X
7.2	Distribute Situational Awareness Message				X
7.3	Distribute Sensor Tasking Message				X

		Capabilities	Receive Sensor Data	Fuse Sensor Data	Distribute Fused Data
	Functional Requirements		CA.1	CA.2	CA.3
7.4	Distribute Sensor Performance Feedback Message				X
7.5	Store Historical Data				X
7.6	Distribute Historical Data				X

B. ARCHITECTURE SYNTHESIS

First, the team allocates the established requisite activities for ASW data fusion to system functions. Next, the functional architecture of the system is defined. The functional architecture establishes the processes through which the system functions exchange information. The functional architecture also defines the specific data to be exchanged. This functional architecture along with the non-functional requirements defined in Chapter III drive the physical architecture of the ASW data fusion system.

1. Functional Architecture

The functional architecture of the system establishes the sequential flow of operations within the system and the dependencies between each of the system functions. The team used the Innoslate tool to develop multi-tiered IDEF0 diagrams as the initial step of defining the functional architecture. The IDEF0 diagrams allowed the team to define the inputs, outputs, and controls for each of the ASW data fusion operational activities. The development of the IDEF0 diagrams contributed to the development of multi-tiered functional flow block (FFBD) diagrams, also developed using Innoslate, and further refine the functional architecture by depicting the time-ordered sequence of the operational

activities. Figure 25 depicts the top-level IDEF0 for the ASW data fusion system. Figure 26 depicts the top-level FFBD for the ASW data fusion system.

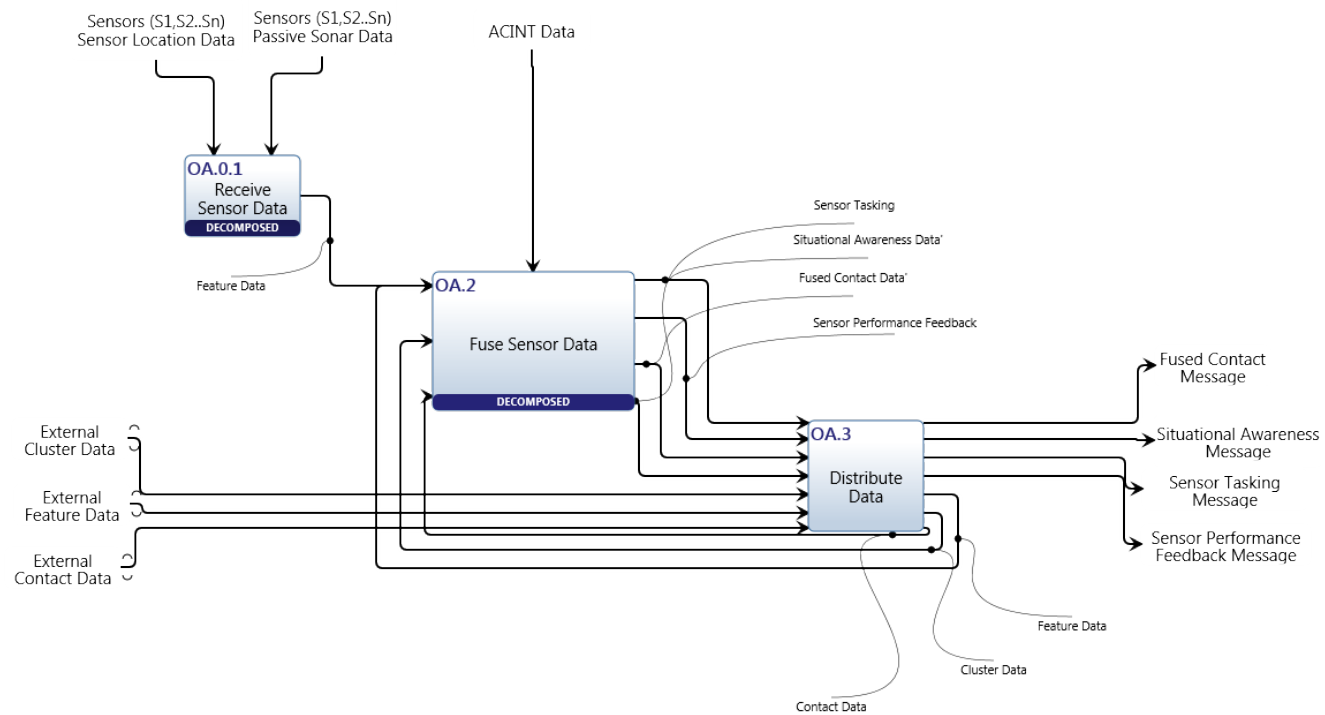


Figure 25. Top-level IDEF0

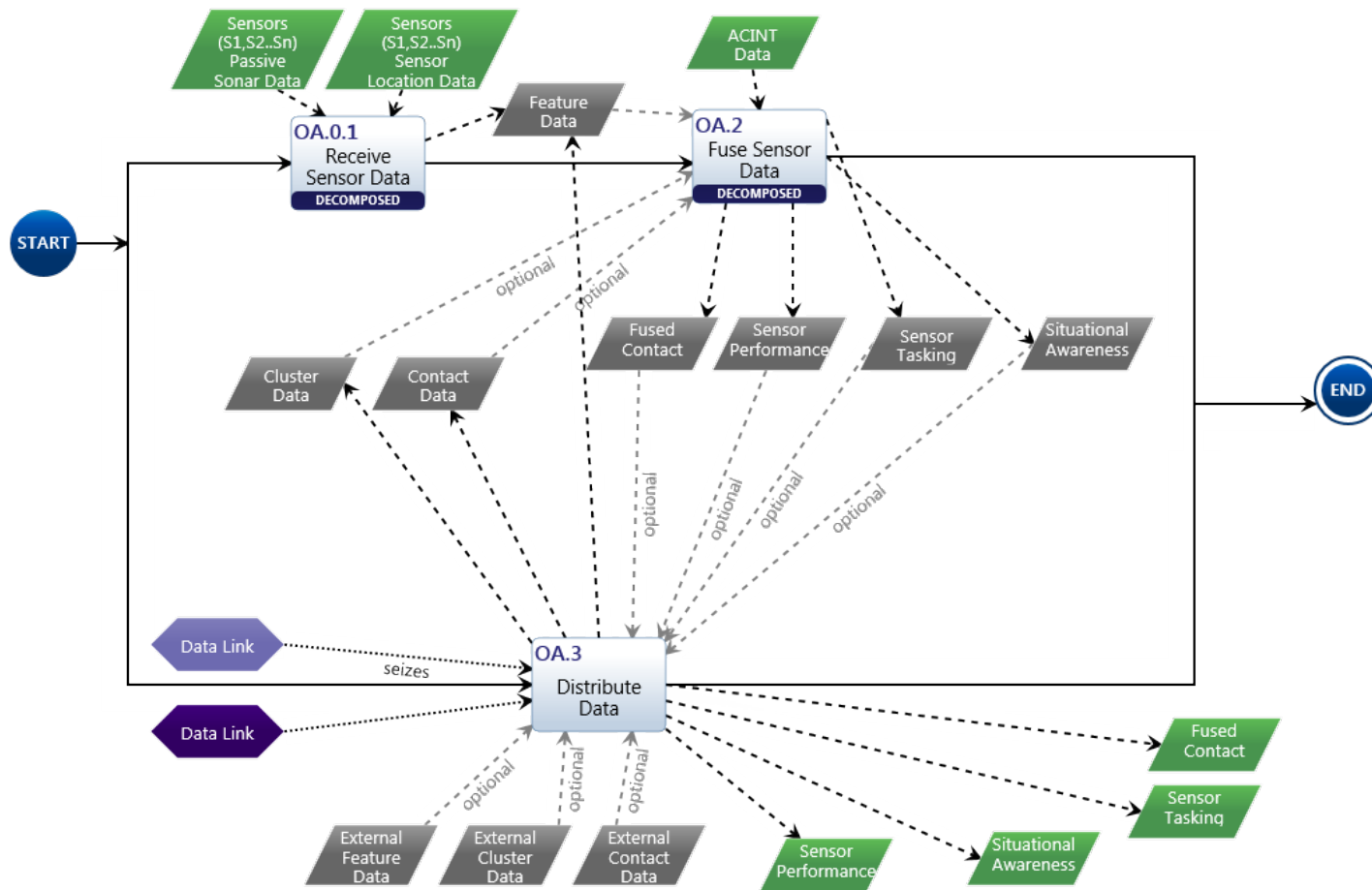


Figure 26. Top-Level FFBD

Figure 26 depicts the three top-level functionality groupings of the ASW data fusion system: Receive Sensor Data, Fuse Sensor Data, and Distribute Fused Data. The Receive Sensor Data function serves as the system's interface to the acoustic sensor network, receiving all passive acoustic data along with the locations of the providing sensors. The Receive Sensor Data Function detects signals within the passive acoustic data and sends those signals along with the sensor provider positions to the Fuse Sensor Data function group as "Feature Data." Figure 27 depicts the IDEF0 for the decomposed Receive Sensor Data function with Figure 28 depicting the associated FFBD. The Fuse Data Function aggregates the received feature data and, through its fusion processes, develops Fused Contacts, Sensor Performance Feedback Data, Sensor Tasking Suggestions, and Situational Awareness Data. The Distribute Data Function receives outputs from the Fuse Data Function and disseminates them to external systems. The Distribute Data Function operates in parallel with the Receive Data and Fuse Data functions because it also receives externally generated Feature, Cluster, and Contact Data information for inclusion in the fusion processes.

The Fuse Sensor Data function group is where the majority of the work of the ASW data fusion system takes place. Figure 29 depicts the IFED0 for the decomposed Fuse Sensor Data function, which establishes the required input, output, and controls for each of the Fuse Sensor Data activities. Figure 30 depicts the associated FFBD for the decomposed Fuse Sensor Data function, which further refines the functional architecture by depicting the time-ordered sequence of the Fuse Sensor Data function activities. Appendix D contains IDEF0 diagrams further decomposing the Fuse Sensor Data function group.

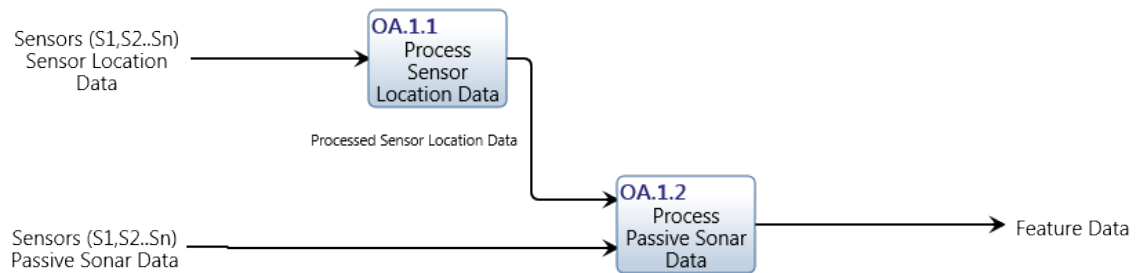


Figure 27. Receive Sensor Data Function IDEF0

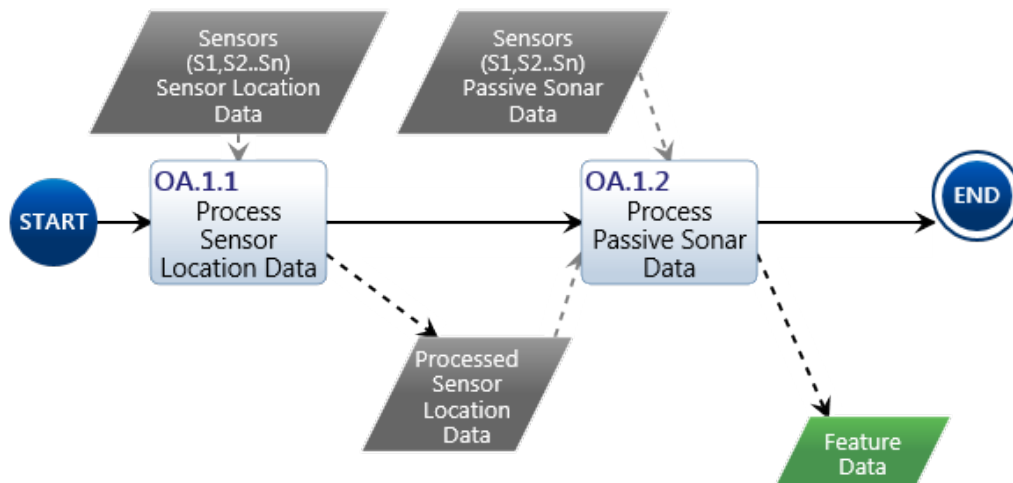


Figure 28. FFBD of the Decomposed Receive Sensor Data Functionality Group

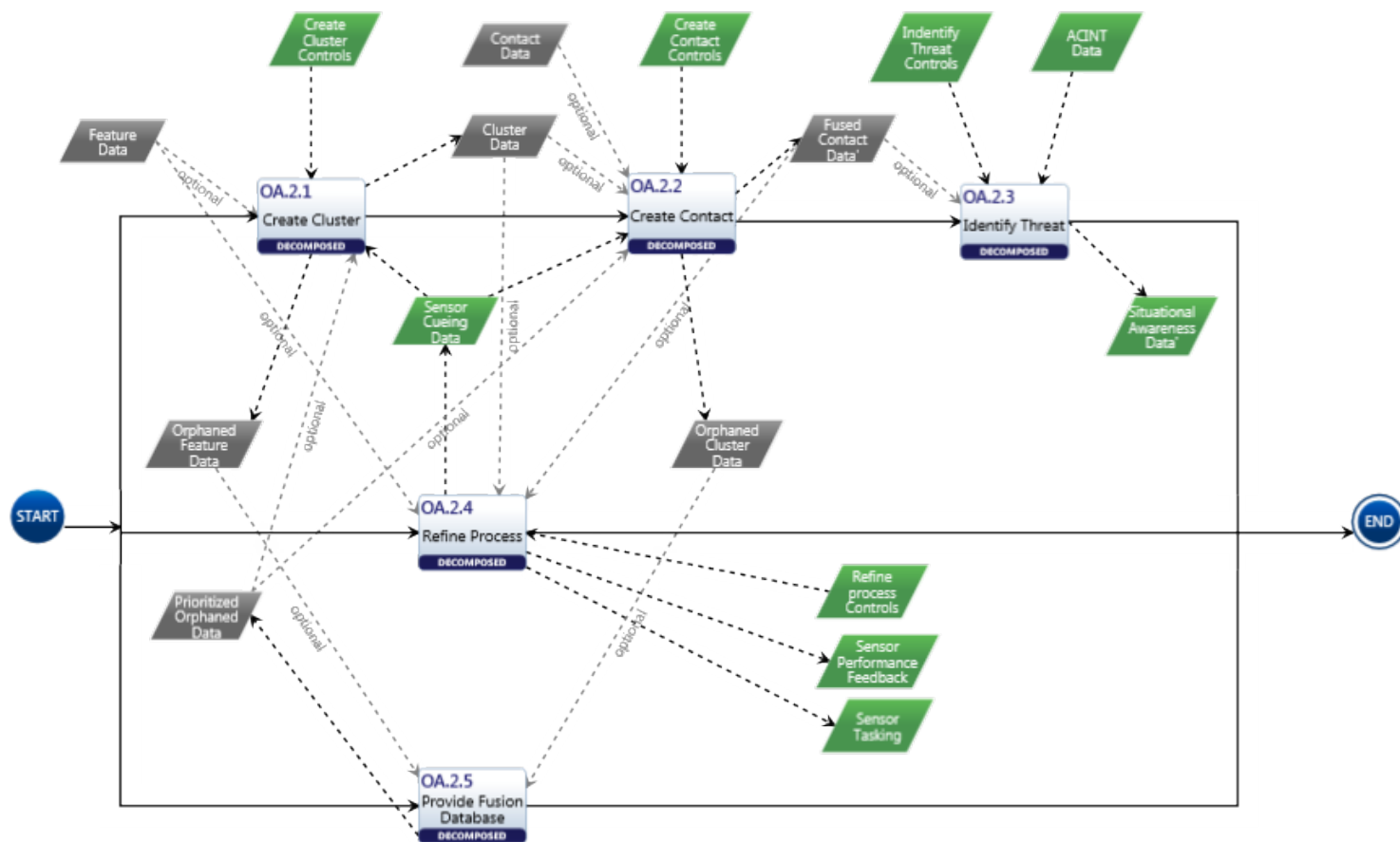


Figure 30. FFBD of the Decomposed Fuse Sensor Data Functionality Group

Figure 30 depicts the existence of three parallel streams of functionality within the Fuse Sensor Data function group. Within the top stream of functionality, the Create Cluster, Create Contact and Identify Threat functions operate in series, with the Create Contact function dependent on the Create Cluster function and the Identify Threat function dependent on the Create Contact function. The Create Cluster function receives Feature Data generated from the Receive Sensor Data function and external systems. The Create Cluster function determines the relationships between the elements of Feature Data, aggregates related Feature Data elements into Cluster Data, and sends Cluster Data to the Create Contact function. Cluster Data contains a detected entity's signal frequency, its bearing from a known location, and a high-level entity classification. The Create Contact function receives Cluster Data, aggregates it based on frequency and time, and creates Contact Data. Contact Data contains the tracked entity's location, along with a calculated AOU, and course and speed information. Figure 31 depicts the aggregation of Cluster Data into Contact Data with an AOU.

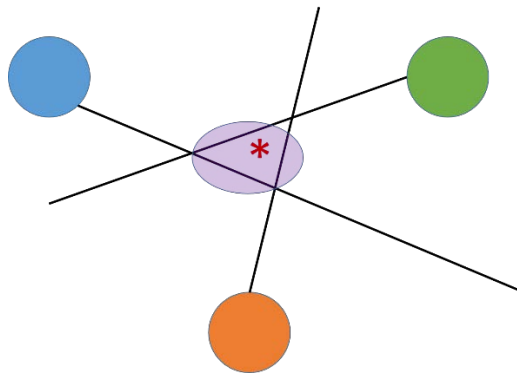


Figure 31. Aggregation of Cluster Data into Contact Data with AOU

While the Create Cluster and Create Contact functions operate sequentially, the Refine Process function operates in parallel with them. It receives the Feature Data, Cluster Data, and Contact Data, calculates the level of performance from each providing sensor and uses those performances to provide Sensor Cueing to the Create Cluster and Create Contact functions. Sensor Cueing Data is used by those functions to prioritize data from specified sensors based on the calculated performance of those sensors. The calculated

Sensor Performance Data is also sent to the Distribute Fused Data function group (see Figure 1) for distribution to external C2 systems. The Create Cluster, Create Contact, and Refine Process functions create a continual feedback loop, which uses calculated sensor performance to refine the quality of the Fused Contact Data. The Refine Process function also identifies large AOU's that exist because of too few sensors, poor sensor geometry, or poor sensor performance, and sends Sensor Tasking Suggestions to the Distribute Fused Data function group for distribution to C2 systems, which in turn can deploy mobile or semi-mobile sensors to improve system performance.

The Identify Threat function operates in series with the Create Cluster and Create Contact functions. It interfaces with an external ACINT database to identify the contacts being tracked by the system. The Identify Threat function sends these contact identities, along with their threat potentials, as Situational Awareness Data to the Distribute Fused Data function for distribution to external C2 systems. The Provide Database function operates in parallel with the other functions providing storage and retrieval for unfused "orphaned" feature data and cluster data.

2. Input / Output Data

Thus far, this capstone report has described the various forms of input/output data that the ASW data fusion system functions consume and provide in a general sense. This section outlines the requisite information contained within each form of data in order to fully define the terms used.

Feature Data objects contain attributes of the acoustic data detected by the reporting passive sensors including frequency and bearing. The time of detection, along with the ID and location of the detecting sensor are also contained within the Feature Data objects. Cluster Data objects contain frequency, bearing, bearing rate, and Doppler shift of the detected entity, as well as the associated time, an identifier for the Cluster Data object and a reference to the aggregated Feature Data objects that were used in the creation of the Cluster Data object. Contact Data objects contain the positional information of a detected entity (latitude, longitude, depth), the time and area of uncertainty (AOU) associated with the reported position, as well as the directional velocity and gross classification of the

entity. Each Contact Data object also contains an identifier for the entity and a list of the Cluster Data identifiers that were used in its composition. Sensor Cueing Data objects contain information that can be used to prioritize data from specified sensors based on the estimated bearings of entities that are currently being tracked. Each Sensor Cueing Data object contains optimized bearing information, contact identification, and time. Sensor Performance Feedback objects contain information that can be used to prioritize data from specified sensors based on the calculated performance of those sensors. Each Sensor Performance Feedback object contains the identification of the relevant sensor and its calculated detection range. Sensor Tasking Suggestion objects contain suggestions for the placement of additional sensors when large AOU's are reported by the system. Each Sensor Tasking Suggestion object contains the sensor type, location, and settings for an additional, suggested sensor. Situational Awareness Data objects contain the identification, time, friend or foe determination, and limiting lines of approach of a tracked entity. Table 7 summarizes the data contained in each term.

Table 7. ASW Data Fusion System Terminology

Term	Data Contained
Feature Data	Frequency
	Bearing
	Time
	Sensor ID
	Sensor Location
Cluster Data	Frequency
	Bearing
	Bearing Rate
	Doppler Shift
	Time
	Cluster ID
	Feature Data[]
Contact Data	Latitude
	Longitude
	Depth
	Time
	AOU
	Velocity
	Gross Classification
	Contact ID
	Cluster Data[]
Sensor Cueing Data	Optimized Bearing Information
	Contact ID
	Time
Sensor Performance Feedback Data	Sensor ID
	Observed Sensor Range
Sensor Tasking Suggestions	Sensor Type
	Sensor Location
	Sensor Settings
Situational Awareness Data	Contact ID
	Time
	Identity Friend or Foe
	Limiting Lines of Approach

3. Physical Architecture

Physical system architectures fall into one of three categories: centralized, decentralized, and distributed. The team considered each of these alternatives for the ASW data fusion system. The team considered each alternative regarding its benefits and

drawbacks under the conditions provided for the operational scenarios outlined in Chapter III, as well as the constraints presented by the ASW platforms regarding processing power, storage capability and satellite network availability.

a. Centralized Architecture

In centralized system architectures, a single location stores all functions of a system. Required input data is transmitted to that system, transformed into output data and distributed to all interested parties. Figure 32 is a representation of the ASW data fusion under a centralized physical architecture.

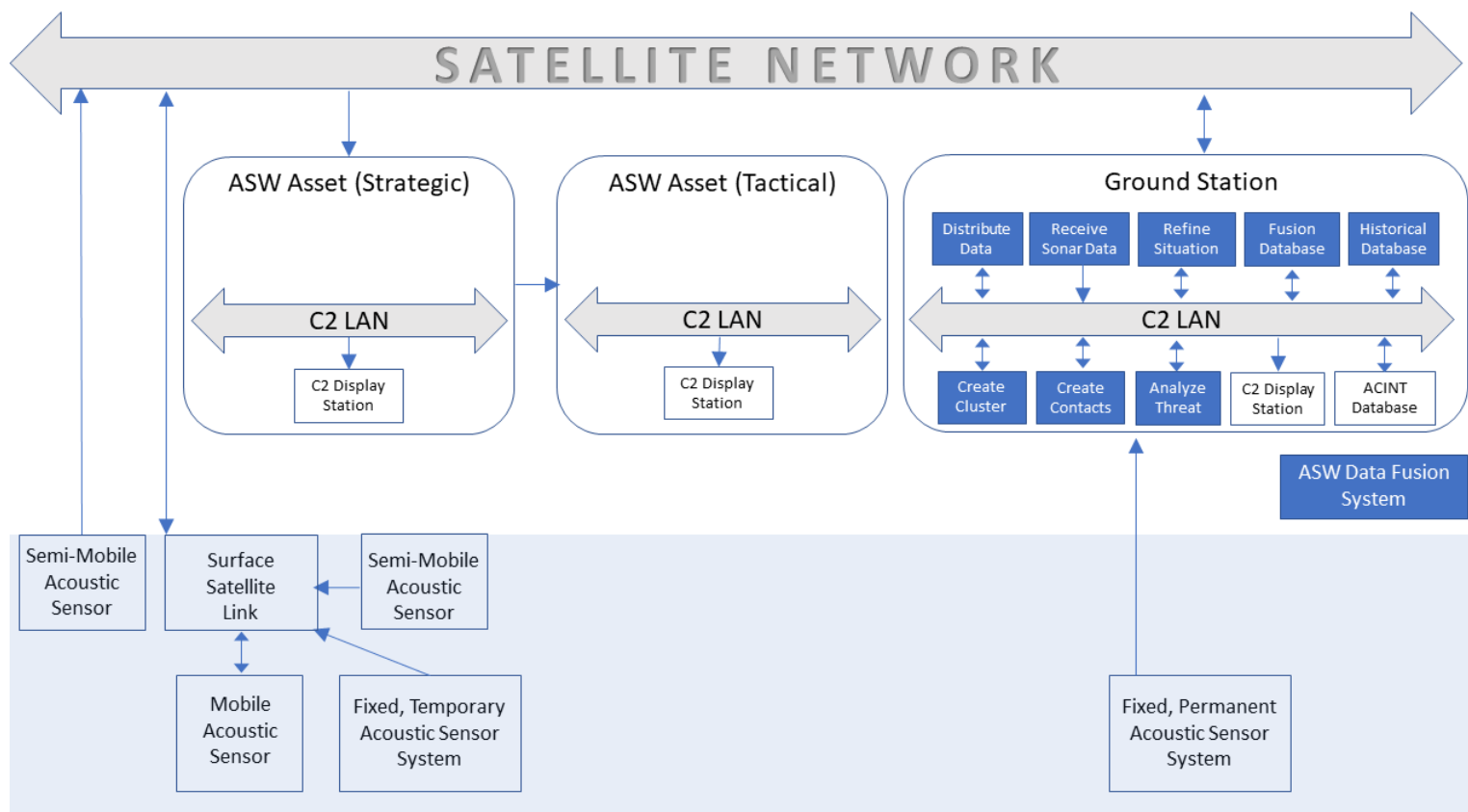


Figure 32. Centralized Architecture

One benefit of a centralized system is it is far less complex than decentralized and distributed systems because of the minimization of interfaces to external systems regarding the data types flowing between the systems. Minimization of complexity of the transport layer is also evident since input data requires transportation to a single, known receiver and output data is generated from a single, known source. Additionally, centralized architectures are highly maintainable since they exist in a single location and thus have a single maintenance locality. Despite these advantages, there are significant drawbacks to centralized system architectures. Centralized systems are slower than decentralized and distributed systems since they incur the time delay associated with distributing the output data to remote entities, which are simply clients of the system. Low throughput also results in additional time delays; a “bottleneck” exists in the transport layer since all data must flow to a single location. This bottleneck results in delayed data receipt, and reduced scalability since input data must be limited to mitigate throughput issues.

b. Decentralized Architectures

In decentralized system architectures, all functions of a system exist at every C2 location (e.g., ground stations, surface platforms, and air platforms). Required input data is transmitted to each C2 platform, processed into Fused Contact Data, and is immediately available for use by C2. Figure 33 is a representation of the physical architecture of the ASW data fusion system deployed under a decentralized physical architecture.

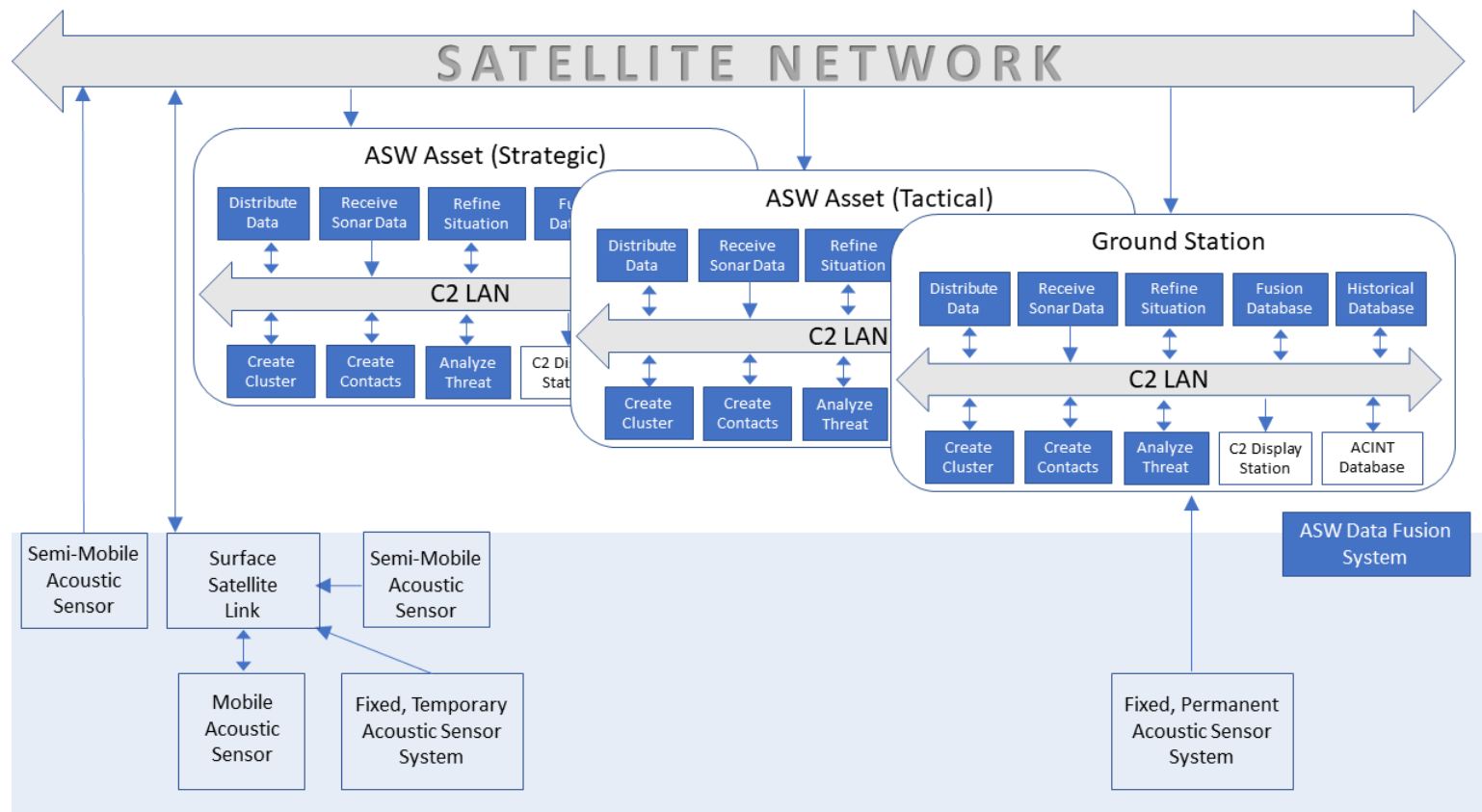


Figure 33. Decentralized Architecture

One clear benefit of decentralized system architectures is the elimination of the latency involved in the distribution of output data since each platform processes its data. Additionally, decentralized systems are highly portable, since they must be designed to operate on a wide variety of platforms. Despite the benefits, decentralized architectures have quite a few drawbacks. One such drawback is decreased maintainability since the system exists in many places and within many external systems, each of which has its maintenance schedule. Additionally, decentralized systems impose significant (and in some cases, unattainable) processing and storage requirements upon the deployed platforms since each platform is responsible for the entirety of the system and its processes.

c. Distributed Architecture

In distributed systems architectures, the system functions are not required to be co-located and can exist in whichever location best suits the operational scenario and processing constraints of the assets. Function(s) receive required input data, and those functions, in turn, transmit their output data to other system functions (local or remote) that require it. Figure 34 is a representation of the physical architecture of the ASW data fusion system under distributed system architecture.

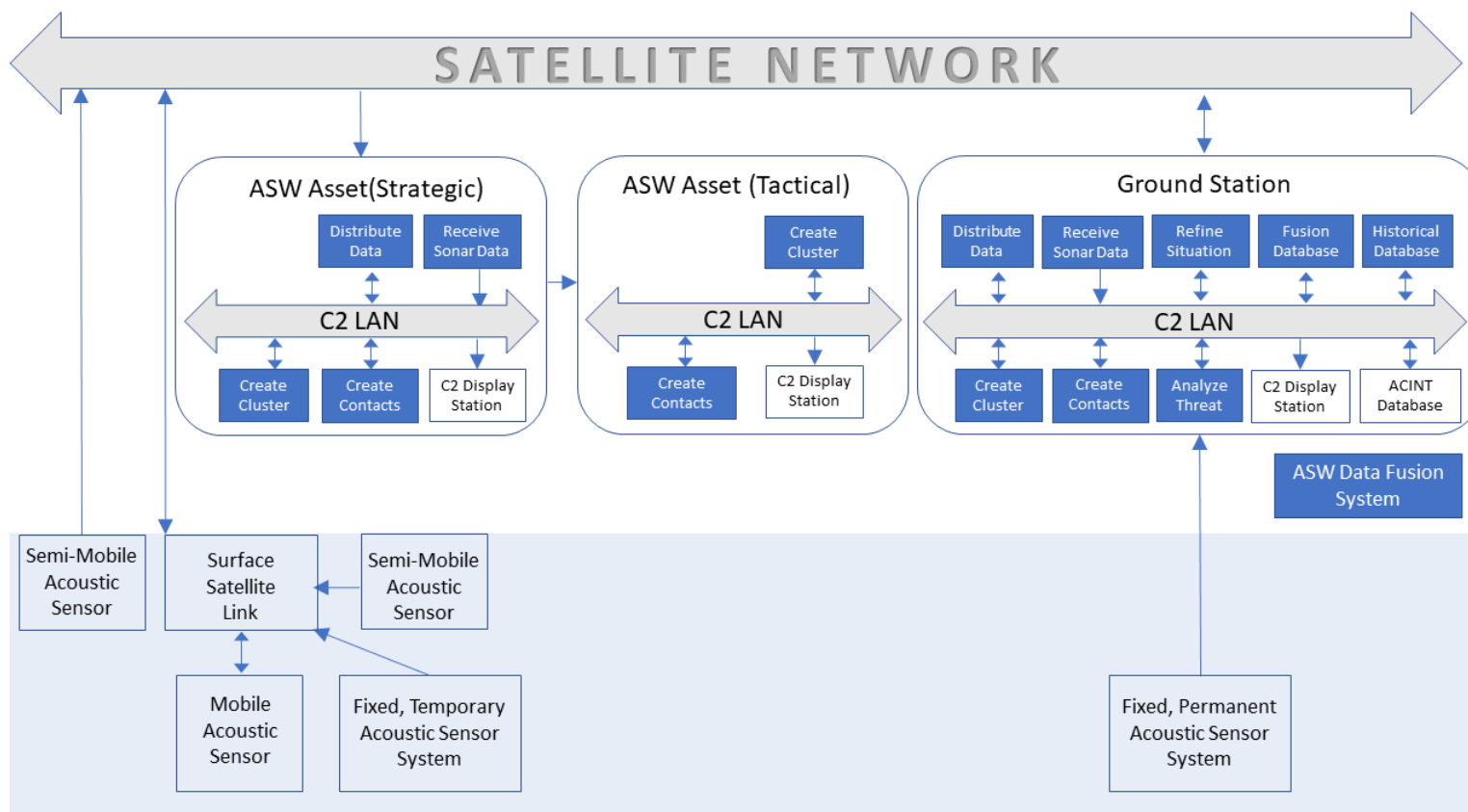


Figure 34. Distributed Architecture

The advantages of distributed system architectures are numerous. The primary advantage of such architecture is its flexibility; the limited processing power and storage capability of some platforms no longer presents a problem since those platforms become clients of the system. Further, platforms with the requisite processing power and storage capability can maximize their strategic advantage by hosting some (or all) of the system functions and receive output data faster than they would have under the centralized configuration. This flexibility enables the system to support a multitude of operational scenarios, thus maximizing its adaptability.

d. Analysis of Alternatives

When selecting a physical architecture for the ASW data fusion system, feasibility is first considered. Due to the processing and storage requirements of the ASW data fusion system, the decentralized architecture is not feasible since many ASW assets have neither the processing power nor the storage capability to host the system. Both the centralized and distributed system architectures options remain feasible and require analyzation regarding their benefits and drawbacks. The team uses the MOEs defined in Chapter III to evaluate the centralized and distributed physical architecture alternatives. These MOEs consist of timeliness, maintainability, adaptability, and scalability. A description of the significance of each of these MOEs regarding the physical architecture of the system follows.

Timeliness: Centralized architecture platforms requiring fused data for situational awareness must wait for the acoustic data to be transmitted to the central location, processed into fused contact data, and distributed back out. The “back and forth” routing of data delays the receipt of the fused data. Additionally, the centralized architecture suffers from throughput issues, which will further delay the receipt of the fused contact data. These time delays result in decreased confidence the fused data accurately represents the current situation. The distributed physical architecture can mitigate some of these time delays since functions of the ASW data fusion system can reside onboard the ASW assets with required processing power and storage capability (e.g., the strategic assets). In Figure 28, the strategic asset hosts the Receive Data, Create Cluster, and Create Contact functions, so fused data is available for use by C2 upon creation. The Identify Threat and Refine

Situation functions, residing at the ground station, assess and refine the fused data. The data is then distributed to the strategic assets for increased situational awareness. The fact they can host some of the ASW data fusion system functions gives them a distinct strategic advantage in terms of timeliness.

Maintainability: Because the centralized system resides in a single location, it is much easier to maintain than the distributed system, which can reside on many platforms, each of which has a separate maintenance schedule. The centralized system also increases its maintainability due to its significantly lower complexity stemming from the minimization of external interfaces.

Adaptability: Adaptation to ASW assets based on their processing power and storage capability is a fundamental advantage of the distributed architecture's configurable design. Distributed architecture design allows for certain functions to reside on board whichever asset has the requisite capabilities. In fact, one configuration of the distributed system is a centralized configuration, with all ASW data fusion functions hosted by the C2 ground station, and all ASW assets as clients of the system. Though this configuration seems disadvantageous, it is nonetheless an option of the highly configurable architecture. The centralized system does not have the configurability afforded by the distributed system and thus is not as adaptable.

Scalability: The ASW data fusion system must be able to support the addition of sensors. Because of its throughput issues, degradation of the centralized system increases as the quantity of sensors increases. The number of sensors able to be handled by the centralized system, before degradation, is a function of the specific satellite connection used and the implementation of the software interface; neither of which are addressed in this report. In contrast, the distributed system is highly scalable. The support for additional sensors is constrained only by the number of platforms available for hosting the Receive Data function since the distributed design disseminates processing responsibility across platforms.

e. Analysis Results

Table 8 lists the evaluations of the decentralized, centralized, and distributed physical architectures in terms of their feasibility, timeliness, maintainability, adaptability, and scalability.

Table 8. Physical Architecture Analysis Results

	Feasible	Timeliness	Maintainability	Adaptability	Scalability
Centralized	Yes	Low	High	Low	High
Decentralized	No	High	Low	Low	Low
Distributed	Yes	High	Medium	High	High

The distributed physical architecture is superior to the centralized architecture in all but one category: maintainability. Though the centralized architecture is far more maintainable than the distributed architecture, the advantages afforded by the distributed system regarding timeliness, adaptability, and scalability far outweigh its reduced maintainability. Therefore, the team selected the distributed system architecture for the ASW data fusion system.

4. Interface Definition

The functional and process architectures define the types of data flowing to and from each of the ASW data fusion functions. Having also defined the physical architecture of the ASW data fusion system, it is now possible to specify the internal and external system interfaces. Specifically, how will the data be exchanged between the ASW data fusion system functions and what information must the data exchanged contain? Herein, the internal and external system interfaces of the ASW data fusion system are specified.

a. External System Interfaces

The ASW data fusion system must be able to accept data from fixed, mobile, and semi-mobile acoustic sensors. Bottom-mounted hydrophones, sonobuoys, wave gliders, UUVs, and ship-mounted sensors are all providers of valuable acoustic data but are considered out of the scope of the ASW data fusion system (Figure 4) since modifications

to them are considered infeasible. However, each of these sensor system types is designed with the ability to provide its data to a satellite network:

- **Fixed, bottom-mounted hydrophones:** Fixed, bottom-mounted hydrophones provide acoustic data to a satellite network via a surface satellite link(s) or cables. Cabled connections can provide data to a satellite network via C2's satellite uplink.
- **Sonobuoys:** RF sonobuoys provide acoustic data to a satellite network via satellite uplink nodes. Satellite-enabled sonobuoys provide acoustic data to a satellite network via their built-in satellite links.
- **Wave gliders:** Wave gliders provide acoustic data to a satellite network via built-in satellite links.
- **UUVs:** UUVs provide acoustic data to their own, embedded processes which process and transmit it to surface satellite link(s).

Thus, the ASW data fusion system must be able to interface with external sensor systems indirectly via a satellite network. The data provided by these systems may be raw or processed to varying degrees (i.e., feature data, cluster data, contact data). The external interface requirements identified through this analysis of external sensor systems are as follows:

- The Receive Data function shall receive raw acoustic data from a satellite network.
- The Create Cluster function shall receive feature data from a satellite network.
- The Create Contact function shall receive cluster data from a satellite network.
- The Create Contact function shall receive contact data from a satellite network.

- The Create Contact function shall send contact data to a satellite network.
- The Identify Threat function shall receive ACINT Data from an external ACINT Database.
- The Identify Threat function shall send Situational Awareness Data to a Satellite Network.
- The Refine Process function shall send Sensor Performance Feedback Data to a Satellite Network.
- The Refine Process function shall send Sensor Tasking Suggestions to a Satellite Network.

It is expected the legacy external-sensor systems will provide data to the satellite network in differing formats. While it would be possible for the ASW data fusion system to support these different formats natively, it would impose a significant amount of complexity to the system and dramatically hinder system maintainability. Rather than including native support of legacy data formats, it would be preferable to provide external components to translate legacy data into the ASW data fusion system's specified data format.

b. Distributed System Interfaces

The distributed architecture of the ASW data fusion system imposes a unique set of requirements upon the ASW data fusion external interfaces. The team selected a distributed architecture to provide maximum adaptability for the system, and thus it cannot be pre-determined where each of the ASW data fusion system functions will exist. Further, it is possible more than one of each function can exist at any time. The implication is the ASW data fusion functions must be autonomous and unaware of the input data providers and the output data receivers. The team identified the interface requirements for the ASW data fusion functions through this analysis of the ASW data fusion distributed architecture:

- Each ASW data fusion system function shall operate autonomously from other functions.

- Each ASW data fusion system function shall be unaware of its data input providers.
- Each ASW data fusion system function shall be unaware of its data output receivers.

There are a variety of ways to accomplish this strict decoupling. One such method would be the use of multicast groups. Each data type has a pre-defined multicast group; senders of each data type send their output data to the appropriate multicast group address, and receivers connect to the same multicast group address to receive the data. In this example, the network routers are the mechanisms providing the necessary decoupling. Another method to accomplish this decoupling is the use of a publish-and-subscribe model. Using pre-defined data “topics,” senders publish their data to the appropriate topic and receivers subscribe to that topic to receive the data of interest. Alternatively, in data-centric publish/subscribe systems, functions publish their data, and receivers subscribe to data of a specific type. In both of these cases, the decoupling of the functions is provided by the specific publish/subscribe software chosen. The team provides these examples as a means of showing concrete, real-world examples of how modern distributed software systems accomplish decoupling.

c. Internal System Interfaces

In addition to interfacing with external systems, the ASW data fusion system functions must be able to interface with each other. As stated previously, the ASW data fusion system functions must operate autonomously and unaware of each other, due to the selected distributed architecture. The accomplishment of this operation varies in multiple ways and, in each of them, a network (satellite or local, depending on their distributed configuration) provides the necessary decoupling mechanism. The internal interface requirements of the ASW data fusion system are listed in Appendix C.

C. PERFORMANCE CHARACTERIZATION

Performance characterization of the ASW data fusion architecture is critical for stakeholder buy-in for future system development. Modeling and simulation is a critical

part of the performance characterization and the final step of the systems engineering process.

1. Markov Chain

The nature of the top-down systems engineering process utilized by the team lends itself to the modeling of the system as a Markov Chain. A Markov Chain is a stochastic process where the probability of the subsequent events relies on the state achieved in the previous event. The basis of the architecture, the kill chain, can be modeled directly as a Markov chain with each step of the kill chain providing the next state in the process. The product of the first phases of the systems engineering process is the development of success trees for the top- and second-level functions of the systems architecture. These success trees provide the probability for each of the state changes in the Markov chain.

2. Modeling Paradigm

During the systems engineering process, the probability of success for each of the steps in the process lacks an assigned threshold. Characterizing a system without threshold values can be qualified as difficult at best. However, the ASW data fusion system proposed by the team is not without a predecessor system: the human operator-based data fusion system. By comparing the performance of the human system to the ASW data fusion system directly, many variables (some of which are unknown or unknowable) are canceled out, leaving only the performance altering variables remaining. Therefore, it is possible to prove the utility of the system and give a comparative performance augmentation over that of the current human operator-based system.

Applying the modeling paradigm of comparative analysis and the Markov process, the modeling effort first characterizes the current, human system. Figure 35 depicts the Markov chain for the human system.

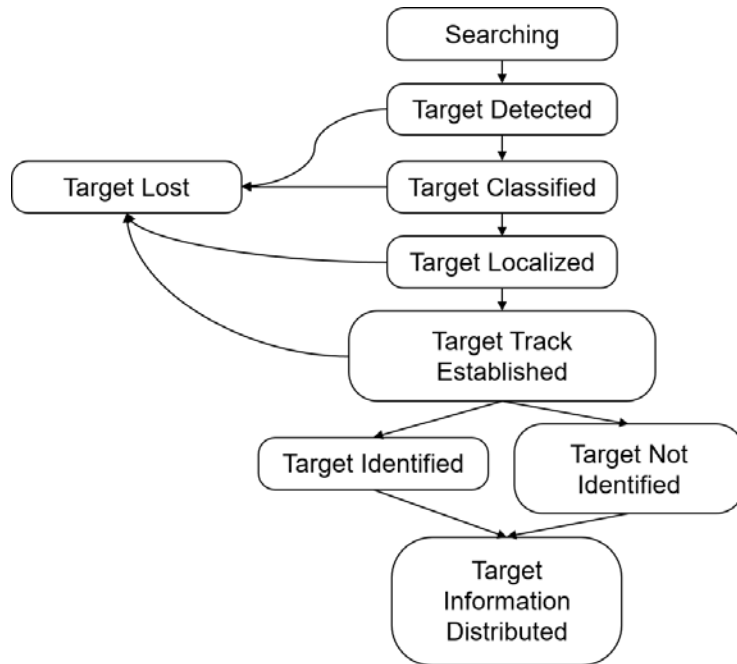


Figure 35. Human-System Markov Chain

This chain serves as the basis for the ASW data fusion architecture. The primary difference between the human operator and the ASW data fusion system occurs during Target Detection. The human operator receives information from multiple sources simultaneously, determines the presence of usable data, and forwards that data to the next step in the chain. All information rejected by the operator, whether correctly rejected or not, is lost. This is significant. By comparison, rather than discarding unused data, the ASW data fusion architecture system retains it and reprocesses it, providing multiple opportunities to refine the fused data solutions with the incorporation of data that had previously been unused. Figure 36 depicts the Markov chain for the ASW data fusion system with the states remaining the same as the human model marked in teal.

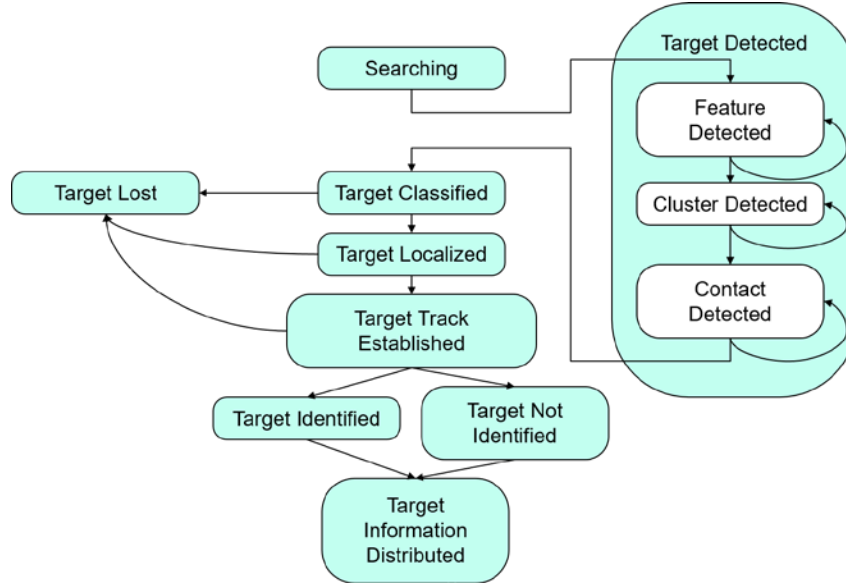


Figure 36. ASW Data Fusion Markov Chain

These Markov chains then served as the basis for the creation of a simulation model in ExtendSim located in Appendix E. The simulation model remains the same between the human system and the ASW data fusion system with the only differences being the probability and resource numbers fed into the simulation.

To simplify the simulation, the number of sensors providing acoustic data was limited to three. During typical operations, three sensors provide a reasonably accurate contact location without overtaxing a human operator. The actual system, for both the human and the ASW data fusion system, could theoretically be scaled to an infinite number of sensors, limited only by the constraints imposed by legacy systems. However, as the quantity of sensors increases human performance decreases exponentially. By limiting the number of sensors to three, the model can represent the highest success rate for the human system.

3. Simulation Analysis

The team utilized a two-fold approach to fully characterize the performance of the ASW data fusion system over that of the human system.

Time is a significant factor in the successful prosecution of submerged targets. The first run compares the performance of the human system to the ASW data fusion systems without the augmentation of the probability of detection gained from enhanced processing. This preliminary run characterizes the performance of the ASW data fusion system solely concerning time.

The second run of the simulation utilizes the enhancements to signal processing brought by the ASW data fusion system. This final run characterizes the expected performance increase of ASW prosecutions with the implementation of the ASW data fusion system.

a. Human-System

The human system serves as the baseline of comparison for the ASW data fusion system. For this run of the simulation, it is assumed a single operator is processing the data from the three sensors with the operator requiring some time (a normal distribution centered at two minutes) detect a target. Additionally, the probability of detection, which is a function of the operator's skill level and sensor performance, is set at 0.50. Table 9 presents the average results from 100 runs of the model.

Table 9. ASW Data Fusion Human Simulation Results

	Lost Time	Lost Detect	Lost Classify	Lost Track	Success with ID	Success without ID	Total Data Packets
Average	928.92	44.81	2.3	4.62	3.48	22.41	1006.54

The probability of moving to the next phase of the chain is equal to the number of packets moving to the next phase divided by the number of packets entering the phase. Lost Detect, Lost Classify, and Lost Track are the number of data packets moving from their respective phases to Target Lost. Lost Time are the number of packets not detected

due to the data being too old and are summed with the packets moving from detect to target lost. Table 10 shows the number of packets entering and leaving each phase.

Table 10. ASW Data Fusion Human Simulation Packet Totals Each Phase

	Target Detected	Target Classified	Target Localized	Target Track Establish	Target Identified	Target Not Identified
Packets Entering	1006.54	32.81	30.51	25.89	25.89	25.89
Packets Leaving to Next Phase	32.81	30.51	25.89	25.89	3.48	22.41
Packets Leaving to Target Lost	973.73	2.3	4.62	0	0	0

Figure 37 shows the probabilities through the Markov chain. Table 11 presents the Markov matrix of the human system results.

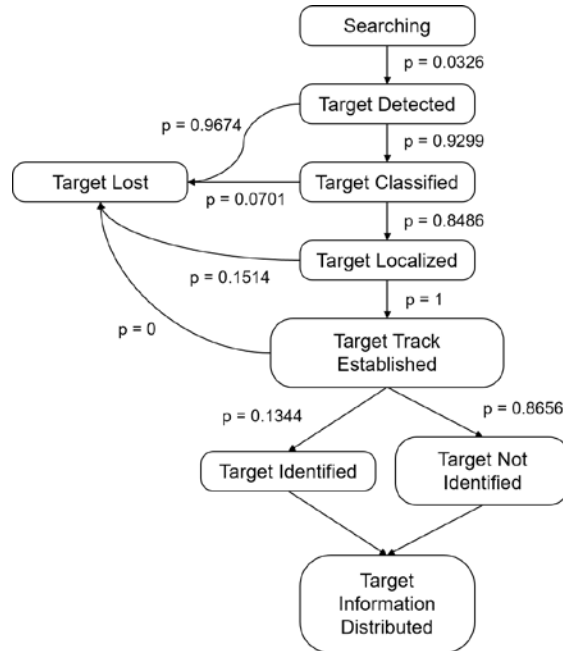


Figure 37. Markov Chain with Probabilities for the Human Simulation

Table 11. Markov Matrix of the ASW Data Fusion Human Simulation

	Search	Detect	Classify	Localize	ID	NoID	Lost
Search	0	0.0326	0	0	0	0	0.9674
Detect	0	0	0.9299	0	0	0	0.0701
Classify	0	0	0	0.8486	0	0	0.1514
Localize	0	0	0	0	0.1344	0.8656	0
ID	0	0	0	0	1	0	0
No ID	0	0	0	0	0	1	0
Lost	0	0	0	0	0	0	1

The probability getting to particular stage in the kill chain is the product of the probabilities of reaching the previous stages in the series. For example, equation (5) shows the formula for calculating the probability to localize (i.e., gain a track).

$$P_{Localize} = P_{SearchToDetect} * P_{DetectToClassify} * P_{ClassifyToLocalize} \quad (5)$$

Replacing the variables with the results from the Markov analysis yields the following results.

$$0.0257 = 0.0326 * 0.9299 * 0.8486$$

The probability of the human system to gain a track is 0.0257 or 2.57% with the probability of gaining target identification of 0.0035 or 0.35%.

b. ASW data fusion system

The first run of the ASW data fusion simulation utilizes the same factors as the human system for identification. The simulation is modified to increase the number of resources (from 1 to 9999) and decrease the recognition time (a normal distribution with a mean of 2 minutes and standard deviation of 30 seconds, decreased to a normal distribution with a mean of 6 seconds and standard deviation of 2 seconds) since a computer can process information in parallel unlike the human operator and at a much greater speed. Table 12 presents the average results from 100 runs of the model. Table 13 shows the number of packets entering and leaving each phase.

Table 12. ASW Data Fusion System Simulation Results

	Lost Time	Lost Detect	Lost Classify	Lost Track	Success with ID	Success without ID	Total Data Packets
Average	0	516.65	25.29	45.72	61.47	351.51	1000.64

Table 13. ASW Data Fusion System Simulation Packet Totals Each Phase

	Target Detected	Target Classified	Target Localized	Target Track Establish	Target Identified	Target Not Identified
Packets Entering	1000.64	483.99	458.7	412.98	412.98	412.98
Packets Leaving to Next Phase	483.99	458.7	412.98	412.98	61.47	351.51
Packets Leaving to Target Lost	516.65	25.29	45.72	0	0	0

Figure 38 shows the probabilities through the Markov chain. Table 14 presents the Markov matrix of the ASW data fusion system results.

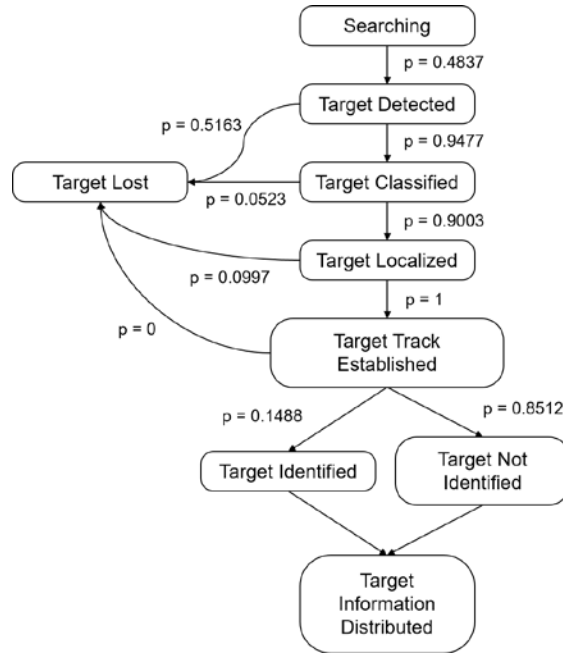


Figure 38. Markov Chain with Probabilities for the ASW Data Fusion System Simulation

Table 14. Markov Matrix of the ASW Data Fusion System Simulation

	Search	Detect	Classify	Localize	ID	NoID	Lost
Search	0	0.4837	0	0	0	0	0.5163
Detect	0	0	0.9477	0	0	0	0.0523
Classify	0	0	0	0.9003	0	0	0.0997
Localize	0	0	0	0	0.1488	0.8512	0
ID	0	0	0	0	1	0	0
No ID	0	0	0	0	0	1	0
Lost	0	0	0	0	0	0	1

The probability of the ASW data fusion system with no processing enhancements to gain a track is 0.4127 or 41.27% with the probability of gaining target identification of 0.0614 or 6.14%. By just automating the process and eliminating the bottleneck of the human operator, the success of an ASW prosecution increases nearly twenty-fold.

The second run of the ASW data fusion simulation models the expected performance increase in the probability of detection from 0.50 to 0.80. The increase in the probability of detection stems from the sequential processing of the architecture and the addition of sensor tasking recommendations. In the earlier models, sound data was either continued along the chain or lost. In the ASW data fusion architecture, once the sound has been received and made into a feature, it will continue in the system until it is able to be aggregated into a cluster. Similarly, clusters will remain until able to be aggregated into contacts. The retaining and recycling of data effectively gives multiple chances to continue sound data along the chain before the data is too old to be relevant. The multiple attempts increase the probability of detection commensurate to increasing the number of sensors in the area. The system tracks sensor performance, provides sensor tasking recommendations, and recommends changes in sensor processing. For example, passive sonobuoys can alter their signal processing from a circular to a cardioid pattern thereby increasing gain along a selected bearing. The gain increases the directivity index of the sensor which increases the probability of detection in accordance with equation (3) presented in Chapter III. Table 15 presents the average results from 100 runs of the model. Table 16 shows the number of packets entering and leaving each phase.

Table 15. ASW Data Fusion System Simulation with Performance Enhancements Results

	Lost Time	Lost Detect	Lost Classify	Lost Track	Success with ID	Success without ID	Total Data Packets
Average	0	205.55	41.77	38.58	141.06	574.05	1001.01

Table 16. ASW Data Fusion System Simulation with Performance Enhancements Packet Totals Each Phase

	Target Detected	Target Classified	Target Localized	Target Track Establish	Target Identified	Target Not Identified
Packets Entering	1001.01	795.46	753.69	715.11	715.11	715.11
Packets Leaving to Next Phase	795.46	753.69	715.11	715.11	141.06	574.05
Packets Leaving to Target Lost	205.55	41.77	38.58	0	0	0

Figure 39 shows the probabilities through the Markov chain. Table 17 presents the Markov matrix of the ASW data fusion system with enhancements results.

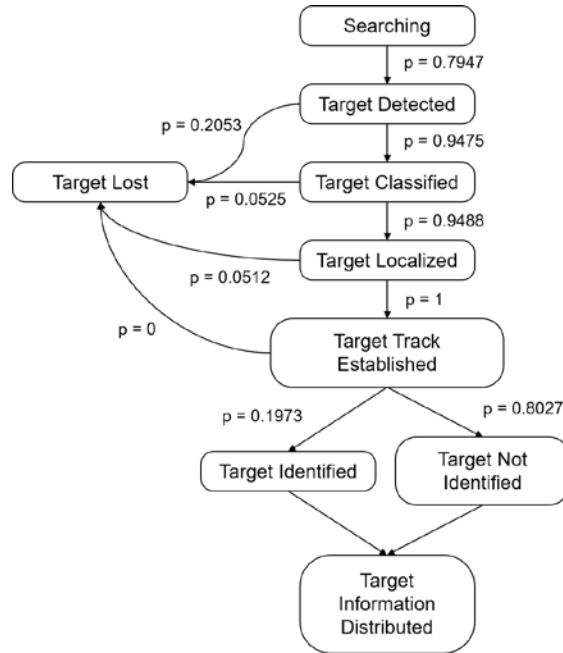


Figure 39. Markov Chain with Probabilities for the ASW Data Fusion System Simulation with Performance Enhancements

Table 17. Markov Matrix of the ASW Data Fusion Simulation with Performance Enhancements

	Search	Detect	Classify	Localize	ID	NoID	Lost
Search	0	0.7947	0	0	0	0	0.2053
Detect	0	0	0.9475	0	0	0	0.0525
Classify	0	0	0	0.9488	0	0	0.0512
Localize	0	0	0	0	0.1973	0.8027	0
ID	0	0	0	0	1	0	0
No ID	0	0	0	0	0	1	0
Lost	0	0	0	0	0	0	1

The probability of the ASW data fusion system with processing enhancements to gain a track is 0.7144 or 71.44% with the probability of gaining target identification of 0.1409 or 14.09%.

Equation (6) represents the increased probability of success between the human-system and the ASW data fusion system.

$$\% \Delta = (DF\ System\ P_{Success} - Human\ P_{Success}) / Human\ P_{Success} \quad (6)$$

Replacing the variables with the Markov outputs yields the following results.

$$26.80 = (0.7144 - 0.0257) / 0.0257$$

The increased probability was a total improvement of over 2680% when compared to the human system.

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V. RECOMMENDATIONS/CONCLUSION

No system exists for combining mobile and stationary underwater sensors into a coherent, distributive network. Without a data fusion system, a limitation exists for strategic/theater planners and tactical operators to accurately identify undersea threats/targets, maintain maritime superiority, and efficiently allocate resources. The team provides an ASW data fusion architecture that builds upon previous data fusion architecture, namely the JDL process model. The utilization of a top-down systems engineering process allowed for the development of an architecture that satisfies the technological gap.

The resultant architecture design is a system of “black boxes.” Each “black box” has a specific function. The details of each functional “black box” will be the subject of future research and design. Each of the “black box” functions is modeled in series utilizing ExtendSim. The benchmark used to determine the success of the architecture is the human ASW operator/analyst, the current ASW data fusion process. Through design and analysis, a distributed architecture configuration has been determined to meet all the system performance requirements. Utilizing the Markov model for comparative analysis, the proposed ASW data fusion architecture consistently exceeds the performance standards of a human ASW operator.

The data from modeling and simulation demonstrates the ASW data fusion system outperforms the human operator by a factor of 20, with simulation results summarized in Table 18. The team concludes the ASW data fusion architecture exceeds the performance standards of the existing human ASW Operator and therefore recommends further research and development.

Table 18. ASW Data Fusion Simulation Results

	Human ASW Operator	ASW data fusion Operator	Improved ASW data fusion Operator
Probability of Gaining a track	2.57%	41.27%	71.44%
Probability of Identifying a contact	0.35%	6.14%	14.09%

A. RISK CONSIDERATIONS

There are two major risks to the ASW data fusion architecture to consider for future development. First is the database management, and the second is the bandwidth limitations for afloat ASW units.

1. Data Standardization

Implementation of distributed enterprise systems requires data standardization. The ASW data fusion system architecture defined in this capstone provides a distributed, enterprise-system approach to the data fusion problem, which is in full alignment with the Navy’s goal to move toward “cloud” based systems. A truly distributed, enterprise system requires data standardization to achieve and maintain system interoperability. The ASW data fusion system must be able to receive data from many different, legacy acoustic systems. It is infeasible to require modifications of the fielded acoustic systems, so the team has proposed supporting these systems by providing data translators capable of translating legacy data to a standard format. Translators such as these must be considered a temporary “band-aid” approach to achieving interoperability. For the ASW data fusion system to achieve ultimate success, the USN should require definition and implementation of data standards for all new acoustic and sensor systems. Defining data standards is a difficult task, and enforcing their use is quite challenging. Data standardization presents one of the largest risks to system success. As retired Army Col. Scott Lambert said, “You have to have standardized data across the disparate systems that allow business processes to function in

a common way. Unless and until you get that data standardization, you can't achieve that synergy across the disparate systems" (Slabodkin 2011, 3).

2. Bandwidth Limitations

Current bandwidth limitations of USN surface ships present a challenge to the distributed ASW data fusion architecture. Considering the total bandwidth allocated for an aircraft carrier, and assuming it has the largest available bandwidth of all naval vessels, minimizing the bandwidth utilization of the ASW data fusion architecture is required.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

The ASW data fusion architecture is presented as a generic architecture for data fusion. There is much more research and development required to further the team's proposal towards a functional system. The following are recommendations for future research.

(1) Development of subsystems

The subsystems used to develop the ASW data fusion architecture are "black box" subsystems. Each subsystem has a function it must accomplish, but the architecture developed in this project intentionally does not specify how each function is accomplished. Future research should include an investigation to existing subsystems and commercial-off-the-shelf systems capable of meeting the system requirements.

(2) Integration of future sensors

This project limits the scope of sensor inputs to passive acoustic sensors. Future research should be conducted to determine how to best integrate other sensors, such as active sensors, environmental data sensors, optical sensors, radar and other sensors that could be used to enhance ASW applications further.

(3) Integration of ACINT database

This project includes the use of the ACINT database for contact classification but does not specify how this information is received, utilized, or integrated into the system.

Future research and design to integrate this database into an ASW data fusion system is required to substantially aid in the identification of contacts based on the acoustic data received.

(4) Impact of environmental data

Environmental conditions substantially impact the performance of all acoustic sensors. This project does not consider the acoustic environment. Future research is required to assess and incorporate environmental conditions (e.g., temperature, depth, stratification of water based on temperature (layering), bottom composition, and salinity) that have an impact to acoustic sensor performance.

(5) Expansion of tracking capabilities

This project does not investigate the requirements to track a contact; rather it focuses on fusing information from multiple sensors to develop a contact with the potential of being tracked and identified. Future research on the utilization of the data output from this system should include expanded options for contact tracking over a given period, with the result being weapons targetable information.

(6) Development of rules and algorithms

For the data fusion architecture to function, there must be an established set of rules to determine what constitutes a feature, cluster, and contact. Future research should focus on developing these rules for the construction of an algorithm to analyze the incoming acoustic data and aid in the automated process of identification.

(7) Definition of KPPs and thresholds

This project uses maximize and minimize only when developing KPPs and the required thresholds. Future research in the definition of these requirements will help to ensure the ASW data fusion architecture meets the requirements of the warfighters utilizing it in real-time ASW applications.

(8) Data standard specification

It is necessary to define and mandate data standards for the ASW data fusion system to achieve ultimate success. The Feature Data, Cluster Data, and Contact Data defined within this capstone are the cornerstones of ASW Data Fusion; standardizing their formats is essential to achieve interoperability. Future research should include the development of these data standards.

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APPENDIX A. STAKEHOLDERS

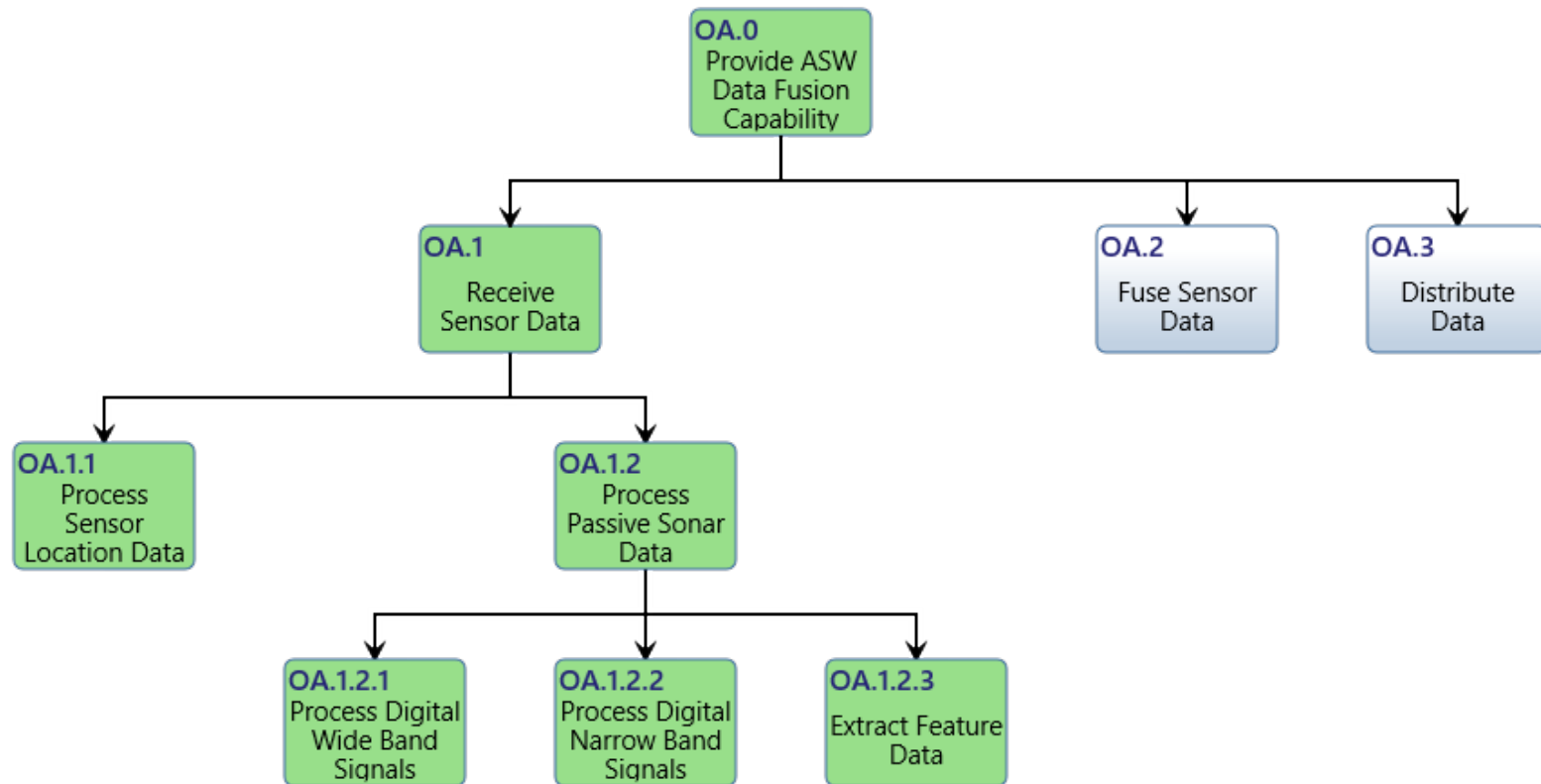
Stakeholder	Type	Primitive Needs	Effective Needs / Goals / Objectives	Concerns
NPS Department of Systems Engineering, Dr. John M. Green	Client / Decision Maker	- Reference architecture - Inclusion of AUVs	- Framework for the study of information fusion concepts for future applications - Adaptability for future technologies - State-of-the-art product that can be expanded upon	- Timeline - Technological advances
Undersecretary of Defense for Acquisition, Technology, and Logistics (USD AT&L)	Decision Maker	Cost effective ASW system	- Adaptability for future technologies - Common architecture to develop and field in order to maintain undersea superiority	- Cost - Maintainability - Availability - Scalability
DoD Deputy Chief Information Officer for Command, Control, Communication and Computers, and Information Infrastructure Capabilities (DoD DCIO C4 & IIC)	Decision Maker	- Integrated undersea warfare data system - Maintain technological advantage	Common architecture to develop and field in order to maintain undersea superiority	- Cost - Maintainability - Scalability - Upgradability - Cybersecurity
Naval Undersea Warfare Center	User / Sponsor	- Integrated undersea warfare data system - Maintain technological advantage	- Common architecture to develop and field in order to maintain undersea superiority - Inclusion of AUV technology	- Cost - Size - Maintainability
Naval Sea Systems Command	Passive sponsor	Expand tactical and technical	System architecture for undersea warfare data fusion including AUVs	Rate of technological advances

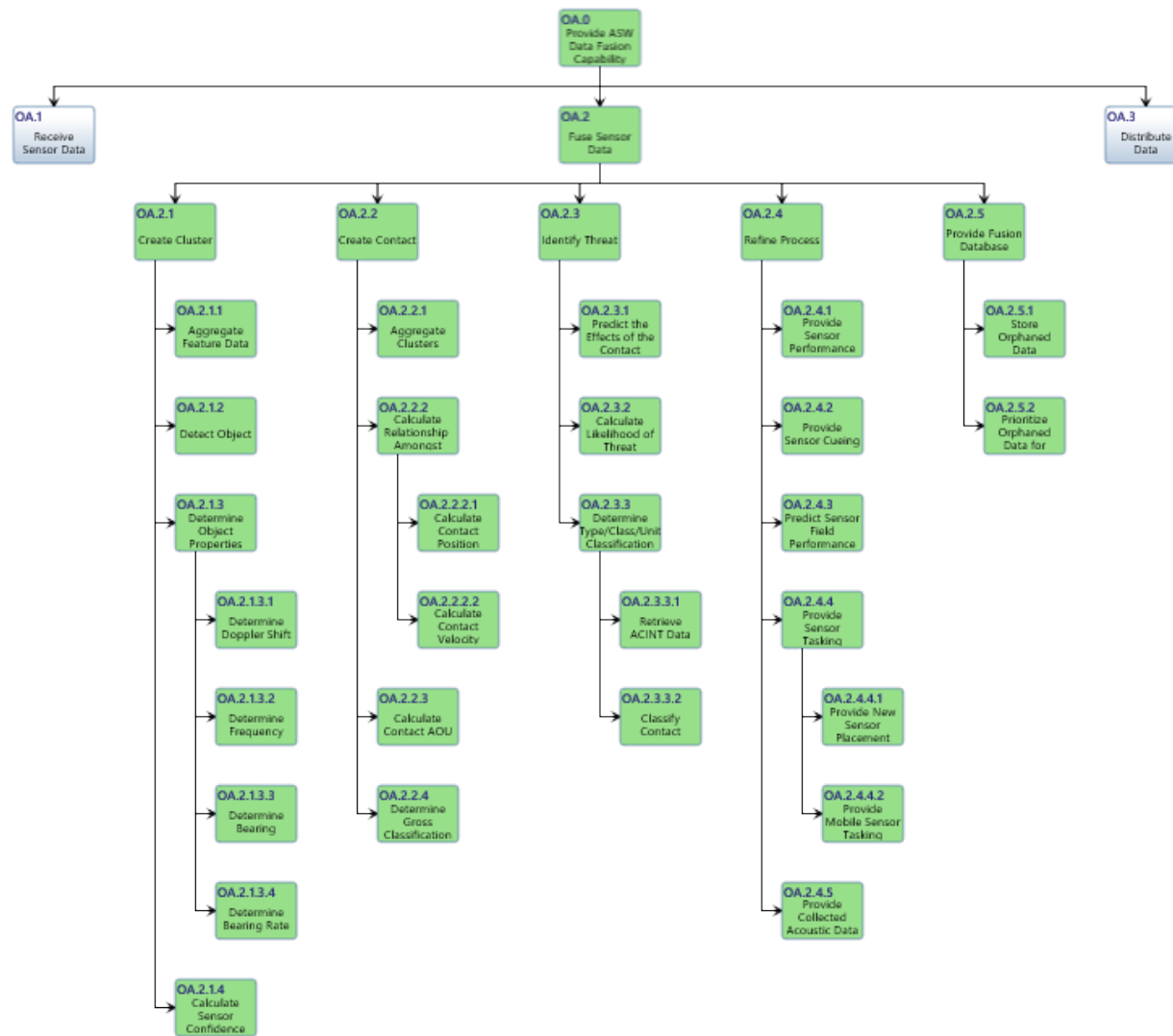
Stakeholder	Type	Primitive Needs	Effective Needs / Goals / Objectives	Concerns
		• advantage over adversaries	• Maintain undersea warfare superiority	• Rate of adversary's advances
Undersea Warfighting Development Center (UWDC)	Sponsor	• Develop submarine tactics utilizing integrated undersea sensors	• Maintain undersea warfare superiority	• Rate of technological advances • Rate of adversary's advances
Naval Aviation Warfare Development Center (NAWDC)	Sponsor	• Develop aircraft tactics utilizing integrated undersea sensors	• Maintain undersea warfare superiority	• Rate of technological advances • Rate of adversary's advances
Naval Surface and Mine Warfighting Development Center (SMWDC)	Sponsor	• Develop surface combatant tactics utilizing integrated undersea sensors	• Maintain undersea warfare superiority	• Rate of technological advances • Rate of adversary's advances
Joint Data Labs	Passive sponsor	• Expanded architecture to include AUVs	• Means to incorporate future technologies into current data fusion model	• Future applications
John Hopkins Applied Research Lab	User	• Undersea warfare sensor data	• Gain access to data and systems for the evaluation of undersea sensor and sensor operator performance • Improve undersea sensor and sensor operator performance	• Data format standardization
Undersea Range Agencies (e.g., SCORE, AUTECH, PMRF)	User	• Undersea warfare sensor data	• Integrate undersea range sensors into distributed network • Increase resolution of range data for more effective training and evaluation.	• Loss of local control of range sensors • Interoperability
Office of Naval Intelligence (ONI)	User	• Undersea warfare sensor data	• Evaluate undersea sensor data to determine submarine type, hull, and performance.	• Data format standardization

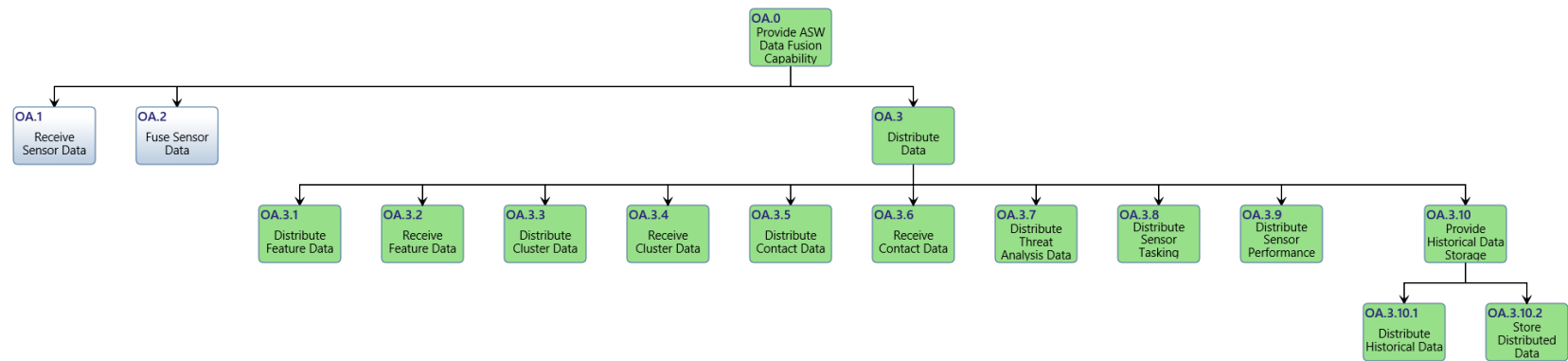
Stakeholder	Type	Primitive Needs	Effective Needs / Goals / Objectives	Concerns
				Unauthorized classified data distribution
Defense Threat Reduction Agency (DTRA)	User	Defend against submarine-launched ballistic missiles	Gain access to timely data to prevent or defend against submarine-launched ballistic missiles	- Undetected adversary - Data timeliness
National Security Agency (NSA)	Sponsor	Provide secure data path	Develop and distribute means to secure data transmissions (e.g., cryptology) from undersea sensors to end users	Unauthorized classified data distribution
CNO	Sponsor	- Effectively allocate resources to ASW - Provide for National Defense	Minimize cost of ASW sensor systems by eliminating excessive redundancy	Cost
Unified Combatant Commanders	User	- Maritime superiority - National Security - Strategic advantage	- Tactical advantage in surface and undersea warfare - Reduced risk to operational forces in any theater of operations	Ability to use all data available to maintain maritime superiority
Navy Theater Commanders	User	Accurate time-now tactical picture	- Ability to position, station and position surface and subsurface assets - Maintain Sea Lines of Communication - Maintain maritime dominance	- Adversary movements not detected - Loss of tactical advantage
Commander, Undersea Surveillance	User	Accurate time-now tactical picture	Ability to distribute seafloor sensor data to tactical/strategic commanders	- Maintainability - Scalability

Stakeholder	Type	Primitive Needs	Effective Needs / Goals / Objectives	Concerns
Submarine Commanding Officers	User	• Integrated, accurate picture of waterspace	• Accurate tactical picture • Safe navigation • Understanding of surrounding environmental conditions • Adversary location and movements	• Undetected adversary • Loss of tactical advantage
Surface Ship Commanding Officers	User	• Integrated, accurate picture of operating area	• Accurate tactical picture • Safe navigation • Best use of organic sensors • Best tactical employment of remote sensors such as helicopters with sonobuoys, AUVs, UAVs • Maritime superiority	• Undetected adversary • Loss of tactical advantage
ASW Aircraft Mission Commander	User	• Integrated, accurate picture of operating area	• Accurate tactical picture • Safe navigation • Best use of aircraft sensors • Maritime superiority	• Undetected adversary • Loss of tactical advantage

APPENDIX B. OV-5A SYSTEM DIAGRAM







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APPENDIX C. REQUIREMENTS LIST

1. Functional Requirements

(1) 1.0 Process Sensor Data Function

The purpose of the Process Data Function is to receive signal data from passive acoustic sensors, extract feature data from the received signals, and provide the feature data to the data fusion process.

- 1.1 The Receive Sensor Data Function shall receive sensor location data.
- 1.2 The Receive Sensor Data Function shall receive digital wideband signals.
- 1.3 The Receive Sensor Data Function shall receive digital narrowband signals.
- 1.4 The Receive Sensor Data Function shall extract feature data from the signal data.
- 1.5 The Receive Sensor Data Function shall provide feature data to the Create Cluster Function.

(2) 2.0 Create Cluster Function

The purpose of the Create Cluster Function is to receive feature data, aggregate feature data into detected clusters and provide detected cluster data to the Create Contact Function.

- 2.1. The Create Cluster Function shall aggregate feature data.
- 2.2. The Create Cluster Function shall detect an object.
- 2.3. The Create Cluster Function shall determine the Doppler shift of the detected object.

- 2.4. The Create Cluster Function shall determine the frequency of the detected object.
- 2.5. The Create Cluster Function shall determine the bearing of the detected object.
- 2.6. The Create Cluster Function shall determine the bearing rate of the detected object.
- 2.7. The Create Cluster Function shall calculate sensor confidence.

(3) 3.0 Create Contact Function

The purpose of the Create Contact Function is to receive cluster objects, aggregate those clusters into a single, fused contact solution, and provide that contact to the Identify Threat Function, Refine Process Function, and Distribution Function.

- 3.1. The Create Contact Function shall aggregate clusters.
- 3.2. The Create Contact Function shall create a single, fused contact solution.
- 3.3. The Create Contact Function shall calculate the contact's position.
- 3.4. The Create Contact Function shall calculate the contact's velocity vector.
- 3.5. The Create Contact Function shall calculate the AOU for the contact.
- 3.6. The Create Contact Function shall determine the gross classification of the contact.

(4) 4.0 Identify Threat Function

The purpose of the Identify Threat Function is to receive fused contact data, classify the contacts using retrieved ACINT data, assess the potential threat of the contacts, and

provide the relevant situational awareness data (classification, threat, and threat likelihood) to the distribution function.

- 4.1. The Identify Threat Function shall retrieve ACINT data.
- 4.2. The Identify Threat Function shall classify contact.
- 4.3. The Identify Threat Function shall predict the effects of the contact.
- 4.4. The Identify Threat Function shall calculate the likelihood of threat.

(5) 5.0 Refine Process Function

The purpose of the Refine Process Function is to continuously assess the results of the fusion processes and provide feedback to those processes in order to improve their performance. Additionally, the Refine Process Function will identify areas of poor performance and provide suggestions for sensor placement/tasking to C2 via the Distribution Function.

- 5.1. The Refine Process Function shall predict sensor field performance.
- 5.2. The Refine Process Function shall provide new sensor placement suggestions.
- 5.3. The Refine Process Function shall provide mobile sensor tasking suggestions.
- 5.4. The Refine Process Function shall provide sensor cueing.
- 5.5. The Refine Process Function shall provide sensor performance feedback.
- 5.6. The Refine Process Function shall provide collected ACINT acoustic data to ACINT database.

(6) 6.0 Data Fusion Storage Function

The purpose of the Data Fusion Storage Function is to store feature and object data, not associated with an aggregation, for future use (solution refinement) by the relevant functions.

- 6.1. The Data Fusion Storage Function shall store orphaned feature data.
- 6.2. The Data Fusion Storage Function shall store orphaned object data.
- 6.3. The Data Fusion Storage Function shall store prioritize objects for contacts.

(7) 7.0 Distribute Fused Data Function

The purpose of the Distribute Fused Data Function is to distribute the Data Fusion results to all interested C2 stations.

- 7.1. The Distribute Fused Data Function shall distribute fused contact message containing contact classification, kinematic data, and AOU.
- 7.2. The Distribute Fused Data Function shall distribute situational awareness message containing likelihood of threat, classification of contact, predicted effects of contact.
- 7.3. The Distribute Fused Data Function shall distribute sensor tasking message.
- 7.4. The Distribute Fused Data Function shall distribute sensor performance feedback message.
- 7.5. The Distribute Fused Data Function shall store historical data.
- 7.6. The Distribute Fused Data Function shall distribute historical data.

The final step of the requirements analysis is the requirements definition. The non-functional requirements are defined below. The functional analysis section in Chapter IV defines the functional requirements.

2. Non-functional Requirements

Non-functional (“ility”) requirements define the quality attributes of the system instead of defining the behavior of the system, which is covered by functional requirements.

a. Performance

- The ASW data fusion system shall locate an HVT within TBD seconds.
- The ASW data fusion system shall report a false HVT detection with a probability of less than TBD %.
- The ASW data fusion system shall achieve an AOU of less than TBD meters for an HVT.
- The ASW data fusion system shall incorrectly identify an HVT with a probability of less than TBD %.
- The ASW data fusion system shall provide targeting information with TBD seconds of detection.
- The ASW data fusion system shall connect to the target network within TBD seconds of startup.
- The ASW data fusion system distribution network shall achieve a time latency of TBD seconds or less.
- The ASW data fusion system shall send data fusion data to the distribution function within TBD seconds of creation.

b. Platform

- The ASW data fusion system shall require at least x MB of RAM.
- The ASW data fusion system shall require at least x GB of hard disk space.

- The ASW data fusion system shall require an x MHz processor.

c. Portability

The ASW data fusion system shall operate on any platform that meets the platform requirements specified.

d. Efficiency

- The ASW data fusion system shall handle acoustic sensor input from at least x different reporting sensors.
- The ASW data fusion system shall handle acoustic sensor input at a rate of x kb/sec
- The ASW data fusion system shall not exceed a CPU usage of x%.
- The ASW data fusion system shall not limit the number of distribution recipients.

e. Maintainability

- The ASW data fusion system shall exhibit a mean time to recovery (MTTR) of no more than x minutes.
- The ASW data fusion system shall monitor system health.
- The ASW data fusion system shall perform an automatic restart in the event of system failure.

f. Reliability

The ASW data fusion system shall exhibit a mean time between failures (MTBF) of no more than x hours.

g. Scalability

- The ASW data fusion system shall allow for the incorporation of future sensor types.

- The ASW data fusion system shall allow for an unlimited number of sensors.

h. Adaptability

Future modifications made to the ASW data fusion system interface specification shall be backward compatible.

i. Interoperability

- The ASW data fusion system shall comply with Department of Defense (DOD) Interoperability and Supportability (I&S) policy and instruction in accordance with reference DODI 8330.01, 21 May 2014, “Interoperability of Information Technology (IT), Including National Security Systems (NSS).”
- The ASW data fusion system shall be interoperable with the host nation, and multinational coalition partners.
- The ASW data fusion system shall be agnostic of distribution recipients.
- The ASW data fusion system shall be agnostic of data sources.
- The ASW data fusion system shall be interoperable with previously fielded, unmodifiable sensor systems.
- The ASW data fusion system shall be interoperable with future systems through the use of open architecture defined interfaces, and modular design.

j. Safety

The ASW data fusion system shall not distribute target classification until an x% degree of certainty is gained on said target.

k. Cyber Security

- The ASW data fusion system shall protect stored data against unauthorized access.
- The ASW data fusion system shall protect distributed data against unauthorized access.
- The ASW data fusion system shall comply with DOD Cybersecurity policy in accordance with reference DODI 8500.01, 14 March 2014, “Cybersecurity.”

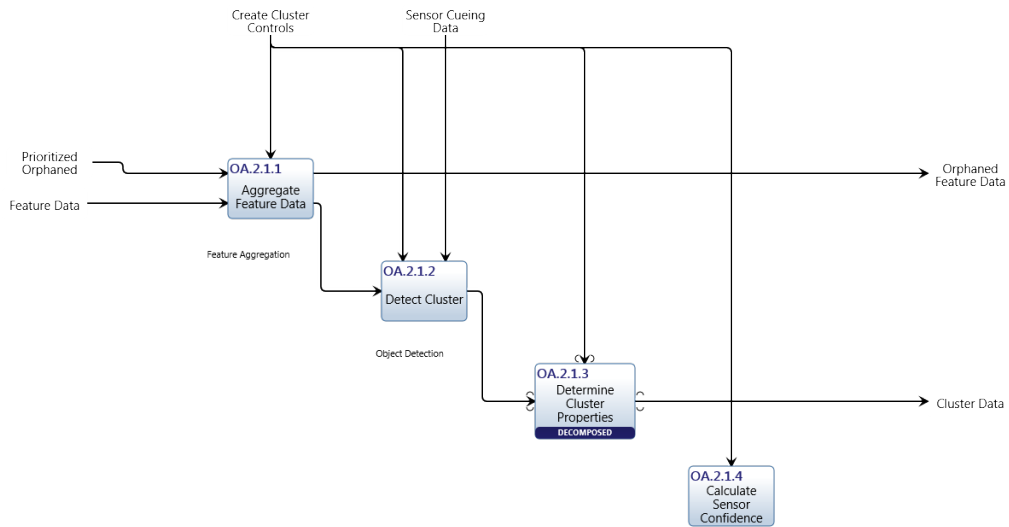
3. Internal Interface Requirements

- The Receive Data Function shall send Feature Data to the local area network (LAN).
- The Create Cluster Function shall receive Feature Data from the LAN.
- The Create Cluster Function shall send Cluster Data to the LAN.
- The Create Contact Function shall receive Cluster Data from the LAN.
- The Create Contact Function shall send Contact Data to the LAN.
- The Support Database Function shall receive Orphaned Feature Data from the LAN.
- The Support Database Function shall receive Orphaned Cluster Data from the LAN.
- The Support Database Function shall receive Orphaned Contact Data from the LAN.
- The Support Database Function shall send Orphaned Feature Data to the LAN.

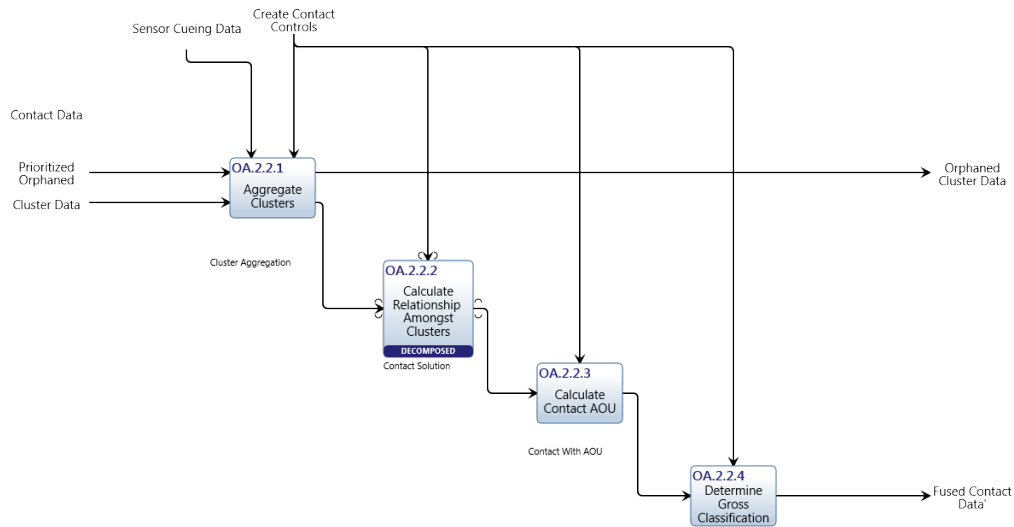
- The Support Database Function shall send Orphaned Cluster Data to the LAN.
- The Support Database Function shall send Orphaned Contact Data to the LAN.
- The Refine Data Function shall receive Feature Data from the LAN.
- The Refine Data Function shall receive Cluster Data from the LAN.
- The Refine Data Function shall receive Contact Data from the LAN.
- The Refine Data Function shall send Sensor Cueing Data to the LAN.
- The Refine Data Function shall send Sensor Performance Feedback Data to the LAN.
- The Identify Threat Function shall receive Contact Data from the LAN.
- The Identify Threat Function shall send Situational Awareness Data to the LAN.

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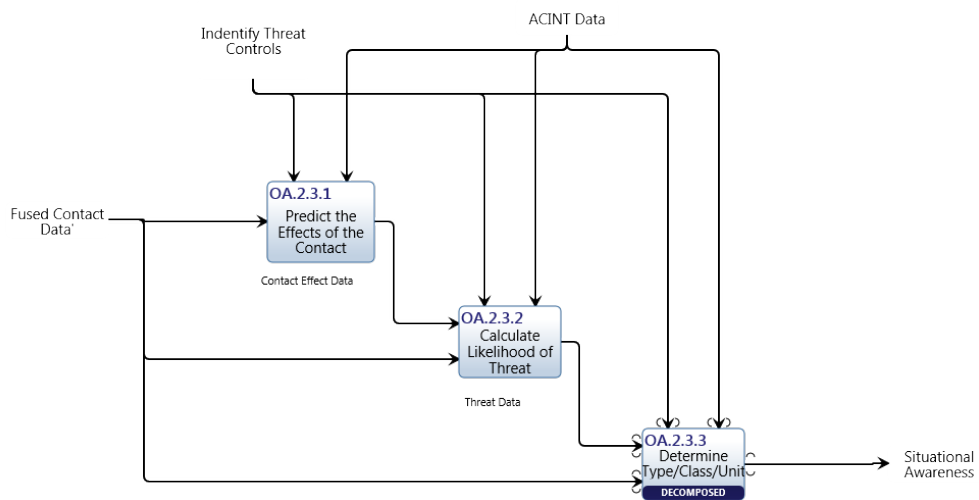
APPENDIX D. FUSE SENSOR DATA IDEF0 DIAGRAMS



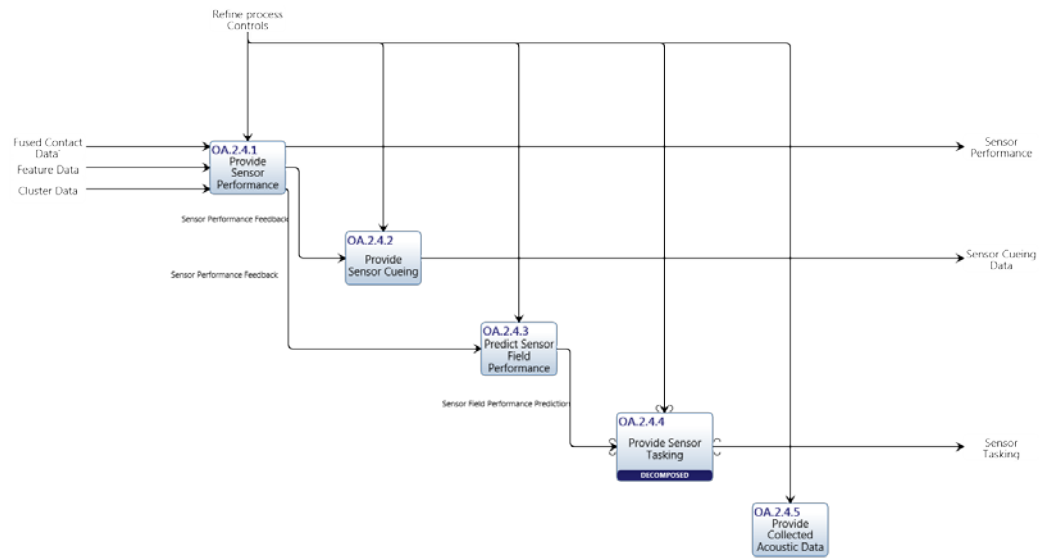
Decomposed Create Cluster IDEF0



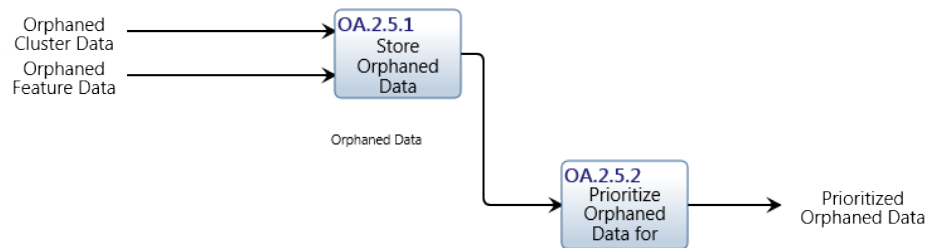
Decomposed Create Contact IDEF0



Decomposed Identify Threat IDEF0

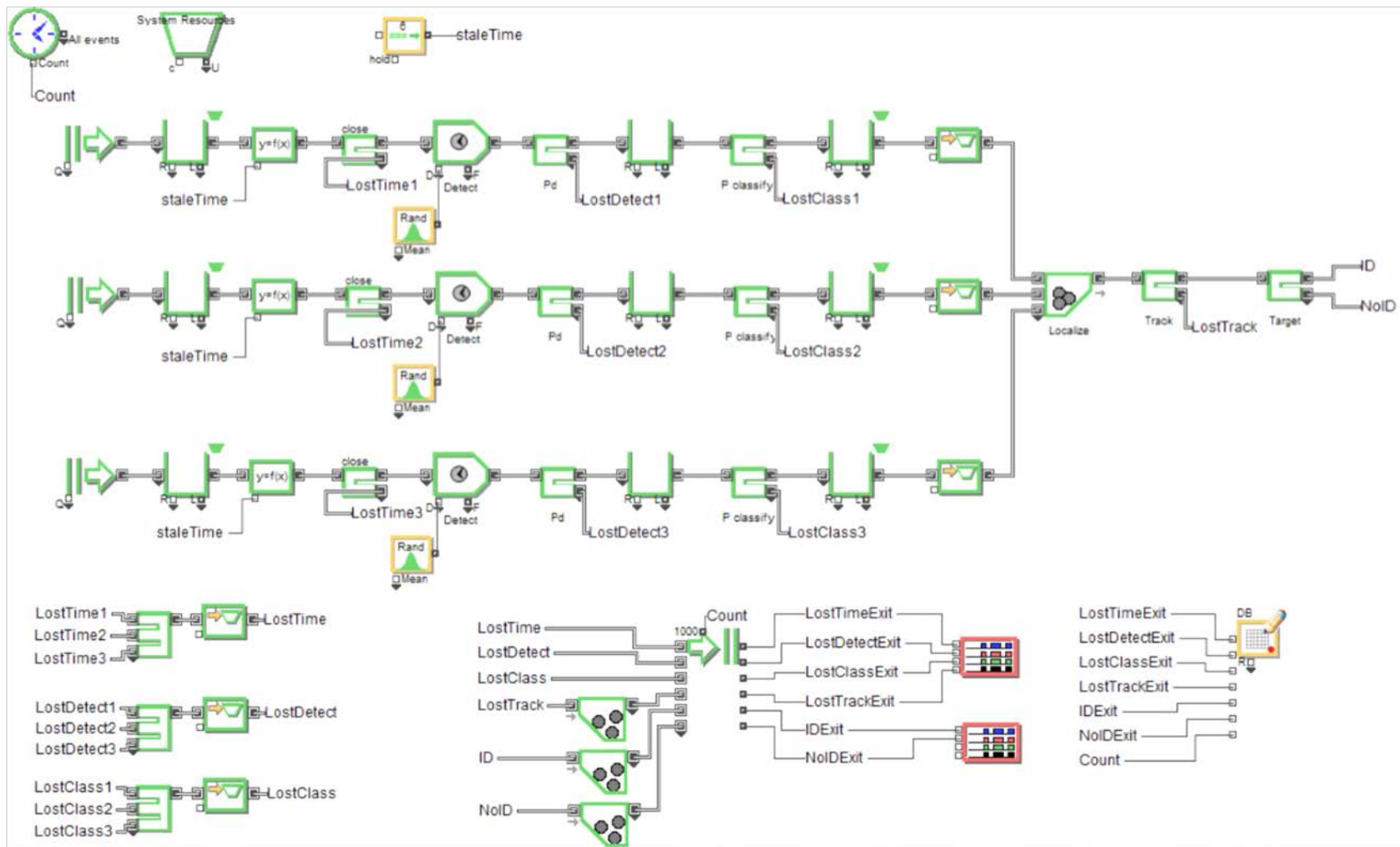


Decomposed Refine Process IDEF0



Decomposed Provide Fusion Database IDEF0

APPENDIX E. EXTENDSIM SYSTEM MODEL



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