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UNMANNED UNDERWATER VEHICLE MISSION SYSTEMS ENGINEERING PRODUCT REUSE RETURN ON INVESTMENT

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SYSTEMS ENGINEERING CAPSTONE REPORT

UNMANNED UNDERWATER VEHICLE MISSION SYSTEMS ENGINEERING PRODUCT REUSE RETURN ON INVESTMENT

by

Kristina Haller, Danielle S. Kolber, Theodore R. Storms,
Jesse B. Weeks, and Wayne Weers

March 2022

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13. ABSTRACT (maximum 200 words)

Unmanned Underwater Vehicles (UUVs) accomplish a wide spectrum of missions ranging from generic to extremely specific. Although not all UUVs can accomplish all missions, there is significant replication of the requirements and the systems across the family of UUVs. The design process for UUVs balances operational requirements, design feasibility, expected performance, schedule, budget, and ultimate system and life-cycle costs. The U.S. Department of Defense does not have an established process for developing UUV Systems Engineering (SE) requirements. This results in duplicative development efforts adding unnecessary costs to UUV programs. This paper investigates the SE requirements and interfaces across various UUV mission spaces to establish complexity and reuse weights. A Constructive SE Cost Model (COSYSMO) is applied to determine the cost advantage to reuse SE requirements for UUV assets across different mission spaces to determine an overall SE effort. Requirements from the baseline mission are then compared with requirements from eight other missions, and the efforts compared to determine a return on investment (ROI) for using previous missions as a baseline. Utilizing the resulting UUV requirement cost versus ROI can serve as a starting point for future UUV program concept design.

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ABSTRACT

Unmanned Underwater Vehicles (UUVs) accomplish a wide spectrum of missions ranging from generic to extremely specific. Although not all UUVs can accomplish all missions, there is significant replication of the requirements and the systems across the family of UUVs. The design process for UUVs balances operational requirements, design feasibility, expected performance, schedule, budget, and ultimate system and life-cycle costs. The U.S. Department of Defense does not have an established process for developing UUV Systems Engineering (SE) requirements. This results in duplicative development efforts adding unnecessary costs to UUV programs. This paper investigates the SE requirements and interfaces across various UUV mission spaces to establish complexity and reuse weights. A Constructive SE Cost Model (COSYSMO) is applied to determine the cost advantage to reuse SE requirements for UUV assets across different mission spaces to determine an overall SE effort. Requirements from the baseline mission are then compared with requirements from eight other missions, and the efforts compared to determine a return on investment (ROI) for using previous missions as a baseline. Utilizing the resulting UUV requirement cost versus ROI can serve as a starting point for future UUV program concept design.

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List of Acronyms and Abbreviations

ASW Anti-Submarine Warfare

CN3 Communication or Navigation Network Node

CONOPS Concept of Operations

COPLIMO Constructive Product Line Investment Model

COSYSMO Constructive Systems Engineering Cost Model

DOD Department of Defense

DoDAF Department of Defense (DOD) Acquisition Framework

DON U.S. Department of the Navy

Excel Microsoft Excel

GPS Global Positioning System

INID Inspection and Identification

Innoslate Innoslate Model-Based Systems Engineering (MBSE) software

IO Information Operations

ISR Intelligence, Surveillance, and Reconnaissance

LOE Level of Effort

MBSE Model-Based Systems Engineering

MCM Mine Countermeasures

MOE Measure of Effectiveness

MOP Measure of Performance

OO Oceanography

PD Payload Delivery

PM Person-Months

ROI Return on Investment

SE	Systems Engineering
SV	System Viewpoint
SWARM	Smart Warfighting Array of Reconfigurable Modules
SysML	System Modeling Language
TCS	Time Critical Strike
UAV	Unmanned Aerial Vehicle
USN	U.S. Navy
UUV	Unmanned Underwater Vehicle

CHAPTER 1:
Introduction

Unmanned Underwater Vehicles (UUVs) are advanced versatile systems that are procured by the U.S. Department of the Navy (DON) for use by forward deployed forces. During and in regions of conflict, UUVs are deployed singularly or within Smart Warfighting Array of Reconfigurable Modules (SWARM) configurations [1]. UUVs are favored as the warfighters' future [2].

Missions requiring UUVs can vary from surveillance of an area to an area specific payload delivery [3]. Missions may be conceptually different, but still require similar capabilities. For example, in a surveillance mission, the UUV must be able to navigate to a point of interest [3]. This requirement is also true when delivering a payload to a point of interest [3]. The requirement to autonomously navigate to specific location is true across both missions [3]. Designing system requirements for reusability across different missions yields increasing savings in Systems Engineering (SE) labor as more missions are included in the reuse portfolio. If the baseline UUV mission SE requirements are designed for reuse, it will increase the initial labor investment. However, the Constructive Systems Engineering Cost Model (COSYSMO) will show that if enough requirements and interfaces are reusable across different missions, this initial investment will have a high Return on Investment (ROI) [4].

Nine major missions are required by the DON: Intelligence, Surveillance, and Reconnaissance (ISR), Mine Countermeasures (MCM), Anti-Submarine Warfare (ASW), Inspection and Identification (INID), Oceanography (OO), Communication or Navigation Network Node (CN3), Payload Delivery (PD), Information Operations (IO), and Time Critical Strike (TCS) [3]. Requirements for each mission will be identified and compared for likeness across missions. A systems modeling approach will define the necessary actions and interfaces required for each mission. Model-Based Systems Engineering (MBSE) System Modeling Language (SysML) diagrams created using Innoslate MBSE software (Innoslate) will represent the action, inputs, outputs, and requirements of each independent UUV mission. From the models created, requirements and interfaces will be defined and input into COSYSMO. Outputs from COSYSMO will contain the total Level of Effort (LOE) needed, in Person-Months (PM), to perform the SE for each mission [5]. COSYSMO will provide LOEs for independent and reuse scenarios of mission SE artifact development [6].

ROI assessment enables an informed decision on whether to invest more initially to receive savings later. COSYSMO results will be analyzed for ROI. Using ROI values, program managers and sponsors can make informed investment decisions to develop cross-program, and ultimately DON-wide cost savings. Implementation of SE artifact reuse does not have to stop with the DON, but can expand to include all Department of Defense (DOD) UUV mission development efforts.

1.1 Overview

Interest in UUV platforms is expanding as technologies continue to advance while resources become increasingly constrained [2]. The identification and implementation of SE artifact reuse across UUV missions is critical in determining potential cost savings. COSYSMO provides an industry-validated means to compare program SE LOEs while incorporating reuse of SE artifacts [4]–[7]. This thesis investigates multiple key system requirements and interfaces to identify and provide ROI estimates for providing support across district missions by UUVs developed via a product line approach to SE.

1.2 Research Objective

This investigation of reusable system requirements and interfaces for UUVs intends to identify efficiencies from applying a product line method to the SE process across different missions. The goal of this research is to determine, by means of COSYSMO analysis, whether it is advantageous to develop reusable requirements and interfaces for an initial UUV mission, and then reuse or delete those requirements for follow on missions. Metrics for this analysis will be in terms of SE labor (PM). Ultimately, an ROI will be calculated for reuse verses independent development efforts and will be evaluated to determine if the investment is lucrative or not.

1.3 Research Focus

The research investigates the potential benefits of using a product line approach for the SE of the nine main UUV missions in [3]. The specific questions this research intends to address are:

1. What are the activities, interfaces, and requirements of each of the nine UUV missions?
2. What are the complexities of the identified requirements and interfaces?
3. What is the optimal baseline mission for SE artifact reuse?
4. What is the reusability of the baseline mission's SE artifacts for the remaining missions?
5. What are the LOEs for each mission's development using traditional and reuse methods?
6. What is the ROI for applying a product line approach to the UUV mission SE efforts?
7. Does operational modularity duplicated across UUV missions save on SE labor costs when the original system is designed for reuse, while still satisfying UUV demands?

1.4 Thesis Methodology

Nine UUV missions will be evaluated from the Concept of Operations (CONOPS) statements in [3]. The process will begin with modeling each mission in Innoslate to generate MBSE diagrams. The architecture model will follow SysML, which is a common language used in support of illustrating hierarchies and ontologies [8]. The MBSE diagrams will consist of activity, interface, and requirement diagrams of key mission-driven systems for all nine UUV missions. Comprehensive requirements will be derived from the activity and interface diagrams. The requirements and interfaces will be classified as one of three defined complexities: *Easy, Nominal, Difficult*, and input to COSYSMO to determine the LOE required to develop the SE artifacts for each mission using the traditional siloed development approach. The architecture breakdown of mission profiles will support classifying each and every requirement and interface within a mission [5].

Then the ISR mission will be selected as the reuse baseline. SE artifacts will be categorized into defined reuse levels: *New, Designed for Reuse, Modified, Deleted, Adopted, Managed* [6]. All ISR mission SE artifacts will be designated as *Designed for Reuse*.

SE artifacts will be compared across missions and duplicates identified. For example, for a reconnaissance or a bottom survey mission the sensor package, propulsors, and material types will be cross-utilized to provide a common cost and product line solution for both missions. The resulting database of classified requirements and interfaces will be input into version 2.0 of COSYSMO producing values that can be compared with those for traditional development.

The resulting LOEs will be used in ROI calculations determining the benefit of utilizing the identified reuse relationships across the nine UUV missions. The primary deliverable for this research is the analysis that identifies a cumulative ROI showing the additional benefit gained from each mission added to the portfolio.

1.5 Thesis Assumptions

The following assumptions were held throughout this thesis and supporting research and analysis. They served to both bound the analysis and provide a stable base of reference in a diverse and dynamic space. Their presentation order implies neither importance nor significance.

- The CONOPS provided in [3] describe the UUV missions with uniform accuracy, depth, and detail.
- The SysML diagrams capture all required activities, systems, and interfaces from the CONOPS.
- Requirement extraction from the SysML diagrams was consistent across missions.
- Interface definition was consistent across missions.
- Requirement and interface classification for both complexity and reuse was consistent across missions.
- SE artifact complexity does not change from mission to mission.
- All missions are performed by a medium class UUV.
- The ISR mission is the best reuse baseline for the nine mission portfolio.
- COSYSMO will reasonably predict UUV program development efforts.
- The CONOPS in [3] were generalized such that decomposition of the extracted requirements to the “sea level” [9] would introduce an unreasonable level of subjectivity in the requirement definition and classification.

1.6 Thesis Organization

Nine UUV missions are analyzed throughout this paper examining SE artifact reuse across the overall portfolio. The underlying reuse classification and ultimate ROI derived from it through COSYSMO are the core of this effort. The following is an overview of each chapter contextualizing them in the overall thesis.

Chapter 1 (this chapter) introduces the thesis framework while illustrating the research's overview, problem definition, and scope. Chapter 2 is the literature review supporting this study. The concepts and backgrounds of UUVs, their use, MBSE, and other key principles are introduced and explained. Additionally, the nine UUV missions detailed. Chapter 3 discusses the thesis methodology including the tool selections, modeling approaches, and mission relations for assigning COSYSMO 2.0 reuse classifications. Chapter 4 discusses and documents the classifications of each mission's requirements and interfaces, the COSYSMO derived LOEs, and the resulting and varying ROIs from applying a product line approach to the UUV mission portfolio SE. The chapter concludes with answers to the research questions. Chapter 5 summarizes the overall findings of this thesis and closes with recommendations for future study on UUV mission SE artifact reuse and COSYSMO application.

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CHAPTER 2:
Background

This chapter provides background on various aspects and subsystems of UUVs, a deep dive on the various missions considered, MBSE, software used for the analysis in this thesis, and other tools used throughout this thesis.

2.1 Unmanned Underwater Vehicle Overview

Unmanned Underwater Vehicle (UUV) platforms are uniquely advantageous for the warfighter to successfully execute a mission without risking loss of life. UUVs are a beneficial platform due to platform design, low construction cost, range of vehicle sizes, and mission versatility. Figure 2.1 provides an illustration of a generic UUV design. The U.S. Navy (USN) utilizes UUV platforms with multiple payload modules to successfully execute a wide variety of missions. UUVs are commonly smaller than Navy surface ships. Naval surface ships include surface ships and smaller combatant craft platforms. The overall size of UUVs is advantageous: UUVs can be easily transported and deployed by various methods including their onboard power. Alternative methods of UUV delivery include surface ships, small combatant crafts, and air delivery methods. The UUV gives the ability for deployment of UUVs to occur anywhere that a host vehicle is located. Depending on the mission requirements and environmental factors, there is a set time frame of available power onboard before the UUV needs to be recalled to the host vessel for charging purposes.

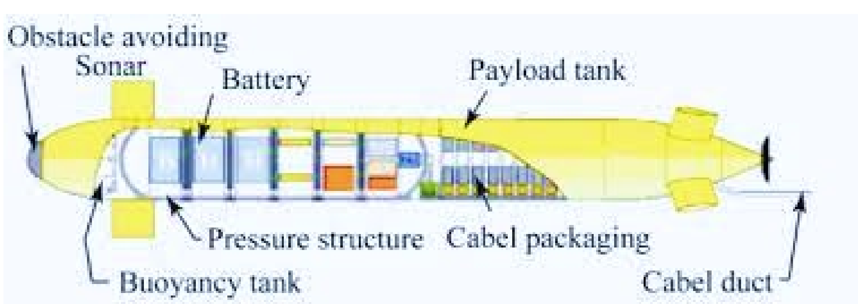

Figure 2.1. Generic UUV Design. Source: [10].

High-level functioning systems are composed of an object or a group of objects and processes that have been created to deliver a beneficial function or mission assignment, the mission is carefully crafted and designed around the mission requirements [11]. UUVs represent a system of systems, where each unique component onboard the UUV exists to support the mission requirements [11]. Success of a mission is due to the component's unique way of fulfilling a needed mission requirement. For UUV design optimization purposes, both the components and systems onboard the UUV are expected to be optimized with respect to size restrictions, power requirements, and cost effectiveness. The process of UUV design optimization varies from relatively simple to very high in complexity dependent on the mission and the respective mission requirements [11].

UUV platforms represent a category of vehicles that have the ability to submerge within the marine environment and emerge successfully. There exist two categories of UUVs. These two categories are divided into two classes of UUVs: remotely operated underwater vehicles and autonomous underwater vehicles. This research effort will focus on UUVs in the latter category throughout this thesis.

UUVs are divided into the subsystems of a pressure hull, hydrodynamic hull, ballast, power/energy, electrical power distribution, propulsion, navigation, avoidance, mast, maneuvering control, communication, locator and emergency equipment, and payload [3]. A general view of a UUV is shown in Figure 2.1.

2.1.1 Pressure Hull

The pressure hull is a crucial structural component that withstands the hydrostatic pressure of the ocean as the vehicle travels to depth. The pressure applied to the hull by the marine environment as the system descends increases in a linear relation to the depth. As a result, the depth of operation can influence the material that is used for the construction of the hull. For example, if the UUV operation is limited to shallow water, the material can be aluminum [3]. When considering a design of a UUV, the cost of the material used and the volumetric space needed have a codependent relationship. This relationship ensures funds are not wasted by designing an overqualified system. Software tools are commercially available to assist with the trade-off analysis decision making in support of pressure hull specification requirements and needs [3].

2.1.2 Hydrodynamic Hull

A hydrodynamic hull is an external housing shell designed to reduce the drag of the unmanned vehicle while navigating through the water. The trade-off for the hydrodynamic hull examines the speed and endurance versus the efficiency of the propulsion system [3]. The trade-off is at low speeds the UUV will have issues with maneuvering and stability versus the stability of the sensors onboard the UUV at higher speeds. Software tools to assist with determining the hydrodynamics of the designed vessel before fabrication effort begins are commercially available [3]. This hydrodynamic software enables naval architects to model the vessel design prior to committing to the physical build of the UUV. Advanced modeling of the design allows for checks and balances to proceed prior to material purchases and allocation of labor hours.

Hydromechanics is the consideration of the vehicle's effects while moving in a fluid [11]. As the result of the UUV's operational environment, and the three-dimensional mobility of the vessel, how fluids such as water navigate across the hulls is profoundly important in both dynamic and static states. Having a hydrodynamic hull form is crucial to the overall performance of the UUV. The traditional UUV hull form is ellipsoid shaped to support the compression applied when a UUV is submerged. This ellipsoid shape applied to the hull design is also the best hydrodynamic option. The fluid flow across the hull form's surface area is studied in depth by the DON. UUV innovation toward novel hulls is being investigated in support of specialized military missions. As the ellipsoid shape is optimum, sometimes this shape does not encompass specialized payloads. Therefore, improvements are researched to better understand novel hull form design benefits compared to a traditional novel hull form shape of an ellipsoid. Figure 2.2 shows some potential design forms that need further research to understand the benefit and disadvantages to their use.

For UUV operating conditions, the following areas are important for movement: surface conditions, transition condition, and submerged condition [11]. Surface conditions include weather conditions, such as waves, currents, rain, wind, and ice cover, that affect the UUV's ability to conserve on-board power due to the systems providing stability to the vehicle by offsetting surface waves. Within the shallow layer, there can be turbulence produced as a produce of the saltwater and heat from the atmosphere. Transition conditions include the environment of the ocean at the highest level of the water column. This is referenced as the air and sea interference level seen in Figure 2.3. Submerged conditions include the shallow and deep ocean layers. The submerged condition is more complex as internal waves exist within the deep ocean layer. Additionally, the UUV's systems on board must compensate for temperature, salinity, and density changes. All on-board systems must be able to withstand these environmental considerations for successful mission performance.

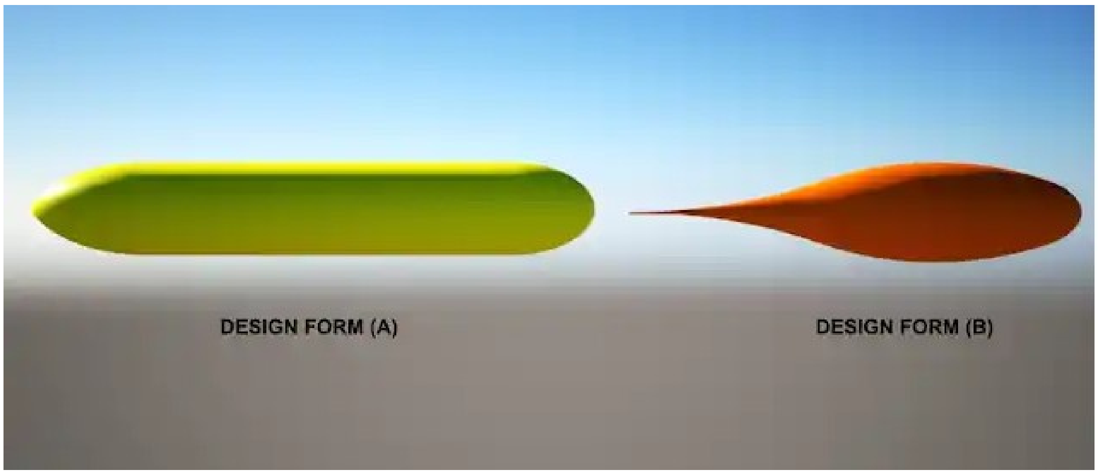

Figure 2.2. Early-Stage Novel Hull Design Forms. Source: [12].

2.1.3 Ballast System

The ballast system operates to obtain neutral buoyancy. Fixed weights attach to the hull to manipulate the buoyancy based on operational need. The addition of weight to a hull section from a new system component will require adding weight on another section to maintain longitudinal balancing. This weight balancing across the hull is important for stability. Variable ballast is available on board the UUV and is used to ascend, descend, or replace deployed payloads while in transit. Temporary emergency weights are considered part of the fixed weight calculations. If there is a system failure emergency, such as loss of thrust or hardware issues, weights are dropped in support of rapid ascent [3].

2.1.4 Power and Energy

Power and energy define how fast and how far the UUV can ultimately travel. There is an increasing desire for a UUV to be faster, travel farther, carry more sensor equipment, and be able to process incoming data at a faster rate. To accomplish the desired improvements, high efficiency batteries are in demand given the limited amount of space within the hull [3]. Batteries used to support long-range missions are large in size and are a heavy component on board the UUV that contributes to weight and balancing challenges.

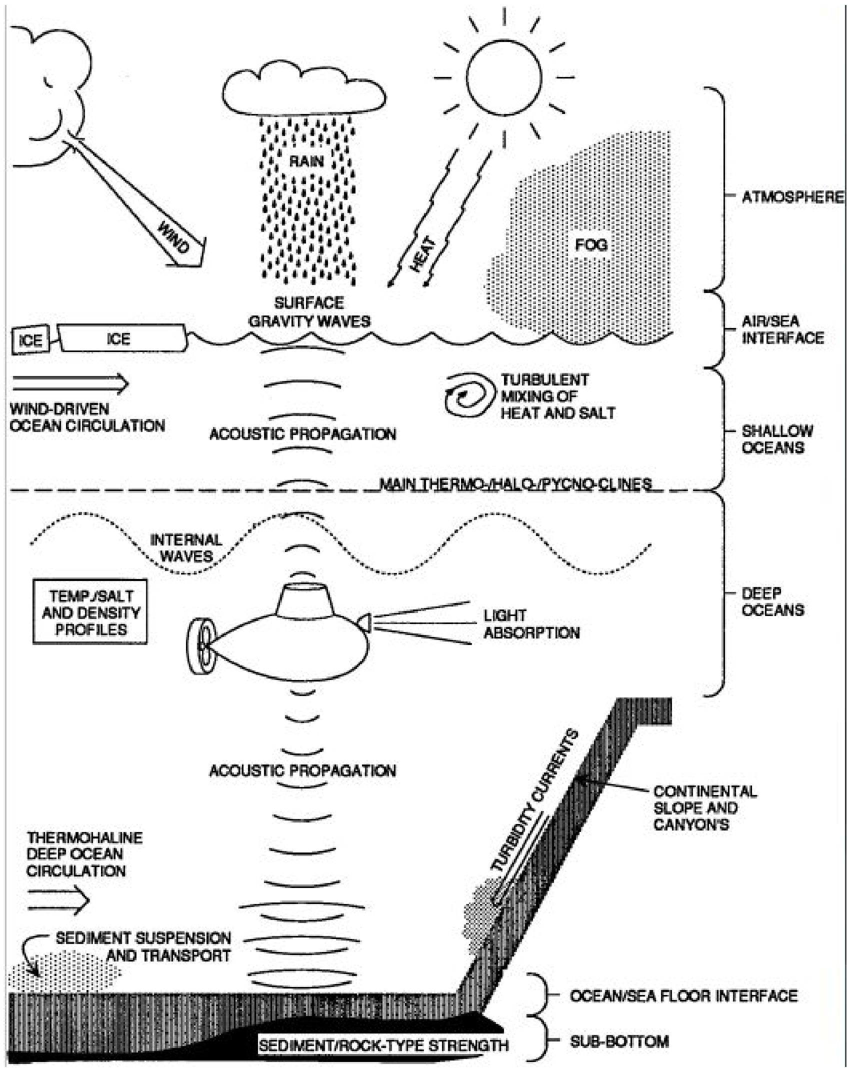

Figure 2.3. Marine Layers Affecting UUVs. Source: [11].

2.1.5 Electrical Distribution

Electrical power distribution uses an electrical bus system to ensure that there is a uniform battery drain from all the systems drawing power, and to handle any ground faults within the system [3]. As a UUV is submerged, the electric bus also ensures no power shortages occur within the hull. Power from the battery bank on board is relayed amongst subsystems that are connected to the interface box. When these components require power, the electrical bus aids in power distribution. These subsystems include the command and control center amongst other electrical-mechanical components.

2.1.6 Propulsion

The propulsion system is primarily made up of brushless motors. This is innovative technology when compared to the brushed motors of the past. There are many advantages to using brushless motors over brushed motors. These advantages include but are not limited to: 1. easier to cool the brushless motor with the use of seawater, 2. with a better cooling method, the brushless motor operated at a higher power level compared to a similar brushed motor, 3. reduced maintenance due to limited pathways to short circuit the motor during use, and 4. reduced electrical noise within the UUV. As the propulsion system transforms to a stronger design to deliver more thrust to the UUV, the strain on the power and energy described above will increase proportionally [3].

2.1.7 Navigation

Navigation utilizes an internal Global Positioning System (GPS) to identify a real time location of the surfaced UUV. While a UUV is submerged, signals are delayed due to the depth and connectivity to the satellite. UUVs use systems similar to the Doppler Velocity Log to delineate position and rate of travel. The Doppler Velocity Log uses sound to measure velocity relative to the sea bottom or sea track and maintains near accuracy to GPS readings for distance traveled. In the case of jamming or trying to maintain stealth status, the use of bottom-terrain mapping has been previously demonstrated to be accurate. The information that is required to make an accurate bottom-terrain mapping is gathered during the OO mission discussed in Section 2.4.5 [3].

2.1.8 Obstacle Avoidance

Obstacle avoidance is both an active and passive method used to prevent damage to the UUV. Active methods include the use of sonar, where a single beam sounder can identify an object's path or a multi-beam can detect, track, and identify an unknown object. Passive methods include additions to prevent the propeller from seizing due to fishing nets or other flora and fauna obstructions. A collaboration between the detection system and the maneuvering system prevents damage to the UUV and finds alternative routes when the path forward is blocked [3].

2.1.9 Mast

The mast is used to support electromagnetic sensors, and communication and navigational antennas. Depending on the platform of opportunity used to launch and recover the UUV, the mast can become an obstacle to deployment from the host platform into the marine environment. An example of this situation is when a UUV is deployed or recovered through a submarine torpedo tube.

At the surface, the UUV may experience large roll motions that affect the optical sensors that are located at the top of the mast. The mast is considered outside of the pressure hull, therefore the sensors contained within the mast must be protected from the ambient pressure of the water [3]. These communication interfaces include satellites, which can include other data interface points such as other UUVs or surface ships. The mast allows the UUV to both upload and download data. This data transmission is either continuous, on-demand, or at scheduled intervals. This data includes GPS strings for the real-time location of the UUV. The GPS assists in keeping the UUV on the prescribed course of the mission. The GPS location also supports host vessel correspondence for pick up. Other data that is sent along this communication link includes any data the UUV collects, such as digital recordings, sample measurements collected, and any other specific data collected.

2.1.10 Maneuvering and Control

Maneuvering and control for the UUV is accomplished through managing the control planes or multiple thrusters. If a mission requires the action of hovering, the UUV will travel against the marine current to remain in a hovering position. An alternative approach to hovering can be performed by the UUV's use of multiple thrusters to maintain position. Complex systems are in development to maintain maneuverability capabilities in an emergency event of lost or jammed controlled surfaces [3]. If the UUV is using thrusters to turn, this action can lead to instability from the thrusters rotating about the keel and thus corrective action would be needed to maintain position stability.

2.1.11 Communication

Communication of the UUV to the host platform is necessary to maintain mission effectiveness. This communication starts the mission or relays data that has been collected. Acoustic communication methods exist for transmission however they have low rates of data transfer and drain power very quickly. The communication link may need to be enhanced by nodes to assist with data transfer while submerged. The mast height can affect the range at which communication can be transferred. UUVs operate in stealth, to avoid detection, a design trade off between the height of the mast and range of communication ensures optimization of communication efforts while remaining in stealth [3].

2.1.12 Auxiliary Systems

The locator and emergency equipment onboard the UUV will be used when the mission is completed or there is retrieval failure due to adverse environmental conditions. The position of the UUV is transmitted by GPS via a broadcast signal. As a host platform approaches for recovery of the system, strobing lights and intervolved pings assist recovery operations [3]. Figure 2.4 illustrates some of the subsystems on board a general UUV.

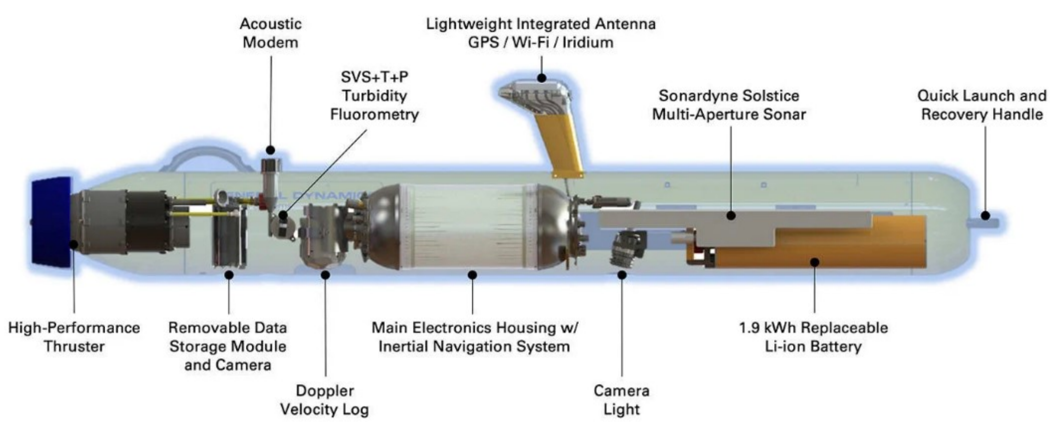

Figure 2.4. UUV Subsystems. Source: [13].

2.2 Unmanned Underwater Vehicle Use

Although UUVs vary widely, it is important to understand that all UUVs share common design elements. Currently in practice, UUVs are designed, developed, and built independently of each other. UUVs are created out of the following components: hull structure, propulsion plant, electrical plant, command/surveillance, auxiliary systems, outfit, and furnishings. Additionally, UUVs fulfilling certain military missions can contain armament [11]. If there was collaboration to optimize UUV on board systems, an ROI for savings across designs could be developed. Analyzing the resulting ROI can tell whether the collaboration is advantageous.

Collaboration on UUV design needs to begin at the conceptual and preliminary design stages. The concept design phase supports the study of multiple early design choices that would fulfill the mission and the mission requirements. Once the conceptual design phase ends, a selection of the best-fit design choice is made. This design choice then moves into the preliminary design phase. The preliminary design phase continues the design development into more of the advanced design phase. If known areas of high ROI are identified between the nine main missions UUVs support, this information can be used in the conceptual and preliminary design stages. This known and shared knowledge helps accelerate the design phase by utilizing previous design information. UUV operational procedure requirements and the mission system design aspects vary widely due to the varying practices of naval architects supporting submersible design and the extent of intricacy of the UUV design [11].

As UUVs are small naval assets, they can be transported to a desired location before deployment. This lifts many limitations on where geographically UUVs can conduct their respective missions. UUV marine environments include water environments defined as shallow ocean, deep ocean, and the atmosphere above the water's surface known as the air/sea interface [11]. UUV missions take place in all marine environments regardless of the water environment being freshwater, brackish, or saltwater. These marine environments include all coastlines, lakes, shallow oceans, deep oceans, and shallow water areas. The unique ability to operate in a multitude of environments and water depths support UUV versatility and uniqueness to the USN and DOD.

UUVs perform different mission types. These vehicles are primarily used in missions to replace humans. In utilizing a UUV vice a human, the mission can be carried out more efficiently, and without risk to human safety [3]. With technology advancements focused on communication robustness, increased range due to battery life on board, and the eliminated risk loss of human life, UUVs are critical to aiding the warfighter, and are considered expendable if the need arises [2]. Figure 2.5 illustrates typical steps the UUV must take to complete a mission.

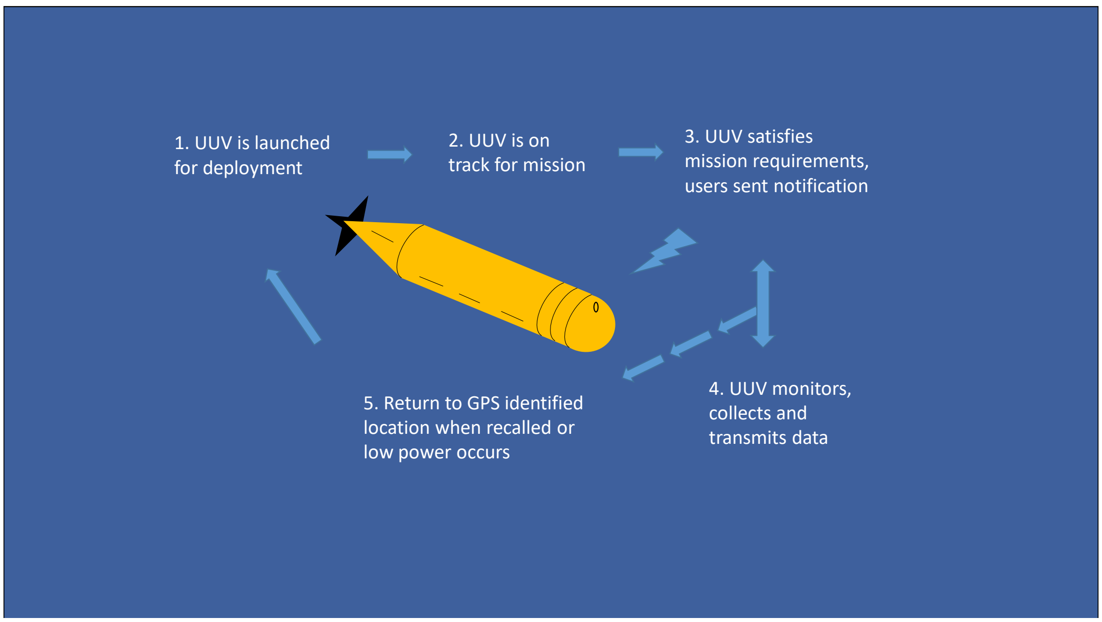

Figure 2.5. Basic UUV Mission Actions

2.3 Model-Based Systems Engineering

Model-Based Systems Engineering (MBSE) is a practice in which SE elements are modeled in a digital domain [14]. MBSE workspaces are supportive of creating a multitude of real-time diagrams dependent upon the engineer's needs. Multiple modeling software programs exist; for this analysis Innoslate [15] was the software of choice. Developers use the graphical user interface of Innoslate to create a workspace to develop their model diagrams.

When developing models with Innoslate, a typical activity diagram consists of branches (also known as actors), activities performed by those actors, and necessary inputs and associated outputs to move from one activity to the next. Innoslate is a flexible modeling platform that allows users to modify activities, inputs and outputs, actors, and requirements at any time. Activities performed by the actors can be assigned resources and time duration models for completion. Those two capabilities will not be used during this UUV mission analysis, but can prove useful in other SE efforts.

Utilizing linking capabilities, Innoslate has the power to generate interface and requirement diagrams from developed activity models. Once a design space is developed, different view graphs of diagrams within the software tool can be called upon within the design space. The MBSE software tool affords the ability to generate and open a digital display of the requested diagrams within the workspace. Innoslate allows for both the import of organized data and newly assembled database creations within the design spaces to be called upon when software users select a desired diagram.

This research has been focused on developing MBSE diagrams of nine mission profiles that will be explained in Section 2.4. These diagrams were developed within Innoslate, the main diagrams produced include activity, requirement, and interface diagrams. Innoslate is a powerful MBSE tool engineers can utilize in a digital modeling environment. These diagrams are discussed below in greater detail.

Activity diagrams are representative of each UUV platform's start to finish workflow. This workflow path illustrates actions, loops, decision making, and trigger-events. These diagrams allow for a validation of the life cycle of the system.

Interface diagrams are representative of the input and outputs between each of the systems and subsystems onboard UUVs. This architecture maps directional signals representative of incoming and outgoing interactions that follow the plausible operation of events. The diagrams will display the coordination between the UUV, host, and other components related to the mission.

Requirement diagrams illustrate the requirement dependencies by representing the dependencies in detail such as their name and description with additional details of support identified within child levels. These diagrams illustrate the relation of requirements for each of the nine missions.

SE represents an incredibly involved process for system alignment where multiple checks are performed between corresponding systems. These corresponding systems interact at various times throughout a mission and require communication, connectivity, and power. MBSE tools like Innoslate offer a digital design space to model and map out requirements. The digital design space allows for logical inquiry of checks and balances by the design engineer. In addition, last minute redesigning of systems, interfaces, and requirements can be easily updated prior to the manufacturing phase. This organization of data by MBSE is illustrated in Figure 2.6.

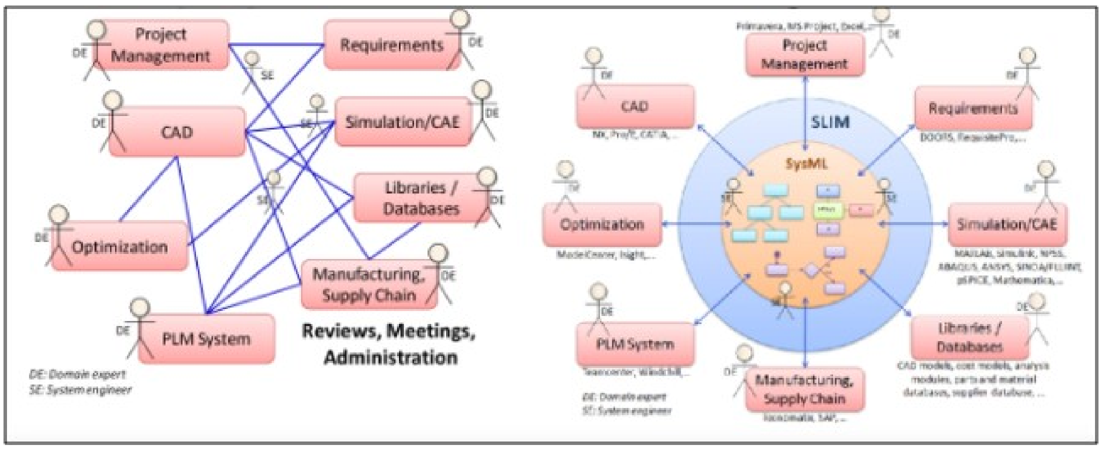

Figure 2.6. Regular Design versus MBSE Design. Source: [16].

The advancement of using MBSE for digital modeling and modeling simulations affords engineers and the software user a behind the scenes preview of how that current state digital MBSE design would be executed. The ability within Innoslate to organize hierarchy and ontology within each database allows for cross-system coordination and requirement checks to be performed within. This digital insight provided by MBSE within Innoslate provides advanced insight on system relations and requirements, and permits the ability to update changes in real-time models to assist with prompt decision making.

2.4 Typical Unmanned Underwater Vehicle Missions

This section discusses in detail the nine typical UUV missions outlined in [3]. These missions and CONOPS detailed in [3] are the fundamental data used in this thesis.

2.4.1 Intelligence, Surveillance, and Reconnaissance

Intelligence, Surveillance, and Reconnaissance (ISR) has the objective of allowing the host to gain access to inaccessible bodies of water through sensors. The objective can be accomplished using intelligence collection, chemical detection, and monitoring of harbors or waterways above and below the water. The intelligence collection is accomplished by gathering signals, measurements, and imaging of the area to know when the surroundings change. Chemical detection is defined by not just observing the chemicals but also the biological readings, nuclear/radiological readings, and if there are any explosives in the area. All the mission objectives are accomplished by either leaving sensors deployed in the area continually reporting data or by a sensor array that is attached to the UUV. A SWARM configuration is needed to succeed in such a broad range of objectives.

The CONOPS for this mission is as follows: the UUV is launched from a platform of opportunity, travel to the desired location, gathers data to fulfill objectives over a prescribed period while avoiding threats, transmit the gathered data to the host, and lastly travel back to the host. The platforms of opportunity are submarines, surface ships, aircraft, or shore facilities. As the UUV is collecting data at the designated location, the UUV will adjust the hovering position to avoid threats or to extract additional information that the current position cannot observe.

The transmission of data can occur in real time or semi-real time if the operational environment allows the signal to be sent to relay stations. If the operational environment does not allow for the use of relay stations, then the UUV will store the data and deliver it when returned to base. To complete an extended mission, the power supply will introduce the greatest hurdle to overcome, as the draw on power is not only by the sensors but also the maneuvering of the UUV [3]. Throughout this mission, the UUV is extracting information for the host that is away from the area of interest. While actively surveilling marine bodies of water, interesting obstacles can be documented and results can be analyzed for level of threat.

2.4.2 Mine Countermeasures

Mine Countermeasures (MCM) have the objective of creating safe travel routes and operational areas. This is accomplished by reconnaissance of the area of interest, destroying or relocating the mines, and rendering mines inoperable by effecting the signal produced in the mine. When reconnaissance of an area is to occur, the UUV will detect mines within the area and characterize the detected mines. The characterization of the mine would include the classification and identity methods for removal. When performing the detection of the mines, it was analyzed that the sensors with a short-range detection in a clustered environment are preferred.

Within the mission profile of MCM there are three fundamental tasks to focus on when accomplishing the mission, they are very-shallow-water, surface, and explosive ordinance disposal. Typically, the UUV that is designated as MCM has close relations to the ISR vessel, relying on the data provided. The information that can be obtained by the ISR mission can inform whether a mine has moved, or whether mines have been laid recently. Another mission that can assist with identifying mineable areas is the OO mission. The details of the OO operations are discussed in Section 2.4.5.

The CONOPS, Figure 2.7, for this mission are simplified to the operations of destroying, neutralizing, spoofing, and jamming signals. Figure 2.8 illustrates the diverse types of mines and depths of operations that are enveloped by this mission to secure safe travels, and therefore, how important the adaptability of the UUV is to successful mission completion. To start the CONOPS, the UUV will be deployed from the platform of opportunity to travel to the operating area to begin searching for mines. As the UUV explores the area, priority between the different sensors on board will constantly shift so all range circumstances are covered. After performing the operation, the UUV will return to the host to relay information and repair the system [3]. This mission profile has a high chance for the UUV to be destroyed due to the proximity to the mine when neutralization actions occur.

Figure 2.7. MCM Mission CONOPS. Source: [2].

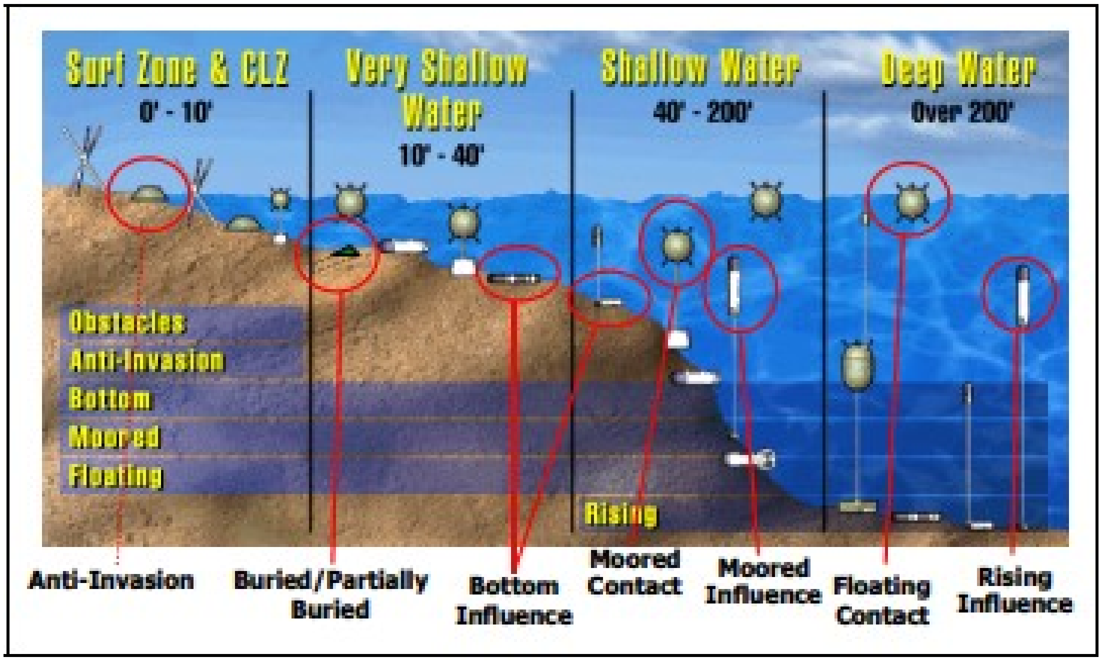

Figure 2.8. MCM Battlespace. Source: [2].

2.4.3 Anti-Submarine Warfare

Non-weapon engagement interactions with submarines is the objective of the Anti-Submarine Warfare (ASW) mission. The goal of this mission profile is to adhere to rules of engagement and strive to not escalate the encounter. The CONOPS for this mission, Figure 2.9, is monitoring harbors for all submarine travel activity, participating as a defense within a strike group, and clearing and maintaining travel lanes. The "hold at risk" are regions in which all submarines transiting a choke point or port will be monitored. The assumption is that the enemy submarines in the area are known, however the exact sailing occurrence is unknown. Other factors that are considered unknown are the dive location and route taken. Information on the area may be restricted due to adversary presence in the region, therefore the UUV may be required to transit great distances in order to observe the choke point/harbor. The ASW under this task starts once an adversarial submarine is detected, in which the UUV, while in pursuit, must relay identification, provide updates, and avoid counter-detection. When a submarine is within this area of interest, a UUV will investigate findings to classify the potential threat. Once the threat is identified the UUV may tail the submarine before returning to the host.

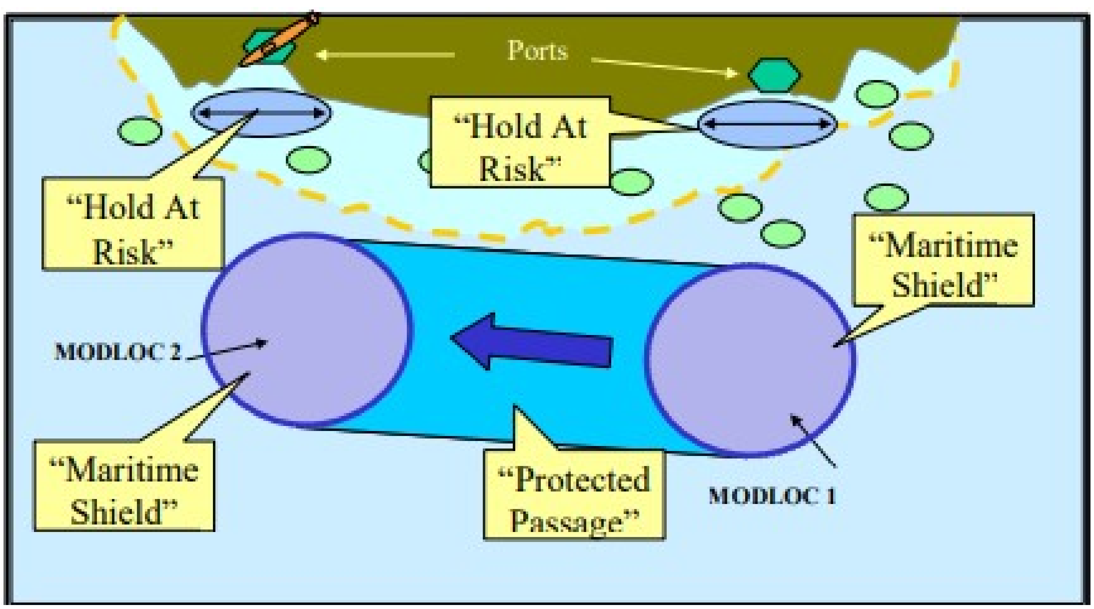

Figure 2.9. ASW Mission CONOPS. Source: [2].

The “protected passage” is similar to the maritime shield, however while the shield is stationary, the passage is during the transit from one location to another. The high value targets will be protected during transit from maximum torpedo range distance. It is important to recall that there is a challenge to maintaining a reasonable false alarm rate, with limited sensors and processing capability. Propulsion issues will become prevalent within this mission when requiring pursuit of submarines [3]. The effort completed within this mission will protect friendly entities from traveling enemies with desires to cause harm to life or property. While exploring marine travel lanes, the UUV will actively investigate for dangerous or suspicious objects to remove from the area, so the travel lanes are clear to support traffic.

2.4.4 Inspection and Identification

Inspection and Identification (INID) has the objective to inspect ship hulls at port for foreign objects to support homeland defense and anti-terrorism actions. Other options include inspecting the hull for survey and repair. The CONOPS for this mission is primarily completed by divers. First the ship is secured before operations can begin, with the included necessity of the assembly of the dive team and coordination with other passing vessels. These actions take a considerable amount of time to assemble and complete. While divers are in the water, there are several hazards that exist, such as poor visibility, disorientation, line entanglement, confined spaces, or unsafe conditions [3]. Using UUVs in place of the human divers provides substantial risk avoidance.

The procedure for UUVs is similar to the process of human divers, such as starting with securing the ship. Then the UUV travels the entire submerged surface of the vessel to systematically gather data to identify abnormalities. The result can be relayed in real-time to the host for review. Figure 2.10 shows an underwater view of a ship’s hull being inspected. The use of UUVs has been a successful replacement of divers in the water to save time and reduce the risk to personnel [3].

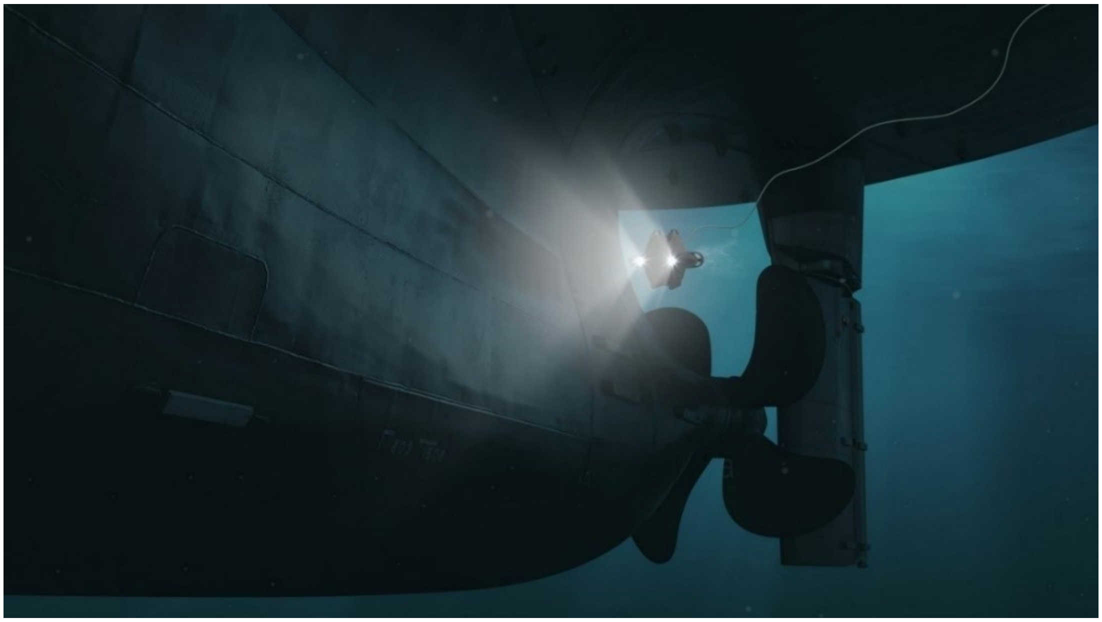

Figure 2.10. Illustration of a UUV Inspecting a Ship's Hull. Source: [17].

2.4.5 Oceanography

Oceanography (OO) has the objective to gather near-shore, or shallow water data collected from imaging, water characteristics, and bathymetry sensors. Imaging sensors include bottom mapping, acoustic imaging, optical imaging, and sub-bottom profiling. Water characteristics include open-current profiles, temperature profiles, salinity profiles, water clarity, and bioluminescence. The missions of MCM and OO overlap. The CONOPS (Figure 2.11) for this mission is piecewise into whether the objective is time-sensitive or not. The non-time-sensitive operations are bottom mapping, sub-bottom profiling, and open-current profiling [3]. The data gathered can be used to update charts and data tables for future analysis. The records gathered can be used to examine changes/shifts in the region over time.

2.4.6 Communication or Navigation Network Node

Communication or Navigation Network Node (CN3) has the objective of acting as communication functions or navigational functions. The communication functions are to act as a node to assist with relaying information to the next recipient, providing an underwater connection to communications, and placing antennas on the surface to assist with relaying information. The navigational functions are to deploy transponders that act as guidance buoys, place surface waypoints to guide submerged vehicles to a destination, and act as forward markers for visual guidance to reference locations. UUVs can provide on-the-spot communication and navigation for the host platform, when they are leading ASW and MCM missions. The positioned UUVs act as navigational beacons for other vessels in the area. Potential future applications could be a GPS navigational system similar to satellite for undersea purposes [3].

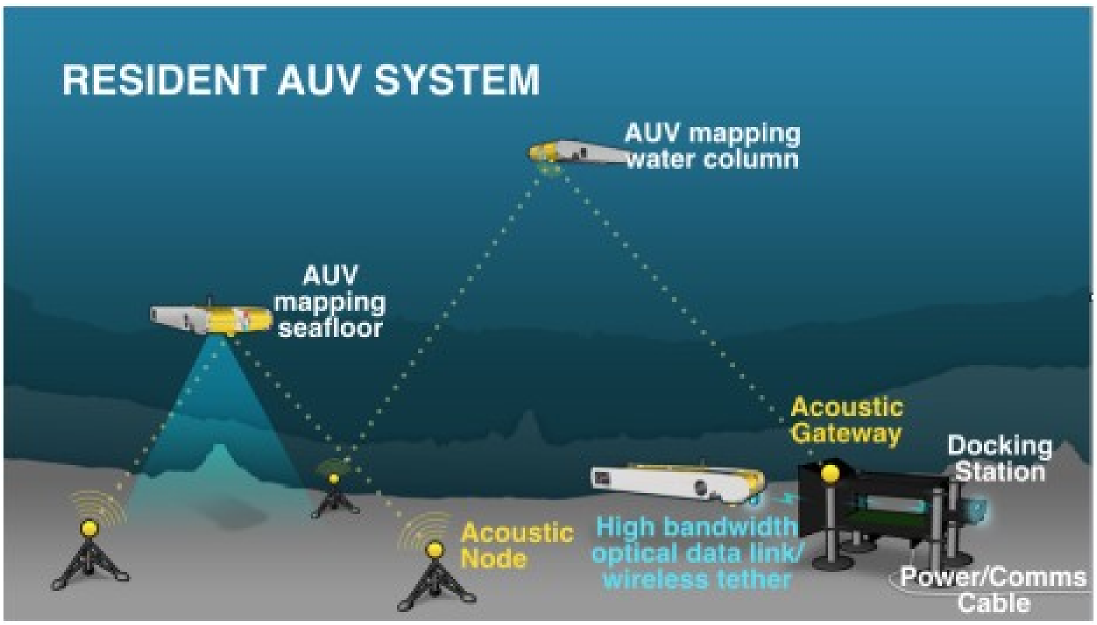

Figure 2.11. OO Mission CONOPS. Source: [18].

The CONOPS for this mission is to support pre-deployed communication nodes or forward deploy vessels that will be traveling in the area after the UUV has arrived. In general, to participate in this mission the UUV needs exposure of the mast to be prevalent, which disrupts the integrity of the UUV's stealth. In addition, as more signals are produced at longer ranges, for both navigational and communicative purposes, the drain on the power supply will increase drastically [3]. As transmission between the surface and submerged entities is difficult, the communication mission will assist with relaying information to other submerged entities. Figure 2.12 illustrates a submerged UUV communicating with a buoy that is relaying the signal to a satellite.

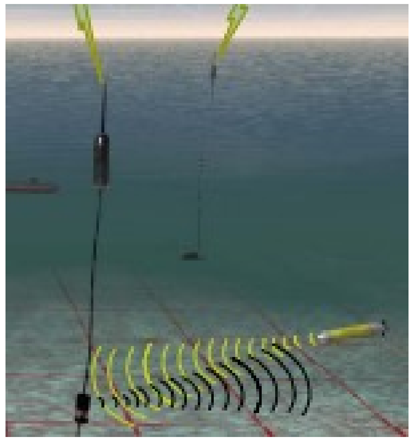

Figure 2.12. Illustration of Submerged UUV Communication. Source: [2].

2.4.7 Payload Delivery

Payload Delivery (PD) has the objective of providing supplies without exposing high-value platforms. Potential delivery operations include supplies to pre-positioned locations to support missions, sensors for other mission types mentioned above, or providing ordnance for personnel in forward deployed locations. The CONOPS will require the UUV to be of a larger variety [3]. Each of the CONOPS threads are expanded as follows.

The positioning supplies are for units that cannot carry their supplies to the mission location. Some of the supplies that are delivered include but are not limited to food, batteries, fuel, and weapons. The payload is placed in locations that prevent intentional or unintentional discovery by adversaries to allow for friendly units to recover and use, shown in Figure 2.13. The premise of this mission is to be dependable and reliable for the delivery of the payload. Delivery of payloads can be completed either before the mission is to occur or while the mission is in progress [3].

Figure 2.13. UUV Payload Delivery Illustration. Source: [2].

The deploying of sensors is to support the mission profile of the OO UUV. The payload is the drifting or stationary equipment that does not need to be attached to the UUV such as buoys that can drift through the ocean while collecting data or bottom mounted sensors for prolonged exposure analysis. Auxiliary equipment needed to gather data and relay information fall in this category, such as mini gliders, that are deployed and retrieved by the UUV to collect data of large areas in a short amount of time. The payload mission can assist the MCM UUV by placing devices in forward areas to detect the surroundings. The devices that the UUV could deploy include a SWARM of smaller UUVs to accomplish MCM tasking elements. Providing ordnance is primarily covered by the other operations mentioned above as they are supplies to provide as packs have limited space, or charges are already spent during continued operations [3].

2.4.8 Information Operations

Information Operations (IO) has the objective of blocking/introducing false communications and being able to produce a signature to have the UUV act as a bigger threat. Jamming or introducing false information can degrade networks by preventing actions that other platforms are not able to accomplish. When acting as a submarine decoy the plan is for the UUV to make adversaries hesitant of action for fear that the threat is real. As the UUVs act as decoys, the adversaries must deplete their ASW resources, which in turn creates an opening for friendlies. The CONOPS for this mission has two phases to accomplish the objective. The first is the interference of communication by blocking or injection false information in an area that is not easily accessible by others. This can be accomplished by electrical signals for blocking communications, and a strong signal is needed to inject information.

The second method for signature manipulation is through purposeful movements and pathing to attract attention. As the UUV is being pursued, evasive action may need to be taken to lose the adversary, however once the evasion is no longer necessary the UUV can return to being a decoy. Through signature manipulation, the enemy sensors will display readings of different entities to induce reactions from enemies in the area Figure 2.14 displays the difference between what the sensors are showing versus what the actual object is [3].

Figure 2.14. UUV Signature Spoofing. Source: [2].

2.4.9 Time Critical Strike

Time Critical Strike (TCS) has the objective of moving the initiation of fire orders closer to enemy targets and away from platforms through a sensor to target approach reducing the visibility of host platforms. The CONOPS for this mission is to have a reduced reaction time for offensive action. The weapon can be held in either the UUV or a deployable system that is dropped by the UUV. Before the operation, the UUV needs to move to the desired location to launch toward the desired target. Once the UUV has arrived at the location, the UUV will rest at the bottom of the ocean to await command to arrive from the host to launch the ordnance toward the target. Alternatively, instead of resting on the bottom of the ocean, the UUV can hover to maintain location and depth to result in a launch when a command is received. After firing the ordnance, the UUV can then return to the host to resupply [3].

Another operation that can fulfill this mission that does not require the UUV to launch the ordnance is to taxi an independent launch platform to the desired location to target an adversary at a later command. After deploying the taxied independent launch platform, the UUV will return to host immediately after placing the current payload. To complete this mission, the launch command would be sent to the launch platform instead of the UUV [3].

2.5 Systems Engineering Levels of Requirements

Multiple levels exist when defining SE requirements. According to Cockburn's Use Case Hierarchy, requirement definition occurs at four levels: sky, kite, sea, and underwater that are consistent with top, mid, low, and component level requirements respectively [9]. When performing COSYSMO analysis, accurate LOE estimates for SE effort come from counting "sea level" requirements [9]. The number of defined requirements increases when moving down the requirement hierarchy. For example, if the ratio from one level to the next is 10:1, every top level requirement decomposes into ten requirements at the next level and so on. Moving up the hierarchy represents answering the "why," while drilling down to the lower level requirements represents answering the "how," and thus require increasing detail [9].

2.6 Return on Investment

Return on Investment (ROI) examines the initial upfront cost for UUV products compared to the long-term gain. This comparison allows for an indication of the actual ROI. In practice, ROI is ideally as high as possible; this would indicate the initial UUV purchase was a favorable investment and gains from its use are witnessed. The research performed in this thesis is to identify reuse of SE artifacts across the UUV missions to determine the total ROI by SE artifact reuse.

COSYSMO will allow for an ROI to be calculated without knowing the physical cost of components. The analysis of each mission CONOPS identifies the required systems on board the UUV. This identification allows a reuse weight to be assigned, defined, and used in COSYSMO 2.0 calculations towards the determination of the ROI.

2.7 Summary

In support of the enthusiasm towards understanding UUV system reuse towards cost reduction and with UUV interests expanding, the nine common missions will be explored, researched, and scrutinized to identify the reuse of SE artifacts to discover ROIs. This detailed analysis supports the breakdown by developing MBSE activity, interface, and requirement diagrams to determine the areas of interest. Reuse weights assigned will later be utilized within COSYSMO to aid in the ROI calculation without knowing the physical cost of components. Future UUV platforms will benefit from reuse and optimization allowing savings to be passed along to the DOD.

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CHAPTER 3: Methodology

This chapter focuses on the methodologies used in analyzing the ROI from using a portfolio approach to the UUV mission SE. Data for the ROI calculation was derived using the COSYSMO process outlined in [5] incorporating the reuse extensions described in [4]. The analysis was restricted to evaluating the requirement and interface SE artifacts. SysML was used via Innoslate to define the inputs into COSYSMO by developing different UUV mission system action, interface, and requirement diagrams. UUV mission types selected for this SE ROI calculation were the main nine missions outlined in [3].

The typical missions outlined in [3] are Intelligence, Surveillance, and Reconnaissance (ISR), Mine Countermeasures (MCM), Anti-Submarine Warfare (ASW), Inspection and Identification (INID), Oceanography (OO), Communication or Navigation Network Node (CN3), Payload Delivery (PD), Information Operations (IO), and Time Critical Strike (TCS). COSYSMO processes will highlight SE labor cost savings from using a portfolio approach incorporating SE artifact reuse to the SE process up to the manufacturing phase. One mission is selected as the SE baseline that will be "reused" by the other missions when developed using a portfolio approach. For this analysis, the ISR mission was selected as the baseline for the SE artifacts. The overall process flow for the UUV SE portfolio ROI analysis is shown in Figure 3.1.

3.1 Mission Definition

The missions for the SE ROI analysis were developed from those described in [3]. A detailed discussion of theses missions is in Section 2.4. The following is a brief summary of the nine missions used in the analysis:

ISR UUV transits to a location of interest where it performs general reconnaissance and surveying before returning for recovery.

MCM UUV transits to a location of interest where it performs general mine sweeping and clearing activities before returning for recovery.

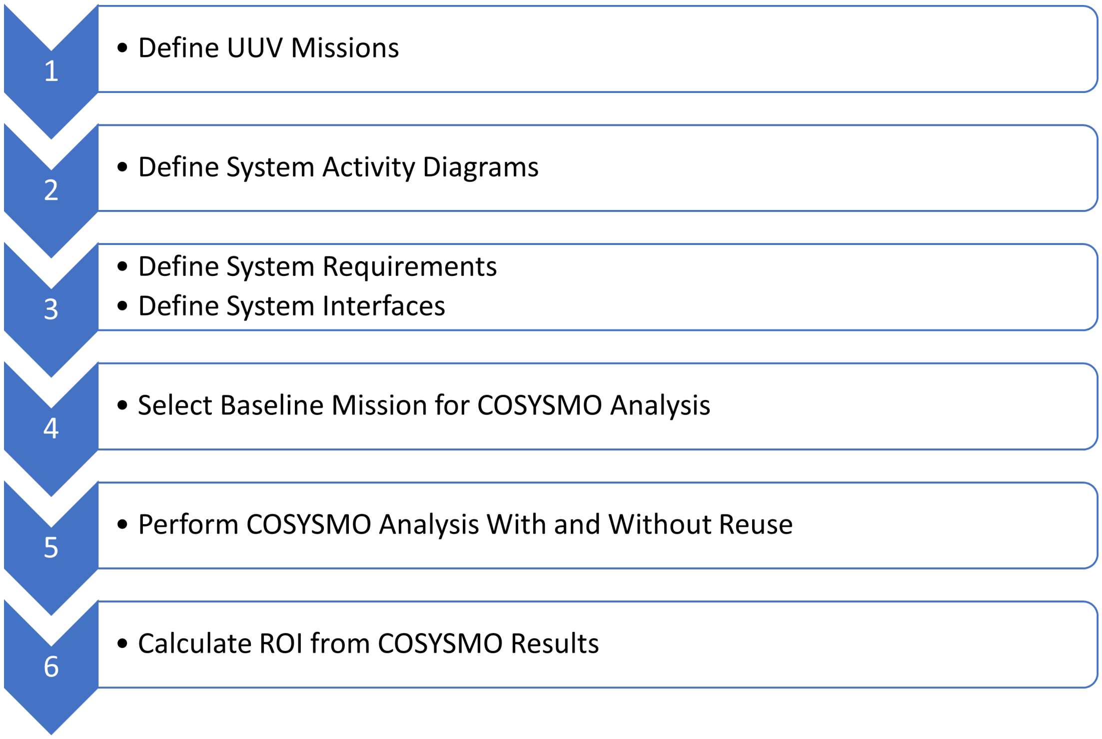


Figure 3.1. Process for Determining ROI

ASW UUV transits to a location of interest where it performs patrol and monitoring operations where it classifies and communicates data on potential submarine activities before returning for recovery.

INID UUV scans the submerged hull of a friendly ship for damage or other irregularities before being recovered.

OO UUV transits to a location of interest where it performs various water column assessments and bottom surveys before returning for recovery.

CN3 UUV transits to a location of interest where it may deploy or act as a relay for communications between surface and subsurface assets, act as surface to subsurface GPS relay, or act as a navigation beacon; before returning for recovery.

PD UUV independently transports and deploys a payload at a location of interest or acts as a supply wagon by following a friendly unit and deploying the payload on command; before the UUV returns for recovery.

IO UUV transits to an area of interest where it performs signal jamming or spoofing to include acting as a decoy for hostile forces after which it returns for recovery if it survives hostile contact.

TCS UUV transports a strike package to a location of interest where it either deploys the package and returns for recovery or loiters in the area until it receives a strike order where it will then launch the package before returning for recovery.

With the different mission types and functionalities defined, the missions are analyzed from a SE viewpoint. Each mission type can be represented by actions (or functions) from which system requirements can be extracted.

3.2 Mission Activity Diagrams

Once the mission CONOPS were fully developed the missions were modeled in SysML using Innoslate beginning with activity diagrams of each of the nine missions. Mission activity diagrams modeled decision nodes and potential actions or functions that can occur depending on the operational scenario. Inputs and outputs between the different activities were defined to flow from one stage to the next. Figure 3.2 shows the overall mission activity diagram for ISR.

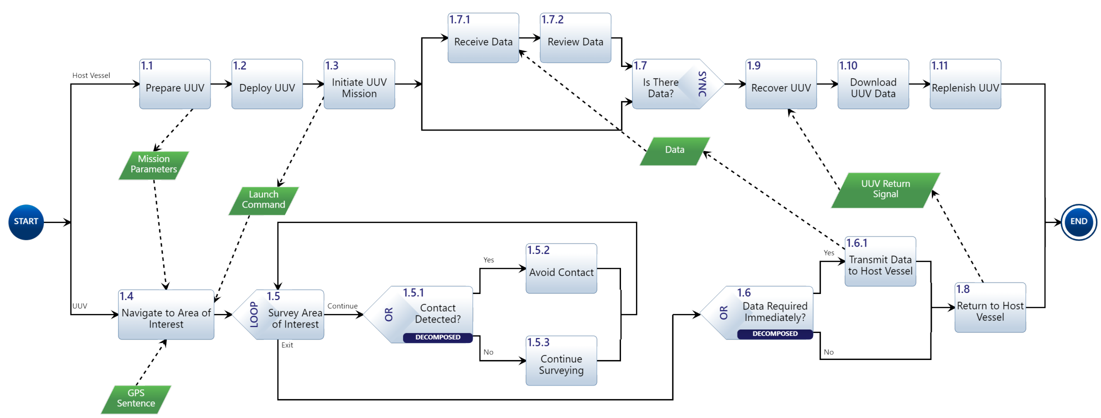


Figure 3.2. ISR Mission Activity Diagram

Figure 3.2 shows the initial inputs required to prepare the UUV (*Mission Requirements* and *Launch Command*) as well the GPS information (*GPS Sentence*) needed during its transit to the mission area. Once the UUV reaches the area of interest it then begins the main mission in the *Survey Area of Interest* activity loop. Within the loop, the UUV's functions are dependent on external actors: If there is a contact the UUV will be required to avoid the contact, otherwise, it continuously surveys as previously programmed. When done surveilling, the data can be transmitted directly to the host vessel, or if the data is not required immediately, the UUV returns to host vessel for recovery and data download. Mission activity diagrams for the remaining eight missions are in Appendix A.1.

Using Innoslate allowed for developing coherent depictions of functional requirements across missions, satisfying DOD Acquisition Framework (DoDAF) System Viewpoints (SVs) 1, 2, and 4 [19]. SV-1 defines system interface description, which for ISR (Figure 3.2) can be seen by the green boxes showing required exchanges between branch actors. The exchanges include directional arrows indicating which actor is generating or consuming the resource, depicting resource flow directionality as defined by SV-2. The activity blocks (white boxes) show the SV-4 system functionality descriptions.

3.3 Mission Requirements Definition

After completing mission activity modeling for each mission, system requirements were derived from functional requirements outlined by the mission activity diagrams. Each of the mission activities was listed and associated system requirements generated to satisfy the necessary functionality. Table 3.1 shows the resulting system requirements needed to satisfy the functions for the ISR mission. Requirement tables for the other eight missions are in Appendix B.

Table 3.1. Resulting System Requirements for ISR

Number	Requirement
R1.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)
R1.0.2	The UUV shall be capable of a top speed of *xx* knots
R1.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*
R1.0.4	The UUV shall avoid detection
R1.1.1	Mission parameters shall be uploadable to the UUV
R1.1.2	The UUV shall receive remote commands
R1.1.3	The UUV shall commence its mission when commanded

Continued on next page.

Continuation of Table 3.1	
Number	Requirement
R1.1.4	The UUV shall be capable of transmitting data in a host ship compatible format
R1.1.5	The UUV shall indicate that it is ready for recovery
R1.2	The UUV shall be deployable from pier or vessel
R1.3.1	The UUV shall know its geographic location
R1.3.2	The UUV shall be capable of open ocean navigation
R1.3.3	The UUV shall be capable of storing waypoints
R1.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of xx size within yy distance
R1.3.5	The UUV shall be capable of tracking its position
R1.3.6	The UUV shall be capable of returning to a position in a search pattern
R1.3.7	The UUV shall return to its point of deployment at mission conclusion
R1.3.8	The UUV shall navigate to a specific location when commanded
R1.4.1	The UUV shall possess acoustic sensors
R1.4.2	The UUV shall discern between an emission and background noise
R1.4.3	The UUV shall track contacts
R1.5	The UUV shall be recoverable from pier or vessel
R1.6	The UUV shall be capable of imaging an area $y'xy'$ in size
R1.7	The UUV shall be capable of collecting environmental data
R1.8	The UUV shall be capable of collecting data nonconsecutively
R1.9	The UUV shall possess a recall mechanism

The number of system requirements is a significant driver of the effort calculated by COSYSMO. However, as implied in Section 1.5, requirements defined in Table 3.1 and Appendix B are above "sea level" and instead fall into the category of "kite level" requirements in Cockburn's use case hierarchy metaphor, as described by Valerdi, which exist between the summary and user requirement levels [9] and cannot be reasonably decomposed further. In his dissertation establishing COSYSMO, Valerdi specifies that "sea level" requirements are required to accurately determine LOEs using COSYSMO [7]. Therefore, as the requirements used in the COSYSMO analysis (Section 3.6) such as those in Table 3.1 are at too high a level of decomposition for accurate COSYSMO LOE calculations, the LOEs presented in this thesis (Chapter 4) do not represent actual effort estimates but proxies for the relative effort analysis. Relative, consistently calculated LOEs are sufficient for ROI analysis. Once the system requirements for each mission activity were defined, the total requirements for each mission was determined. Table 3.2 lists the missions and number of associated requirements.

Table 3.2. Total System Requirements by Mission

Mission	Total Requirements
Intelligence, Surveillance, and Reconnaissance	26
Mine Countermeasures	26
Anti-Submarine Warfare	27
Inspection and Identification	18
Oceanography	24
Communication or Navigation Network Node	25
Payload Delivery	24
Information Operations	22
Time Critical Strike	31

3.3.1 Requirement Decomposition Limitation

As stated previously, the requirements used in the analysis for this thesis were not decomposed to the level required for accurate COSYSMO LOE calculations due to the level of subjectivity it would introduce into the resulting calculation. The following is an illustration of the subjectivity and its resulting impact to the LOE calculations.

The mission descriptions and CONOPS in [3] are devoid of detail and serve only as a high-level summary of the given mission. Focusing on ISR, a few different contexts for mission execution are described, but are generalized insofar as the tactical environment is virtually undefined. Further, both 3,000 (medium class) and 20,000 pound UUV concepts are suggested as mission performers. Finally, a range of autonomy from “self-cued” to “operator-guided” is presented for the executing UUV [3]. This all-encompassing CONOPS results in limited constraints to guide mission decomposition beyond elements that can be drawn directly from the CONOPS. In this thesis, assumptions were established (Section 1.5) to add some specificity to the CONOPS to ensure the mission LOEs could be directly compared; most notably that the missions would be performed by medium class UUVs. However, as the spectrum of missions range from combat in a hostile space (e.g., IO, TCS) to passive in friendly waters (e.g., INID, OO), constraints such as adversary capability and theater cannot be universally applied.

The combination of the generalized CONOPS in [3] and the inability to apply universal constraints, results in further SE artifact decomposition beyond that directly derived from the "sky level" [9] CONOPS being highly subjective. This subjectivity can result in dramatic differences in the resulting decomposition and pursuant COSYSMO analysis. As an example keeping with the ISR mission, examine two possible decompositions of Requirement 1.1.2: *The UUV shall receive remote commands* provided in Tables 3.3 and 3.4. The fist variant is for operations in semi-permissive or otherwise friendly waters where the focus is more on data collection and presence than stealth and the host vessel or other controlling asset can be in the semi-immediate vicinity. The second variant is for operations in hostile waters against a peer adversary where remaining undetected is paramount and the host vessel or control point would be beyond the horizon, at high altitude, in orbit, or operating at depth (in the case of a submarine).

Table 3.3. R1.1.2 Decomposition Variant 1

Number	Requirement	Complexity
R1.1.2.1	The UUV shall receive continuous radio frequency transmitted commands when surfaced	Nominal
R1.1.2.2	The UUV shall receive periodic very low radio frequency transmitted commands with a minimum interval of not more than 30 minutes	Difficult
R1.1.2.3	The UUV shall receive commands with a maximum payload of not less than 10 kilobytes	Nominal
R1.1.2.4	The UUV shall receive commands implementing Unclassified grade encryption	Nominal

Continued on next page.

Continuation of Table 3.3		
Number	Requirement	Complexity
R1.1.2.5	The UUV shall receive continuous acoustically transmitted commands from a maximum range of not less than 1 nautical mile	Nominal

Table 3.4. R1.1.2 Decomposition Variant 2

Number	Requirement	Complexity
R1.1.2.1	The UUV shall receive continuous radio frequency transmitted commands when surfaced	Nominal
R1.1.2.2	The UUV shall receive periodic very low radio frequency transmitted commands with a minimum interval of not more than 30 minutes	Difficult
R1.1.2.3	The UUV shall receive commands with a maximum payload of not less than 10 kilobytes	Nominal
R1.1.2.4	The UUV shall receive commands implementing Top Secret grade encryption	Difficult
R1.1.2.5	The UUV shall receive periodic acoustically transmitted commands with a minimum interval of not more than 30 seconds from a maximum range on not less than 4 nautical miles	Difficult
R1.1.2.6	The UUV shall receive periodic high-bandwidth radio frequency transmitted commands from satellites with a minimum interval of not more than 60 minutes and a maximum payload of not less than 1 gigabyte	Difficult

As a result of the different theaters, the requirement decomposes to variations with different parameters and complexities as well as different numbers of child requirements. The latter variant involves a significantly more complex and challenging environment that results in additional and more challenging requirements. Aside from the raw number of requirements being different, the different complexities result in significantly different COSYSMO results. If the COSYSMO *Complexity Weights* (see Table 3.6) are applied, the two sets of requirements have *Effective Sizes* of 9 and 22 respectively (see Section 3.6). *Effective Size* and COSYSMO calculated LOE have a nearly linear relationship (see Equation (3.1)). While the number of requirements only differs by one, the resulting effort of the latter is twice the former. If a similar disparity were to occur in the decomposition of the remaining requirements in Table 3.1, the resulting calculations would yield dramatically different LOE estimates with both being valid in their context and invalid in the other's while still being a defensible ISR LOEs. Therefore, without having a well-defined, detailed CONOPS, decomposition to the level of Tables 3.3 and 3.4 is unreasonably variant and would result in highly-subjective LOE estimates. While technically inaccurate for COSYSMO LOE estimation, leaving the mission requirements undecomposed results in a more accurate LOE comparison and thus ROI calculation by removing subjectivity from the calculus.

3.4 System Interface Definition

The SysML models were then extended in Innoslate to include interface diagrams. Innoslate generates interface diagrams based on the resource flow between actors. Figure 3.3 is the resulting interface diagram for ISR depicting the required interfaces between actors. Interface diagrams for the remaining eight missions are in Appendix A.2.

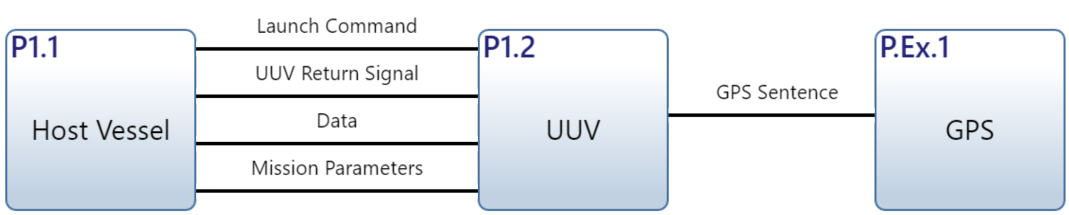


Figure 3.3. ISR Mission Interface Diagram

The number of system interfaces is another significant driver of the effort calculated by COSYSMO, similar to number of requirements. Once the system interfaces for each mission activity were defined, the total interfaces for each mission was determined. Table 3.5 lists the mission and number of associated interfaces.

Table 3.5. Total System Interfaces by Mission

Mission	Total Interfaces
Intelligence, Surveillance, and Reconnaissance	5
Mine Countermeasures	5
Anti-Submarine Warfare	6
Inspection and Identification	3
Oceanography	4
Communication or Navigation Network Node	6
Payload Delivery	10
Information Operations	4
Time Critical Strike	6

With the total number of system requirements and system interfaces per mission now defined, the top level quantity of inputs into the COSYSMO analysis is known. These derived input values are inputs to COSYSMO, with weights applied to each value within an input as shown in Figure 3.4. This diagram also shows inputs that were not taken into consideration and considered out of scope for this thesis.

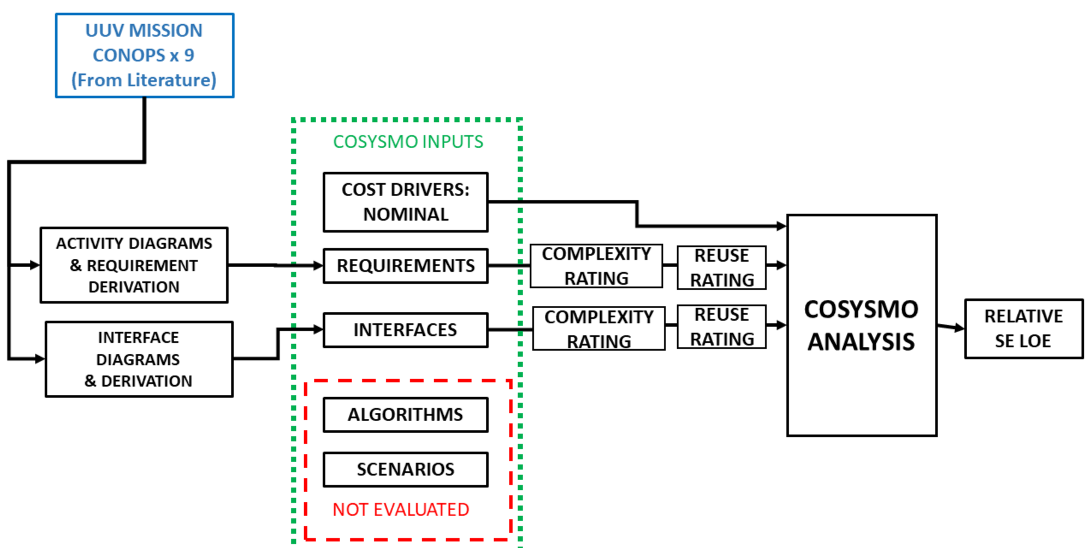


Figure 3.4. Process Used to Complete COSYSMO Analysis

A detailed breakdown of all of the inputs and outputs from the analysis is shown in Figure 3.5. The size element types in this diagram are the interfaces, requirements, scenarios, and algorithms.

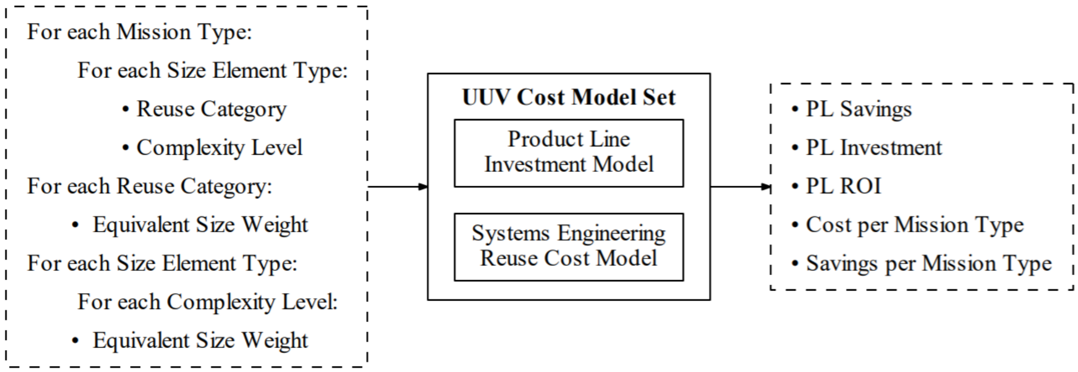


Figure 3.5. Inputs and Outputs for COSYSMO Analysis. Source: [20].

The next section will look at how the baseline mission was determined, and how that is an integral piece for the ROI analysis.

3.5 Baseline Mission Selection for COSYSMO Reuse Analysis

To perform a successful COSYSMO analysis to evaluate the benefit of reusing SE artifacts across missions, a baseline mission must be selected and compared with the other mission to determine the amount of artifact reuse. COSYSMO analysis provides an estimate of effort required for the baseline mission and corresponding effort for other missions when SE artifacts are reused from the baseline mission. The baseline mission was selected based on its overall system similarity to the other missions. ISR was chosen as the baseline mission type for the artifact reuse analysis. ISR requires a UUV to receive a mission, navigate to an area of interest, use different sensors and capabilities to map the area, and return to the host vessel with the stored data. Most missions, with the exception of INID, utilize variants of most (if not all) of the requirements from ISR.

3.6 COSYSMO Analysis

The heart of our ROI research is the COSYSMO analysis of the mission system requirements and interfaces. COSYSMO analysis takes the number of system requirements, interfaces, critical algorithms, and operational scenarios, substitutes into a constructive cost model, and outputs the amount of effort (PM) the SE effort will require [7]. Equation (3.1) is the formula for predicted SE labor in PM leaving the effort multiplier at unity [5].

$$Effort = 0.254 \times (\sum_{k}(\omega_{e,k}\Phi_{e,k} + \omega_{n,k}\Phi_{n,k} + \omega_{d,k}\Phi_{d,k})^{1.06} \quad (3.1)$$

In this equation, variables ω and Φ represent the weight and associated number of size drivers (SE artifacts) with that complexity rating [5]. Table 3.6 lists the size drivers with their complexities and associated weighting factors.

Table 3.6. Weights for COSYSMO Size Drivers. Adapted from [5].

	Easy (ω_e)	Nominal (ω_n)	Difficult (ω_d)
Number of System Requirements	0.5	1.00	5.0
Number of System Interfaces	1.1	2.8	6.3
Number of Critical Algorithms	2.2	4.1	11.5
Number of Operational Scenarios	6.2	14.4	30

Equation (3.1) is the basic equation for COSYSMO SE LOE calculation. For the ROI from SE artifact reuse analysis, the equation is extended to Equation (3.2) with weightings for reuse ω_r [4]. Table 3.7 lists the reuse categories and weights with definitions tailored to our analysis.

$$Effort = 0.254 \times (\sum_{k}(\sum_{r}\omega_r(\omega_{e,k}\Phi_{e,k} + \omega_{n,k}\Phi_{n,k} + \omega_{d,k}\Phi_{d,k}))^{1.06} \quad (3.2)$$

For the UUV mission SE artifact reuse case, the interfaces and requirements for the baseline mission (ISR) were all classified as *Designed for Reuse* with a weighting of 1.38 under the assumption that it would not be known at the time of system development what artifacts a future mission might reuse. The interfaces and requirements for the remaining eight mission were classified as one of the other five reuse categories. The resulting reuse and difficulty classifications for each mission's interfaces are in Appendix C and requirements are in Appendix B. These tables include requirement and interface descriptions, associated complexity and reuse classifications, and the rationale behind the reuse classifications. After tabulating and summarizing the COSYSMO input data (see Section 4.1), the effort for each mission in the independent development and SE artifact reuse cases is calculated.

Table 3.7. Tailored COSYSMO Reuse Categories and Weights. Adapted from [4], [6], [21].

Category	Definition for Requirements	Definition for Interfaces	Weight
New	Similar requirement does not exist in the baseline (completely new)	Similar interface does not exist in the baseline (completely new)	1.00
Designed for Reuse	New requirement and includes extra investment to enable potential reusability	New interface and includes extra investment to enable potential reusability	1.38
Modified	Change to the requirement's MOEs	Interface is tailored to the mission	0.65
Deleted	Similar requirement does not exist in new system	Similar interface does not exist in new system	0.51
Adopted	Change to the requirement's MOPs	Interface is incorporated unmodified with testing	0.43
Managed	Requirement does not change from the baseline	Interface is incorporated unmodified with minimal testing	0.15

3.6.1 COSYSMO Implementation

Equations (3.1) and (3.2) were implemented in a Microsoft Excel (Excel) workbook to calculate the effort required for each mission directly from the tabulated data (see Section 4.1). The Excel implementation of COSYSMO created for this analysis was validated against a different Excel implementation created by Valerdi and extended to perform reuse calculations by Fortune [22]. This "tool" operates in two modes: with (Figure 3.6) and without (Figure 3.7) reuse. The mode of the tool is set through the "Reuse" drop down menu in the top left of the spreadsheet. If "Yes" is selected in the menu, the tool is configured to perform COSYSMO 2 calculations [4], if "No" is selected in the menu, the tool is configured to perform COSYSMO 1 calculations [7].

For the analysis discussed here, only the top portion of the tool is utilized as the lower half modifies the effort multiplier which has been excluded from this analysis and is therefore left at unity. The top portion of the tool uses the number of system requirements, interfaces, algorithms, and operational scenarios at each complexity and reuse category to calculate a final LOE in PM displayed at the bottom right of the tool. A few mission sets in both reuse and independent development cases were entered into the tool; the resulting calculations were compared to the implementation created for this analysis and were found to match exactly.

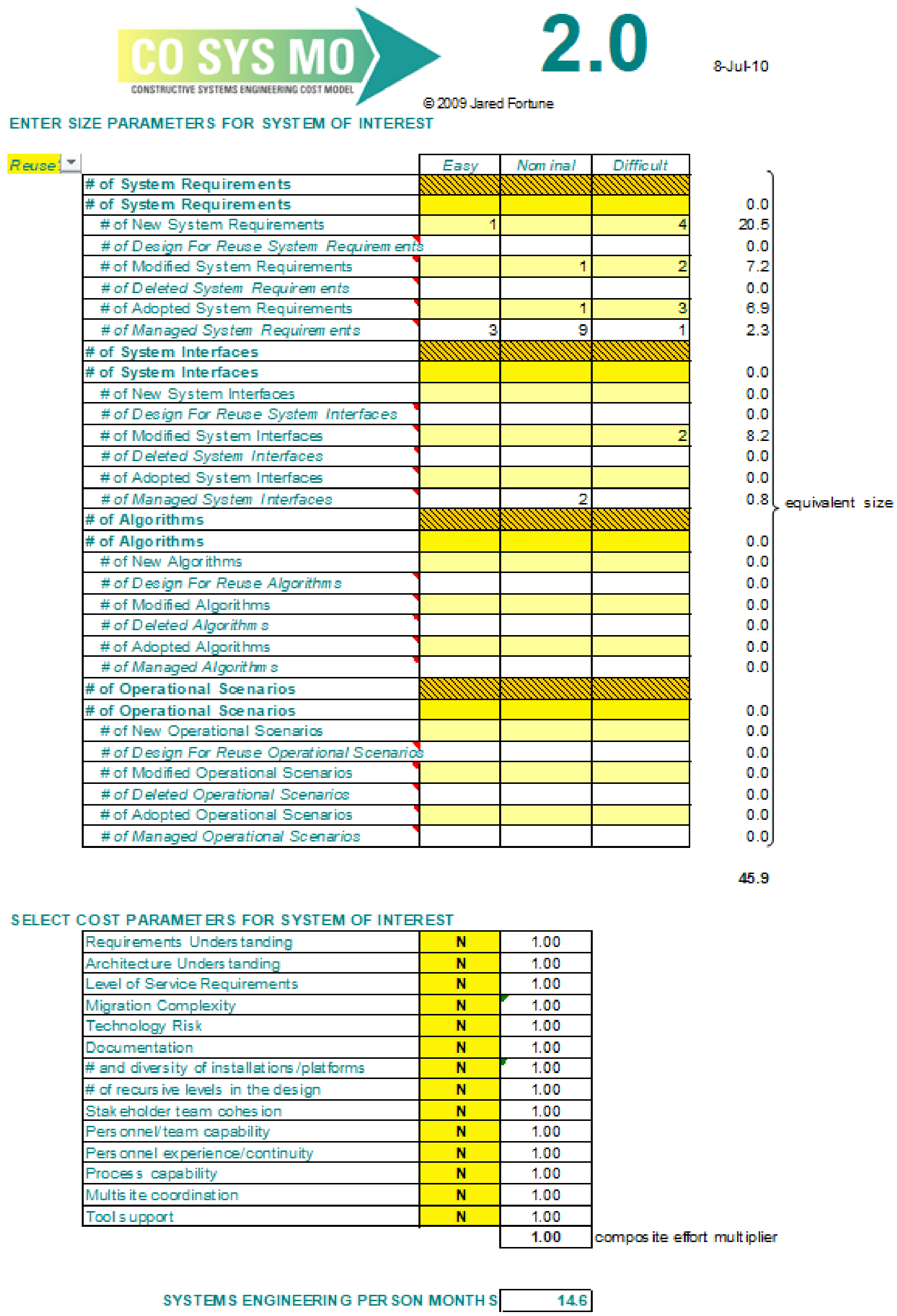
With the LOE for the two SE development cases determined, the analysis moves to calculating the ROI for using a portfolio approach versus independent system development.

3.7 Systems Engineering Return on Investment

According to [23], ROI typically represents how well a company has done, or is doing based on profit calculations. The paper continues to explain that ROI is a basic calculation of net operating income divided by average operating assets. ROI is a way of determining if something is ultimately profitable or a loss.

For the portfolio versus independent development comparison, ROI calculations are used as the metric for determining the cost-benefit of a product line engineering approach. ROI is defined as the net effort savings divided by the product line investment [24]. The "investment" is the extra effort expended to make ISR conducive to reuse (i.e., $\text{ISR}\mathit{DesignedforReuseEffort} - \text{ISR}\mathit{TraditionalEffort}$). The "savings" is the sum of the difference of the traditional and reuse efforts for the remaining set of missions (i.e., $\Sigma(\mathit{TraditionalEffort} - \mathit{ReuseEffort})$). This sum minus the investment into ISR is the net savings shown as the numerator in Equation (3.3). This calculation and interpretation of ROI for SE artifact reuse is consistent with the Constructive Product Line Investment Model (COPLIMO) method for system product line investment modeling of reuse costs and benefits [24].

$$\text{ROI} = \frac{\sum_{i=1}^{8} \mathit{Savings}_i - \text{ISR}\mathit{Investment}}{\text{ISR}\mathit{Investment}} \tag{3.3}$$
$$\text{where } \mathit{Savings}_i = \mathit{TraditionalMissionEffort}_i - \mathit{ReuseMissionEffort}_i$$



COSYSMO 2.0 — CONSTRUCTIVE SYSTEMS ENGINEERING COST MODEL — 8-Jul-10 — © 2009 Jared Fortune

ENTER SIZE PARAMETERS FOR SYSTEM OF INTEREST

Reuse

	Easy	Nominal	Difficult	
# of System Requirements				
# of System Requirements				0.0
# of New System Requirements	1		4	20.5
# of Design For Reuse System Requirements				0.0
# of Modified System Requirements		1	2	7.2
# of Deleted System Requirements				0.0
# of Adopted System Requirements		1	3	6.9
# of Managed System Requirements	3	9	1	2.3
# of System Interfaces				
# of System Interfaces				0.0
# of New System Interfaces				0.0
# of Design For Reuse System Interfaces				0.0
# of Modified System Interfaces			2	8.2
# of Deleted System Interfaces				0.0
# of Adopted System Interfaces				0.0
# of Managed System Interfaces		2		0.8
# of Algorithms				
# of Algorithms				0.0
# of New Algorithms				0.0
# of Design For Reuse Algorithms				0.0
# of Modified Algorithms				0.0
# of Deleted Algorithms				0.0
# of Adopted Algorithms				0.0
# of Managed Algorithms				0.0
# of Operational Scenarios				
# of Operational Scenarios				0.0
# of New Operational Scenarios				0.0
# of Design For Reuse Operational Scenarios				0.0
# of Modified Operational Scenarios				0.0
# of Deleted Operational Scenarios				0.0
# of Adopted Operational Scenarios				0.0
# of Managed Operational Scenarios				0.0

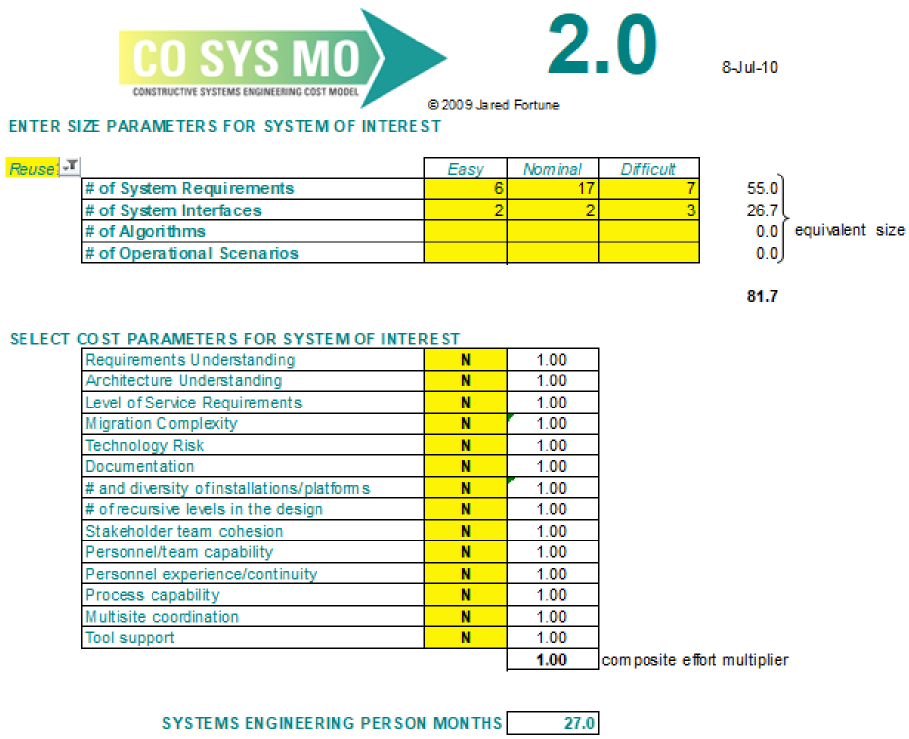
equivalent size: 45.9

SELECT COST PARAMETERS FOR SYSTEM OF INTEREST

Requirements Understanding	N	1.00
Architecture Understanding	N	1.00
Level of Service Requirements	N	1.00
Migration Complexity	N	1.00
Technology Risk	N	1.00
Documentation	N	1.00
# and diversity of installations/platforms	N	1.00
# of recursive levels in the design	N	1.00
Stakeholder team cohesion	N	1.00
Personnel/team capability	N	1.00
Personnel experience/continuity	N	1.00
Process capability	N	1.00
Multisite coordination	N	1.00
Tool support	N	1.00
		1.00 composite effort multiplier

SYSTEMS ENGINEERING PERSON MONTHS 14.6

Figure 3.6. COSYSMO Tool in Reuse Configuration Showing MCM Mission Data. Adapted from [22].



Reuse?	Easy	Nominal	Difficult	
# of System Requirements	6	17	7	55.0
# of System Interfaces	2	2	3	26.7
# of Algorithms				0.0
# of Operational Scenarios				0.0
			equivalent size	81.7

Requirements Understanding	N	1.00
Architecture Understanding	N	1.00
Level of Service Requirements	N	1.00
Migration Complexity	N	1.00
Technology Risk	N	1.00
Documentation	N	1.00
# and diversity of installations/platforms	N	1.00
# of recursive levels in the design	N	1.00
Stakeholder team cohesion	N	1.00
Personnel/team capability	N	1.00
Personnel experience/continuity	N	1.00
Process capability	N	1.00
Multisite coordination	N	1.00
Tool support	N	1.00
composite effort multiplier		**1.00**

Figure 3.7. COSYSMO Tool in Traditional Configuration Showing TCS Mission Data. Adapted from [22].

By definition, the ROI for the baseline mission that has been *Designed for Reuse* (ISR) will be exactly negative one as the *Savings* term drops out and the equation reduces to $-\text{ISR}Investment/\text{ISR}Investment$. The core question this analysis seeks to answer is if the savings gained by the other missions outweighs the extra investment in ISR to enable reuse.

With all the methodologies developed, data gathered, and analysis generated, the evaluation of the analysis can be performed. Chapter 4 further discusses the resulting data from COSYSMO and the corresponding ROI calculations.

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CHAPTER 4:
Findings

The previous chapter focused on the analysis methodologies and the data obtained through them. This chapter will take the next step and discuss the meaning of the data. Initial comparison of COSYSMO outputs for the different missions will be discussed. Then the corresponding ROI data will be evaluated.

4.1 Traditional Versus Reuse Mission COSYSMO Results

COSYSMO analysis allows for an analyst to evaluate SE LOE for stand-alone system development or for system development artifact reuse. System development artifact reuse for the nine UUV mission cases refers to system requirements and interfaces; analysis of algorithms and scenarios was excluded from this thesis. As previously mentioned in Chapter 3, each of the nine missions were analyzed using COSYSMO independently, and then again using the ISR mission as a baseline for reuse. Table 4.1 summarizes the inputs to COSYSMO and Table 4.2 lists the outputs of the COSYSMO calculations for each mission as well as the overall portfolio.

Table 4.1. Mission Requirement and Interface Counts by Reuse Category and Complexity

		Reuse Category													
		Requirements							Interfaces						
Mission	Complexity	New	Designed for Reuse	Modified	Adopted	Managed	Total for Mission	Deleted	New	Designed for Reuse	Modified	Adopted	Managed	Total for Mission	Deleted
ISR*	Easy	0	2	0	0	0	2	0	0	2	0	0	0	2	0
	Nominal	0	16	0	0	0	16	0	0	2	0	0	0	2	0
	Difficult	0	8	0	0	0	8	0	0	1	0	0	0	1	0

Continued on next page.

Continuation of Table 4.1																
		Reuse Category														
		Requirements							Interfaces							
Mission	Complexity	New	Designed for Reuse	Modified	Adopted	Managed	Total for Mission	Deleted	New	Designed for Reuse	Modified	Adopted	Managed	Total for Mission	Deleted
MCM	Easy	2	0	0	0	2	4	0	0	0	0	1	1	2	0
	Nominal	0	0	1	2	8	11	5	0	0	0	1	1	2	0
	Difficult	5	0	3	2	1	11	2	0	0	0	0	0	0	1
ASW	Easy	1	0	0	0	2	3	0	0	0	0	1	1	2	0
	Nominal	4	0	1	3	8	16	4	0	0	0	1	1	2	0
	Difficult	3	0	3	1	1	8	3	0	0	2	0	0	2	0
INID	Easy	1	0	0	0	2	3	0	0	0	0	1	1	2	0
	Nominal	4	0	1	1	4	10	10	0	0	0	1	0	1	1
	Difficult	2	0	3	0	0	5	5	0	0	0	0	0	0	1
OO	Easy	1	0	0	0	2	3	0	0	0	0	1	1	2	0
	Nominal	1	0	2	2	7	12	6	0	0	0	1	1	2	0
	Difficult	2	0	6	1	0	9	3	0	0	0	0	0	0	1
CN3	Easy	1	0	0	0	2	3	0	0	0	0	1	1	2	0
	Nominal	0	0	1	5	6	12	5	0	0	0	1	1	2	0
	Difficult	4	0	3	2	1	10	2	3	0	0	0	0	3	1
PD	Easy	0	0	0	0	2	2	0	0	0	0	1	1	2	0
	Nominal	0	0	1	4	6	11	5	0	0	0	1	1	2	0
	Difficult	5	0	3	2	1	11	2	5	0	1	0	0	6	0

Continued on next page.

		Reuse Category														
		Requirements							Interfaces							
Mission	Complexity	New	Designed for Reuse	Modified	Adopted	Managed	Total for Mission	Deleted	New	Designed for Reuse	Modified	Adopted	Managed	Total for Mission	Deleted
IO	Easy	1	0	0	0	2	3	0	0	0	0	1	1	2	0
	Nominal	1	0	1	3	5	10	7	0	0	0	1	1	2	0
	Difficult	3	0	4	2	0	9	2	0	0	0	0	0	0	1
TCS	Easy	4	0	0	0	2	6	0	0	0	0	1	1	2	0
	Nominal	6	0	2	3	6	17	5	0	0	0	1	1	2	0
	Difficult	4	0	2	1	0	7	5	1	0	1	0	0	2	0

Continuation of Table 4.1

*ISR was selected as the baseline mission for reuse, designating all artifacts as *Designed for Reuse.*

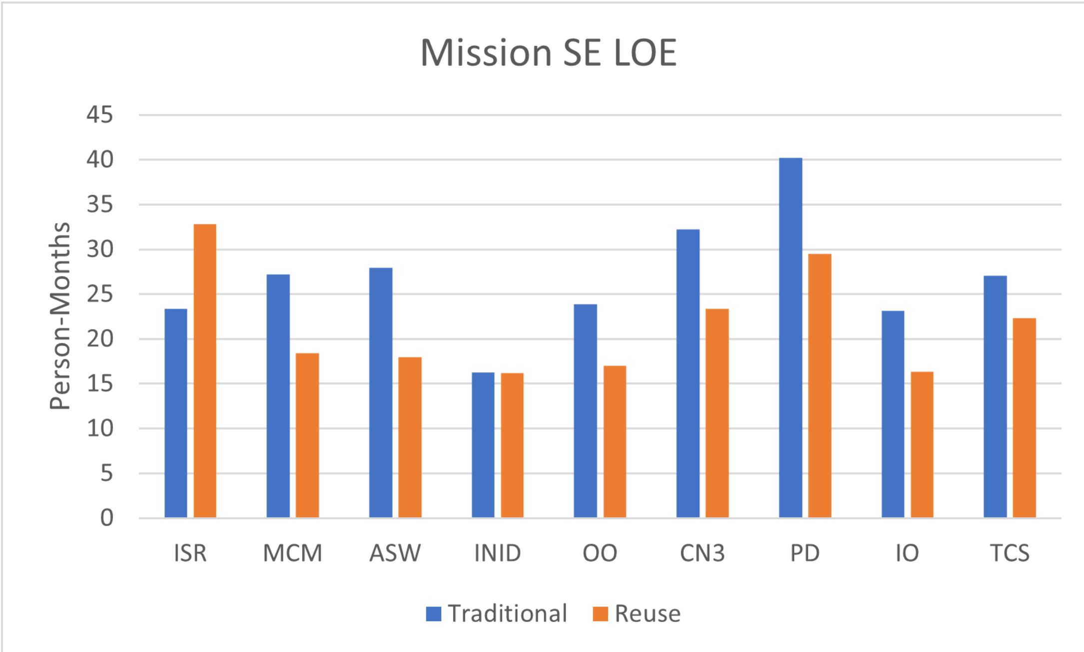
The top half of Table 4.2 is the equivalent sizes and resulting effort for each mission when developed using conventional, isolated SE efforts. The bottom half of the table is the equivalent sizes and resulting effort for each mission when developed using a reuse approach with ISR as the baseline mission. The resulting effort was lower for the with-reuse case except for ISR. This increase in effort is expected since more SE effort is expended to develop ISR in a manner that enables reuse by future efforts. In a portfolio approach, this extra effort is an investment upfront for later savings when the ISR artifacts are reused during development of the other missions. Figure 4.1 shows a summary of the traditional mission SE LOE in PM when ISR is used as a reuse baseline.

Table 4.2. COSYSMO Outputs per UUV Mission

		ISR*	MCM	ASW	INID	OO	CN3	PD	IO	TCS	Portfolio
Traditional	Equivalent Requirements	57.000	68.000	57.500	36.500	58.500	63.500	67.000	56.500	55.000	519.500
	Equivalent Interfaces	14.100	14.100	26.700	14.100	14.100	33.000	51.900	14.100	26.700	208.800
	Equivalent Size	71.100	82.100	84.200	50.600	72.600	96.500	118.900	70.600	81.700	728.300
	Effort	23.325	27.167	27.904	16.264	23.847	32.243	40.228	23.151	27.026	241.154
Reuse	Equivalent Requirements	78.660	51.310	45.130	43.930	47.220	46.800	50.870	45.310	55.590	464.820
	Equivalent Interfaces	19.458	5.475	10.452	6.483	5.475	24.375	37.857	5.475	12.657	127.707
	Equivalent Size	98.118	56.785	55.582	50.413	52.695	71.175	88.727	50.785	68.247	592.527
	Effort	32.816	18.379	17.967	16.201	16.979	23.351	29.497	16.327	22.334	193.849

*ISR was selected as the baseline mission for reuse, designating all artifacts as *Designed for Reuse.*

When evaluating the LOEs presented in Table 4.2 and the remainder of this section, it is important to recall that the values presented are not actual effort estimates but proxies for the relative effort analysis (see Section 3.3). Furthermore, the scope of SE effort is likely understated since the requirements are not decomposed (Section 3.3.1) and would be expanded for a full estimate, and algorithms and scenarios are not included in the calculation. Further, the project cost drivers were excluded from the calculation (Section 3.6); their inclusion could adjust the estimate higher or lower however, the ROI results presented in Section 4.2 would not vary because the cost drivers are multiplicative in COSYSMO.



*ISR was selected as the baseline mission for reuse, designating all artifacts as *Designed for Reuse*.

Figure 4.1. Mission Relative SE LOEs from COSYSMO

The following sections will take a closer look at the COSYSMO results per mission type and provide insights into the data.

4.1.1 Intelligence, Surveillance, and Reconnaissance

Intelligence, Surveillance, and Reconnaissance (ISR) contained five interfaces and 26 requirements. Of the five interfaces, two were defined as easy, two nominal, and one difficult. The 26 requirements contained two easy, 16 nominal, and eight difficult. The COSYSMO analysis determined the independent development effort was 23.32 PM and the with-reuse development effort was 32.82 PM, resulting in an increase in effort of 9.50 PM. The increase in effort was expected as – in the reuse case – ISR is used as the baseline and thus extra effort is expended to design ISR for reuse so the other missions may reuse its SE artifacts in their development. Ultimately, this effort increase will be evaluated against the overall savings from reusing ISR artifacts across the other eight missions. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

ISR Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.3. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 23.32 PM, meaning a single engineer will require 23.32 months to reach the manufacturing phase of system development.

Table 4.3. ISR Traditional Development COSYSMO Output

Equivalent Requirements	57.000
Equivalent Interfaces	14.100
Equivalent Size	71.100
Effort	23.325

ISR Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the reuse baseline, all requirements and interfaces in ISR will be classified as *Designed for Reuse*, which applies a weight of 1.38 to each artifact increasing the resulting sizes by a factor of 1.38. Applying the same interface and requirement complexity weightings as the independent case in addition to the 1.38 reuse weighting derives the new sizes in Table 4.4. As expected and by definition of designing a system for reuse, the size values for the reuse case are greater than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 98.12 results in an LOE of 32.82 PM.

Table 4.4. ISR with Reuse Development COSYSMO Output

Equivalent Requirements	78.660
Equivalent Interfaces	19.458
Equivalent Size	98.118
Effort	32.816

4.1.2 Mine Countermeasures

Mine Countermeasures (MCM) contained four interfaces and 26 requirements. Of the four interfaces, two were defined as easy and two nominal. The 26 requirements contained four easy, 11 nominal, and 11 difficult. The COSYSMO analysis determined the independent development effort was 27.17 PM and the with-reuse development effort was 18.38, resulting in a decrease in effort of 8.79. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

MCM Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.5. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 27.17 PM, meaning a single engineer will require 27.17 months to reach the manufacturing phase of system development.

Table 4.5. MCM Traditional Development COSYSMO Output

Equivalent Requirements	68.000
Equivalent Interfaces	14.100
Equivalent Size	82.100
Effort	27.167

MCM Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the MCM mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as one managed nominal, one managed easy, one adopted nominal, one adopted easy, and one deleted difficult. Requirements are redefined as seven new: five difficult and two easy; 11 managed: two easy, eight nominal, and one difficult; four adopted: two nominal and two difficult; four modified: one nominal and three difficult; and seven deleted: five nominal and two easy. Applying the reuse and complexity weightings derives the new sizes in Table 4.6. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 56.78 results in an LOE of 18.38 PM.

Table 4.6. MCM with Reuse Development COSYSMO Output

Equivalent Requirements	51.310
Equivalent Interfaces	5.475
Equivalent Size	56.785
Effort	18.379

4.1.3 Anti-Submarine Warfare

Anti-Submarine Warfare (ASW) contained six interfaces and 27 requirements. Of the six interfaces, two were defined as easy, two nominal, and two difficult. The 27 requirements contained three easy, 16 nominal, and eight difficult. The COSYSMO analysis determined the independent development effort was 27.90 PM and the with-reuse development effort was 17.97, resulting in a decrease in effort of 9.93. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

ASW Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.7. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which when, substituted into the equation, returns a SE LOE of 27.90 PM, meaning a single engineer will require 27.90 months to reach the manufacturing phase of system development.

Table 4.7. ASW Traditional Development COSYSMO Output

Equivalent Requirements	57.500
Equivalent Interfaces	26.700
Equivalent Size	84.200
Effort	27.904

ASW Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the ASW mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as one managed easy, one managed nominal, one adopted easy, one adopted nominal, and two modified difficult. Requirements are redefined as eight new: one easy, four nominal, and three difficult; 11 managed: two easy, eight nominal, and one difficult; four adopted: three nominal and one difficult; four modified: one nominal and three difficult; and seven deleted: four nominal and three difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.8. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 55.58 results in an LOE of 17.97 PM.

Table 4.8. ASW with Reuse Development COSYSMO Output

Equivalent Requirements	45.130
Equivalent Interfaces	10.452
Equivalent Size	55.582
Effort	17.967

4.1.4 Inspection and Identification

Inspection and Identification (INID) contained three interfaces and 18 requirements. Of the three interfaces, two were defined as easy and one nominal. The 18 requirements contained three easy, 10 nominal, and five difficult. The COSYSMO analysis determined the independent development effort was 16.26 PM and the with-reuse development effort was 16.20, resulting in a decrease in effort of 0.06. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

INID Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.9. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 16.26 PM, meaning a single engineer will require 16.26 months to reach the manufacturing phase of system development.

Table 4.9. INID Traditional Development COSYSMO Output

Equivalent Requirements	36.500
Equivalent Interfaces	14.100
Equivalent Size	50.600
Effort	16.264

INID Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the INID mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as one managed easy, one adopted easy, one adopted nominal, one deleted nominal, and one deleted difficult. Requirements are redefined as seven new: one easy, four nominal, and two difficult; six managed: two easy and four nominal; one adopted nominal; four modified: one nominal and three difficult; and 15 deleted: 10 nominal and five difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.10. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 50.41 results in an LOE of 16.20 PM.

Table 4.10. INID with Reuse Development COSYSMO Output

Equivalent Requirements	43.930
Equivalent Interfaces	6.483
Equivalent Size	50.413
Effort	16.201

4.1.5 Oceanography

Oceanography (OO) contained four interfaces and 24 requirements. Of the four interfaces, two were defined as easy and two nominal. The 24 requirements contained three easy, 12 nominal, and nine difficult. The COSYSMO analysis determined the independent development effort was 23.85 PM and the with-reuse development effort was 16.98, resulting in a decrease in effort of 6.87. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

OO Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.11. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 23.85 PM, meaning a single engineer will require 23.85 months to reach the manufacturing phase of system development.

Table 4.11. OO Traditional Development COSYSMO Output

Equivalent Requirements	58.500
Equivalent Interfaces	14.100
Equivalent Size	72.600
Effort	23.847

OO Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the OO mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as one managed easy, one managed nominal, one adopted easy, one adopted nominal, and one deleted difficult. Requirements are redefined as four new: one easy, one nominal, and two difficult; nine managed: two easy and seven nominal; three adopted: two nominal and one difficult; eight modified: two nominal and six difficult; and nine deleted: six nominal and three difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.12. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 52.70 results in an LOE of 16.98 PM.

Table 4.12. OO with Reuse Development COSYSMO Output

Equivalent Requirements	47.220
Equivalent Interfaces	5.475
Equivalent Size	52.695
Effort	16.979

4.1.6 Communication or Navigation Network Node

Communication or Navigation Network Node (CN3) contained seven interfaces and 25 requirements. Of the seven interfaces, two were defined as easy, two nominal, and three difficult. The 25 requirements contained three easy, 12 nominal, and 10 difficult. The COSYSMO analysis determined the independent development effort was 32.24 PM and the with-reuse development effort was 23.35, resulting in a decrease in effort of 8.89. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

CN3 Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.13. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight.

Equivalent Interfaces is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 32.24 PM meaning, a single engineer will require 32.24 months to reach the manufacturing phase of system development.

Table 4.13. CN3 Traditional Development COSYSMO Output

Equivalent Requirements	63.500
Equivalent Interfaces	33.000
Equivalent Size	96.500
Effort	32.243

CN3 Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the CN3 mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as three new difficult, one managed easy, one managed nominal, one adopted easy, one adopted nominal, and one deleted difficult. Requirements are redefined as five new: one easy and four difficult; nine managed: two easy, six nominal, and one difficult; seven adopted: five nominal and two difficult; four modified: one nominal and three difficult; and seven deleted: five nominal and two difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.14. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 71.18 results in an LOE of 23.35 PM.

Table 4.14. CN3 with Reuse Development COSYSMO Output

Equivalent Requirements	46.800
Equivalent Interfaces	24.375
Equivalent Size	71.175
Effort	23.351

4.1.7 Payload Delivery

Payload Delivery (PD) contained 10 interfaces and 24 requirements. Of the 10 interfaces, two were defined as easy, two nominal, and six difficult. The 24 requirements contained two easy, 11 nominal, and 11 difficult. The COSYSMO analysis determined the independent development effort was 40.23 PM and the with-reuse development effort was 29.50, resulting in a decrease in effort of 10.73. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

PD Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.15. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 40.23 PM meaning, a single engineer will require 40.23 months to reach the manufacturing phase of system development.

Table 4.15. PD Traditional Development COSYSMO Output

Equivalent Requirements	67.000
Equivalent Interfaces	51.900
Equivalent Size	118.900
Effort	40.228

PD Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the PD mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as five new difficult, one managed easy, one managed nominal, one modified difficult, one adopted easy, and one adopted nominal. Requirements are redefined as five new difficult; nine managed: two easy, six nominal, and two difficult; six adopted: four nominal and two difficult; four modified: one nominal and three difficult; and seven deleted: five nominal and two difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.16. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 88.73 results in an LOE of 29.50 PM.

Table 4.16. PD with Reuse Development COSYSMO Output

Equivalent Requirements	50.870
Equivalent Interfaces	37.857
Equivalent Size	88.727
Effort	29.497

4.1.8 Information Operations

Information Operations (IO) contained four interfaces and 22 requirements. Of the four interfaces, two were defined as easy and two nominal. The 22 requirements contained three easy, 10 nominal, and nine difficult. The COSYSMO analysis determined the independent development effort was 23.15 PM and the with-reuse development effort was 16.33, resulting in a decrease in effort of 6.82. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

IO Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.17. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 23.15 PM, meaning a single engineer will require 23.15 months to reach the manufacturing phase of system development.

Table 4.17. IO Traditional Development COSYSMO Output

Equivalent Requirements	56.500
Equivalent Interfaces	14.100
Equivalent Size	70.600
Effort	23.151

IO Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the IO mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as one managed easy, one managed nominal, one adopted easy, one adopted nominal, and one deleted difficult. Requirements are redefined as five new: one easy, one nominal, and three difficult; seven managed: two easy and five nominal; five adopted: three nominal and two difficult; five modified: one nominal and four difficult; and nine deleted: seven nominal and two difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.18. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 50.78 results in an LOE of 16.33 PM.

Table 4.18. IO with Reuse Development COSYSMO Output

Equivalent Requirements	45.310
Equivalent Interfaces	5.475
Equivalent Size	50.785
Effort	16.327

4.1.9 Time Critical Strike

Time Critical Strike (TCS) contained six interfaces and 30 requirements. Of the six interfaces, two were defined as easy, two nominal, and two difficult. The 30 requirements contained six easy, 17 nominal, and seven difficult. The COSYSMO analysis determined the independent development effort was 27.03 PM and the with-reuse development effort was 22.33, resulting in a decrease in effort of 4.70. The ROI for this mission will be discussed in Section 4.2. The next two subsections discuss the development of the effort values.

TCS Traditional Development Results

Traditional development COSYSMO analysis only applies the complexity weights as reuse is not part of the calculation. Applying the *Easy*, *Nominal*, and *Difficult* weightings per requirement and interface derives the equivalent sizes in Table 4.19. *Equivalent Requirements* is the sum of the product between each requirement and its associated complexity weight. *Equivalent Interfaces* is the sum of the product between each interface and its associated complexity weight. *Equivalent Size* is the sum of resulting interface and requirement sizes. *Equivalent Size* is the summation term in Equation (3.1), which, when substituted into the equation, returns a SE LOE of 27.03 PM, meaning a single engineer will require 27.03 months to reach the manufacturing phase of system development.

Table 4.19. TCS Traditional Development COSYSMO Output

Equivalent Requirements	55.000
Equivalent Interfaces	26.700
Equivalent Size	81.700
Effort	27.026

TCS Reuse Development Results

Reuse development COSYSMO analysis incorporates the reuse weights along with the complexity weights to determine resulting sizes and effort. As discussed in Chapter 3, ISR was selected as the reuse baseline. As the TCS mission is reusing ISR development artifacts, the evaluation needs to account for no longer needed ("deleted") requirements and interfaces. In the reuse case, each requirement and interfaces has an additional weight applied based on its reuse classification (Table 3.7). The interfaces are redefined as one new difficult, one managed easy, one managed nominal, one adopted easy, one adopted nominal, and one modified difficult. Requirements are redefined as 14 new: four easy, six nominal, and four difficult; eight managed: two easy and six nominal; four adopted: three nominal and one difficult; four modified: two nominal and two difficult; and 10 deleted: five nominal and five difficult. Applying the reuse and complexity weightings derives the new sizes in Table 4.20. As expected, the size values for the reuse case are less than those of the independent development case. Continuing with the calculation, the new *Equivalent Size* of 68.25 results in an LOE of 22.33 PM.

Table 4.20. TCS with Reuse Development COSYSMO Output

Equivalent Requirements	55.590
Equivalent Interfaces	12.657
Equivalent Size	68.247
Effort	22.334

4.2 Portfolio Approach Return on Investment

Traditional SE processes in the DOD operate in a siloed approach where programs and funding are mission specific and developed in relative isolation. While a conventional ROI calculation would look at the UUV mission portfolio at large, it is also necessary to evaluate the potential savings on a mission-by-mission basis. A conventional ROI calculation would use the method described in Section 3.7 where the net savings (effort reduction for the mission minus the extra effort in ISR) is compared against the net investment (the extra effort put into ISR enabling reuse). However, this calculation is inherently comparing effort across missions (a portfolio approach) and cannot be used to assess individual mission returns.

4.2.1 Individualized Mission Savings

For an individual mission, the savings will be compared using simple percent increase or decrease by dividing the mission savings from SE artifact reuse by the traditional development effort using Equation (4.1).

$$Savings = \frac{TraditionalEffort - ReuseEffort}{TraditionalEffort} \times 100\% \tag{4.1}$$

Table 4.21 lists the savings on a per-mission basis (based on the efforts produced by COSYSMO) when its development costs are considered in isolation as would be the case of a future program leveraging the effort of a previous one in the current DOD system development approach. While ISR has a 41% cost increase as a result of the 1.38 size weight from designing it for reuse, the remaining missions generally have a 30% effort –

and therefore cost – savings. A notable outlier is IO which has a savings of only 0.39% (where the next lowest is 17%). In the case of IO, reusing the SE artifacts from ISR is of minimal benefit due to the large number of deleted requirements. This implies that IO may be better suited for independent development or that IO would be a more appropriate baseline than ISR as discussed in Section 5.1.3.

Table 4.21. Individualized Mission Savings

Intelligence, Surveillance, and Reconnaissance*	-41%
Mine Countermeasures	32%
Anti-Submarine Warfare	36%
Inspection and Identification	0.39%
Oceanography	29%
Communication or Navigation Network Node	28%
Payload Delivery	27%
Information Operations	29%
Time Critical Strike	17%
Portfolio	20%

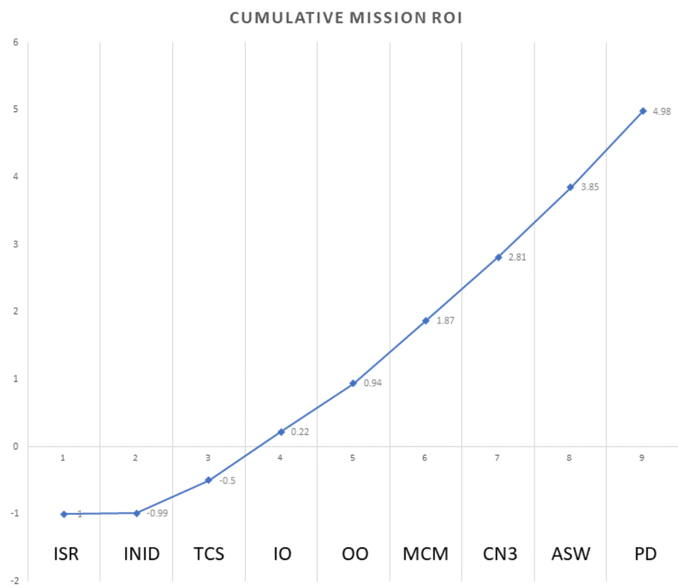
*ISR was selected as the baseline mission for reuse, designating all artifacts as *Designed for Reuse*.

Applying Equation (4.1) at the portfolio level (comparing total effort across all nine missions) identifies a portfolio-level cost savings of 20%. This portfolio-level savings indicates it is in the best interest of the DOD to make an extra investment in first-of-kind projects, developing them with the intention of SE artifact reuse to later realize a cost savings on similar future projects. An additional implication of a given mission's cost savings is that as the development will require less effort it, will also require less time, which translates to a faster delivery to the warfighter. In the increasingly competitive landscape, this future time savings could outweigh any potential financial gain or cost. Turning to a conventional ROI calculation will provide a more direct assessment of the financial advantage of using a portfolio approach to the mission SE processes.

4.2.2 Portfolio Returns

In addition to the general cost savings discussed in Section 4.2.1, performing a stepped ROI calculation on all nine missions identifies the point where the investment in designing ISR for SE artifact reuse results in a financial gain for the portfolio. This is the point where the cumulative savings of the other missions exceeds the investment made in ISR. Figure 4.2

shows the resulting ROI series for the portfolio. Each point on the chart is the addition of another reuse mission to the ROI calculation. The values for this chart were calculated using Equation (3.3) where for each progressive point, the savings for that mission are included in the summation term. To provide the most conservative assessment of where the breakeven point would be, the missions were added to the ROI calculation in order of least to greatest savings; therefore, a different ordering would result in an earlier breakeven point.



*ISR was selected as the baseline mission for reuse, designating all artifacts as *Designed for Reuse*.

Figure 4.2. Cumulative Portfolio ROI Across Missions of Increasing Savings

As can be seen in Figure 4.2, the portfolio has a positive return after the third reuse mission. However, the portfolio would have a positive return after only one reuse mission if a mission with savings greater than the ISR investment (e.g., PD or ASW) was the first developed from the ISR baseline. Additionally, the overall portfolio has an ROI of 4.98, which means that the total savings are nearly five times the investment made in ISR. Generally, when a final consideration is made that an item will cost more to produce in the future due to inflation or other factors, making an early investment to reduce the cost of future programs could have substantially greater returns than those presented here.

4.3 Research Questions

Upon completion of UUV mission reuse analysis utilizing COSYSMO, it is important to revisit the focus areas defined in Chapter 1. This section will provide analysis results and discussions for each focus area.

1. *What are the activities, interfaces, and requirements of each of the nine UUVmissions?*

   Activities, interfaces, and requirements are outlined in Appendices A.1, B, and C respectively.

2. *What are the complexities of the identified requirements and interfaces?*

   Complexity classification for requirements and interfaces can be found in Appendices B and C respectively.

3. *What is the optimal baseline mission for SE artifact reuse?*

   The balance of SE labor savings from reusing requirements and interfaces against the increase in effort from deleting irrelevant requirements and interfaces across the portfolio is optimized for the ideal baseline mission. In this case, the optimal baseline mission to design for reuse is ISR, which contained the basic actions and communications required in each of the other missions while limiting the number of unused requirements and interfaces requiring deletion across the other missions.

4. *What is the reusability of the baseline mission's SE artifacts for the remaining missions?*

   ISR reusability across requirements ranged from 50% to 79% of the other eight missions with an average of 66%. With regards to interfaces, the overlap ranged from 50% to 100% of the other eight missions with an average of 82%. Worth noting is that the 50% minimum is from the additional five interfaces required by PD.

5. *What are the LOEs for each mission's development using traditional and reuse methods?*

   Absolute LOEs could not be derived from mission data outlined in this thesis. The requirements defined (Appendix B) were too high a level of decomposition for accurate COSYSMO labor estimates. As previously stated in Section 3.3, the requirements used in this thesis are considered "kite level" and the necessary level for accurate

COSYSMO LOE estimation is “sea level” (one level deeper) [9]. However, since all mission requirements were defined at the same level, the resulting ROI is still valid from relative LOEs.

6. *What is the ROI for applying a product line approach to the UUV mission SE efforts?*

   Resulting overall ROI across all missions is 4.98. With a near fivefold gain on the investment, designing ISR as the baseline mission for reuse is a lucrative investment. However, it is important to analyze the overall ROI incrementally over the missions to better understand how many missions are required to see a positive return. Revisiting Figure 4.2, the ROI is positive at the third mission that reuses the ISR SE artifacts. However, the return from reuse varies from mission to mission. If a different ordering of missions were used, such as PD first, the ROI would be positive after the first reuse of ISR SE artifacts.

7. *Does operational modularity duplicated across UUV missions save on SE labor costs when the original system is designed for reuse, while still satisfying UUV demands?*

   With the current level of requirement fidelity, the cost savings from SE artifact reuse cannot be determined. COSYSMO cannot accurately predict LOE until the requirements are decomposed to the “sea level.” This research objective is discussed further in Section 5.1.1.

4.4 Summary

A COSYSMO analysis of SE efforts for the nine UUV missions shows there is a benefit to designing an initial UUV mission for reuse. For the example of using the ISR mission as a baseline for reuse, the extra investment into ISR resulted in a 25% SE development effort savings across the other eight missions and a portfolio-wide savings of 20% and an ROI of 4.98. When the time value of money and future decreased equipment transition time to the warfighter are included, there is a clear benefit to using a portfolio approach to DOD system development. While the returns increase with the more systems developed in the portfolio, it has been shown here that even a single system can have significant cost and time benefits from leveraging an existing system that was designed for reuse. The greater implications of this finding and potential extensions of the work described in this thesis will be discussed in Chapter 5.

CHAPTER 5: Conclusion and Future Work

COSYSMO analysis of UUV missions: ISR, MCM, ASW, INID, OO, CN3, PD, IO, and TCS, has yielded an ROI of 4.98. Assuming all missions will be developed, this is a beneficial investment. The following section will take a closer look at future work associated with the results determined in Chapter 4.

5.1 Future Analysis Recommendations

Limitations to the scope of this analysis and current capability of COSYSMO warrant further investigation. Alternate baseline missions, calibration of the COSYSMO parameters, further development of COPLIMO, and other recommendations are discussed below.

5.1.1 Decomposition of Requirements to *Sea Level*

ROI across all missions has been determined utilizing relative LOE values. To better analyze savings across missions and determine accurate LOEs, the current "kite level" requirements need to be decomposed further to "sea level" [9]. Coupled with requirement decomposition, the number of critical algorithms and operational scenarios should be defined per mission. Using this in-depth definition of the missions, accurate LOEs will be defined and can be used to better quantify the ROI and individual mission effort savings. For example, if a mission SE process has an ROI of five, it is a good return, but does not tell specifics on how long it takes to make the return. It is important to further quantify the ROI to understand the overall impact.

The Innoslate models for each mission should be updated in parallel to the decomposition of the current "kite level" requirements. The Innoslate models are useful MBSE products for developing mission requirements and interfaces, but also can be further developed to include operational scenarios for input into COSYSMO. In addition to operational scenarios, the models can be further developed with duration and resource data to be used as a tool for mission analysis by system owners.

5.1.2 Quantification of ROI in Determining the Absolute Value of Baseline Investment

Estimating the absolute versus relative LOE will provide more information for management of UUV mission SE development. With an absolute LOE value and resulting savings across other missions, program managers can make informed value judgments. If the additional time to develop the baseline starts to make reusable technologies obsolete, the value of the ROI may be tainted by the manufacturing or procurement process of the system. According to [25] 3% of all electronic components go obsolete every month. Using this information, the longer the investment takes to pay off in the SE development process, the more the manufacturing phase may negatively impact the ROI. Future analysis or modeling should investigate the relationship between time durations for requirement development and associated technology obsolescence impacts.

5.1.3 Investigation Into Mission Reuse

Results in this thesis are a product of a single baseline mission being designed for reuse and its impact on the LOE for the subsequent missions. Analysis performed shows incremental and total ROI for the eight UUV missions leveraging the SE artifacts from a mission designed for reuse. Future work could evaluate the impacts on overall ROI if design for reuse is applied to additional missions. For example, in this case ISR was designed for complete reuse, but what are the impacts if during MCM system development, technology is developed by the government that allows a single message to carry a GPS location and encrypted data string. If this new communication and navigation method becomes DON mandated, the missions will require a new interface to be designed for reuse and will need to be evaluated for the impact of deleting the old interfaces. COSYSMO analysis should not be a static analysis. It should be evaluated as designs and technologies mature.

Another mission reuse scenario that should be evaluated is a phased approach to requirement and interface reuse. If the DON developed a priority ranking of UUV missions, reuse can be designed into different missions based on the development priority. Depending on which missions have higher priority, reuse can be implemented chronologically and the ROI realized earlier. Mission priority analysis and optimization of reuse can provide insight into the ROI by phasing reuse parameters.

5.1.4 Cross Missional Analysis with Unmanned Aerial Vehicles

Investigating requirement and interface reuse across domains may lead to useful results. UUVs and Unmanned Aerial Vehicles (UAVs) have similar system capabilities with respect to autonomous navigation, surveillance, communications, ultimate return, and refurbishment for the next mission. Investigation into reusing the SE process across systems with similar missions could lead to an ultimate savings from one program to the next. If found to be true, a new protocol of developing systems with similar missions in groups may be instilled rather than the common practices of independent systems being developed by different branches.

5.1.5 Integrated Constructive Product Line Investment Model Development

Utilizing the activity models developed for UUV mission reuse ROI calculations utilizing COSYSMO, a further investigation into the software and hardware required for each mission can occur. The nine mission sizes and reuse percentages can be taken from the COSYSMO model. Then the action blocks from the activity models developed in Innoslate can be decomposed down to a component level, which will provide hardware and software suite definitions to complete necessary mission activities. Cost data associated with hardware can be researched and an effort model developed for the software as inputs for COPLIMO development. Hardware associated data required will consist of system costs based on differences in the COSYSMO model, product line percentages, relative cost of reuse percentages from the COSYSMO model, and investment cost [26]. Software component inputs will consist of estimated average software productivity, per-component product size, unique code percentage, adapted code percentage, relative cost of reuse percentage for unique, adapted, and reused code, and the cost to write code for reuse percentage [27]. This will provide a consolidated and integrated model analysis across disciplines. Compiling ROI data surrounding SE, software, and hardware related to UUV missions can provide guidance for optimal system design with respect to reuse.

5.1.6 Calibration of COSYSMO Parameters

According to [7], COSYSMO is calibrated for "large-scale systems for military applications that employ a disciplined approach to systems engineering" and attempting to use the model outside its calibrated range could "lead to estimates with serious inaccuracies." It should be noted that many UUV programs are not considered large-scale at this time. Various COSYSMO parameters, in particular the alpha constant, should be calibrated with UUV or comparable program of record data to verify they are correct for systems of the size and schedule of USN UUVs.

5.1.7 Analysis of Cost Drivers

A close look at the cost drivers could potentially change the effort predicted by COSYSMO. Off-nominal cost drivers can increase or decrease the LOE estimate. The current analysis assumes a *Nominal* value for all 14 COSYSMO cost drivers [7]. For example, if the mission set is evaluated as a product line, then the cost drivers of *Requirements Understanding* and *Architecture Understanding* would likely change from *Nominal* to *High*, which would decrease the estimated LOE from its *Nominal* baseline.

5.2 Summary

This thesis demonstrated the benefit to ROI from designing SE artifacts for reuse across a spectrum of UUV missions. The current UUV acquisition environment is fragmented across the DON with various departments and program offices developing or procuring systems without collaboration. Performing collaborative development and designing the SE portion of these systems for reuse results in a cost savings. The relative cost savings when the systems are considered as a portfolio is even greater. Returns continue to increase with the number of systems included in the portfolio that can take advantage of the SE portion that was designed for reuse. The benefit of designing for reuse across the UUV mission spectrum can be seen even in a single system if an existing set of designed-for-reuse requirements are used.

The COSYSMO process was used to evaluate the potential SE effort savings across the mission space resulting in the identification of relative cost savings and ROIs between missions. These results outline the clear benefit to a portfolio and design-for-reuse approach. However, numerous assumptions were made as outlined in this thesis. Sensitivity to these assumptions and various inputs should be evaluated to determine future work priorities.

To further this work, the requirements identified in Appendix B should be further decomposed to the "sea level" as recommended in Section 5.1.1. To decompose requirements further, future efforts will likely have to be done at a more restricted distribution level. Any effort to apply COSYSMO to DON UUV development should be evaluated against programs of record to ensure results are comparable with actual effort values.

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APPENDIX A: Mission SysML Diagrams

This appendix contains the SysML diagrams created for each of the nine missions derived from [3]. The development process began with producing Activity Diagrams from the CONOPS described in [3]. From the Activity Diagrams, Interface and Requirement Diagrams were developed based on the Object Nodes exchanged between the Branch Actors [15] and what capabilities a UUV would need to accomplish a given Activity respectively.

A.1 Activity Diagrams

The following are the Innoslate produced SysML Activity Diagrams for the nine mission profiles. Some activities contain decomposed nodes; where that is the case the child diagrams follow their parent.

A.1.1 Intelligence, Surveillance, and Reconnaissance

The following are the Intelligence, Surveillance, and Reconnaissance (ISR) Activity Diagrams derived from the CONOPS in [3].

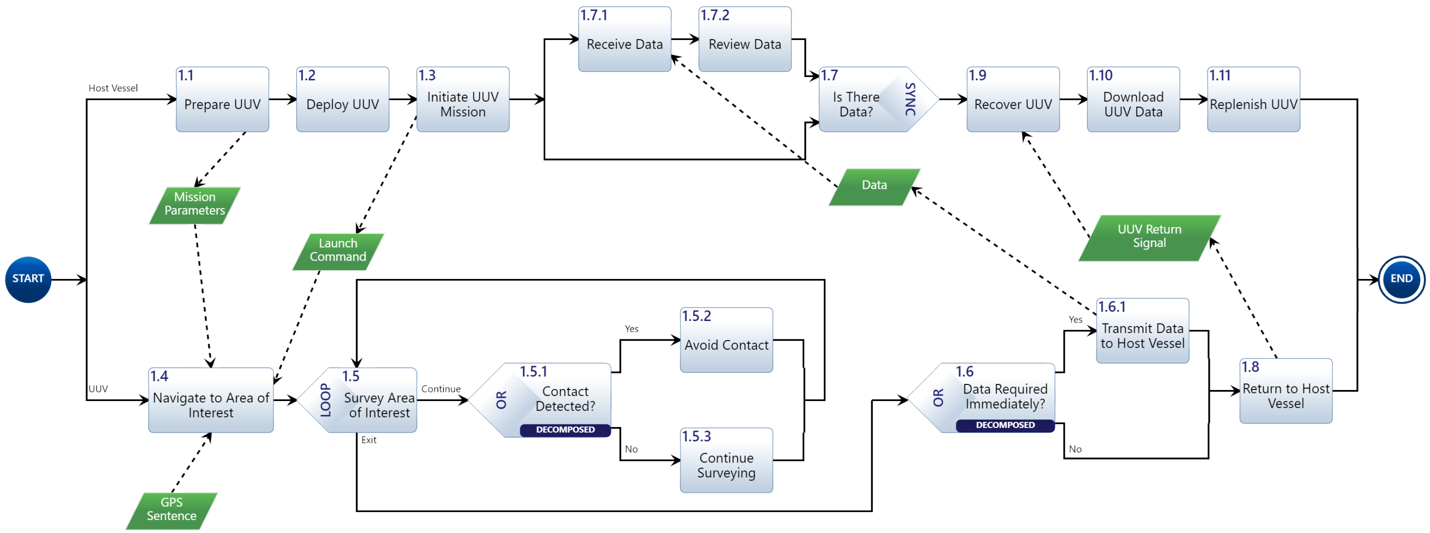
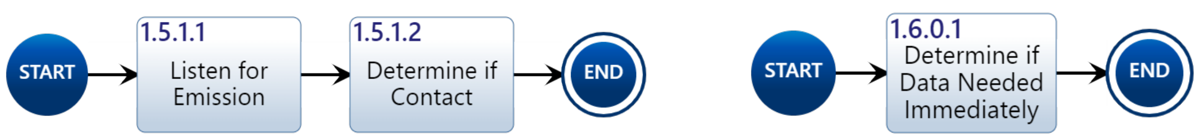


Diagram derived from the CONOPS in [3].

Figure A.1. ISR Activity Diagram



(a) Contact Detection

(b) Data Required

Diagrams derived from the CONOPS in [3].

Figure A.2. ISR Activity Decomposition Diagrams

A.1.2 Mine Countermeasures

The following are the Mine Countermeasures (MCM) Activity Diagrams derived from the CONOPS in [3].

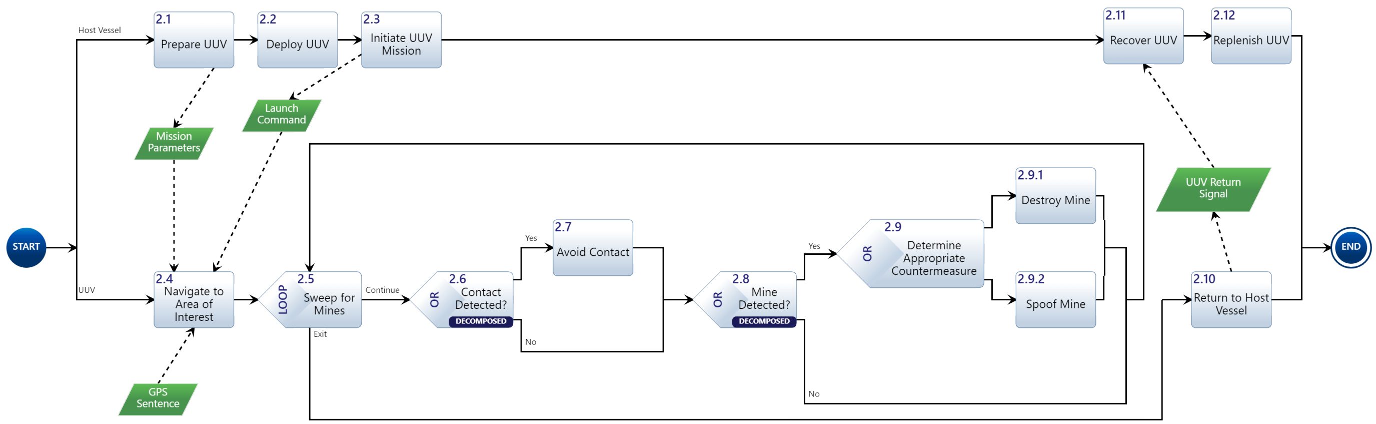
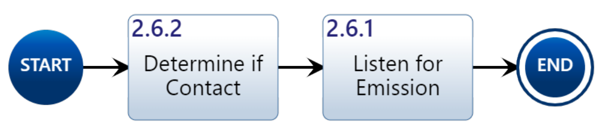
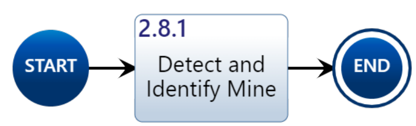


Diagram derived from the CONOPS in [3].

Figure A.3. MCM Activity Diagram



(a) Contact Detection



(b) Mine Detected

Diagrams derived from the CONOPS in [3].

Figure A.4. MCM Activity Decomposition Diagrams

A.1.3 Anti-Submarine Warfare

The following are the Anti-Submarine Warfare (ASW) Activity Diagrams derived from the CONOPS in [3].

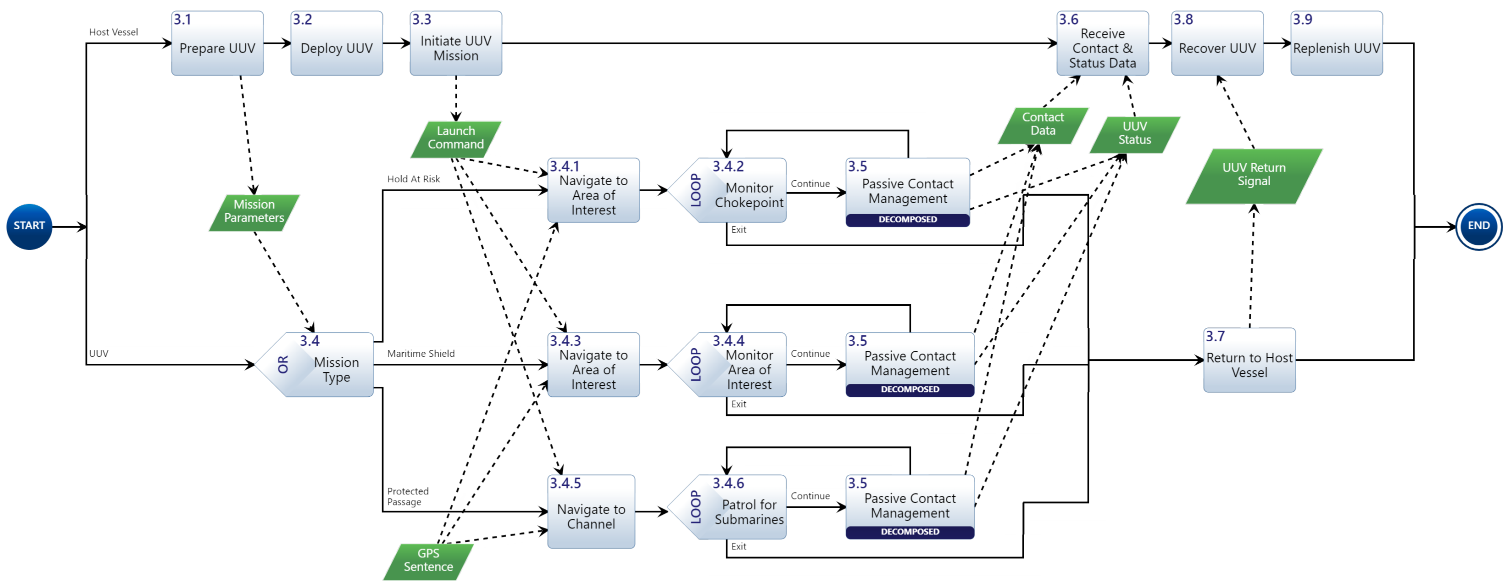


Diagram derived from the CONOPS in [3].

Figure A.5. ASW Activity Diagram

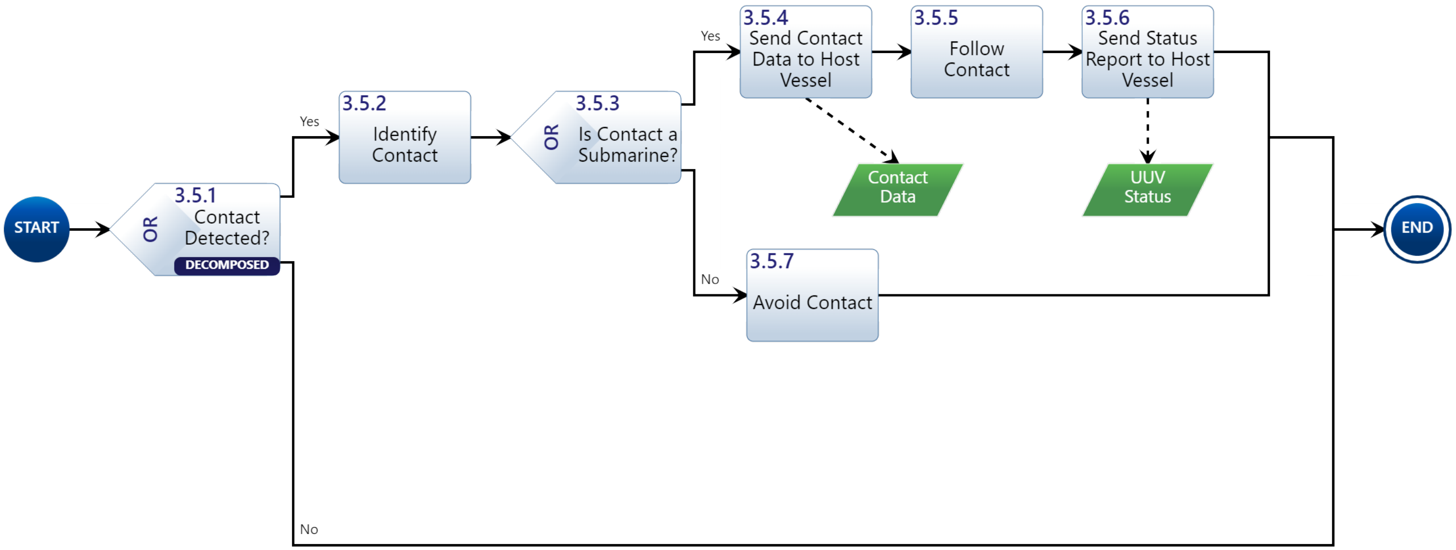


Diagram derived from the CONOPS in [3].

Figure A.6. ASW Contact Management Activity Decomposition Diagram

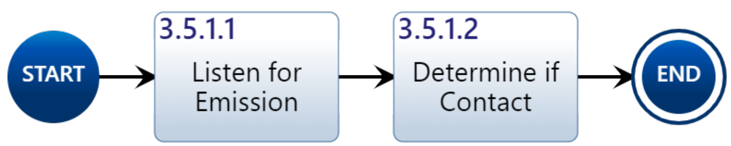


Diagram derived from the CONOPS in [3].

Figure A.7. ASW Contact Detected Activity Decomposition Diagram

A.1.4 Inspection and Identification

The following are the Inspection and Identification (INID) Activity Diagrams derived from the CONOPS in [3].

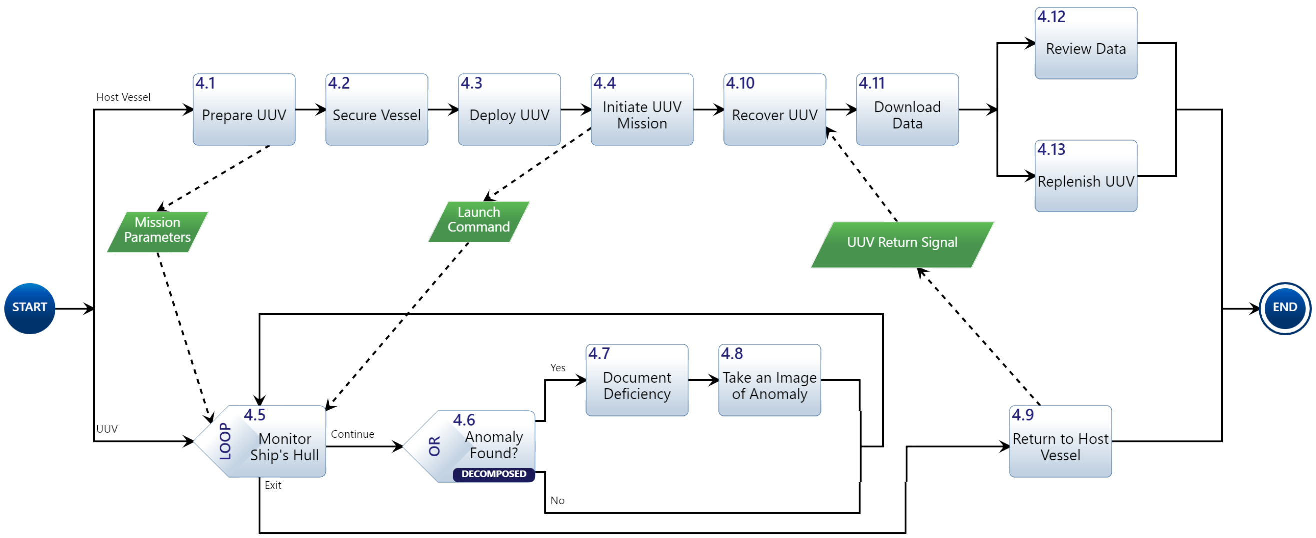


Diagram derived from the CONOPS in [3].

Figure A.8. INID Activity Diagram

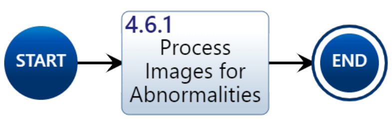


Diagram derived from the CONOPS in [3].

Figure A.9. INID Anomaly Found Activity Decomposition Diagram

A.1.5 Oceanography

The following is the Oceanography (OO) Activity Diagram derived from the CONOPS in [3].

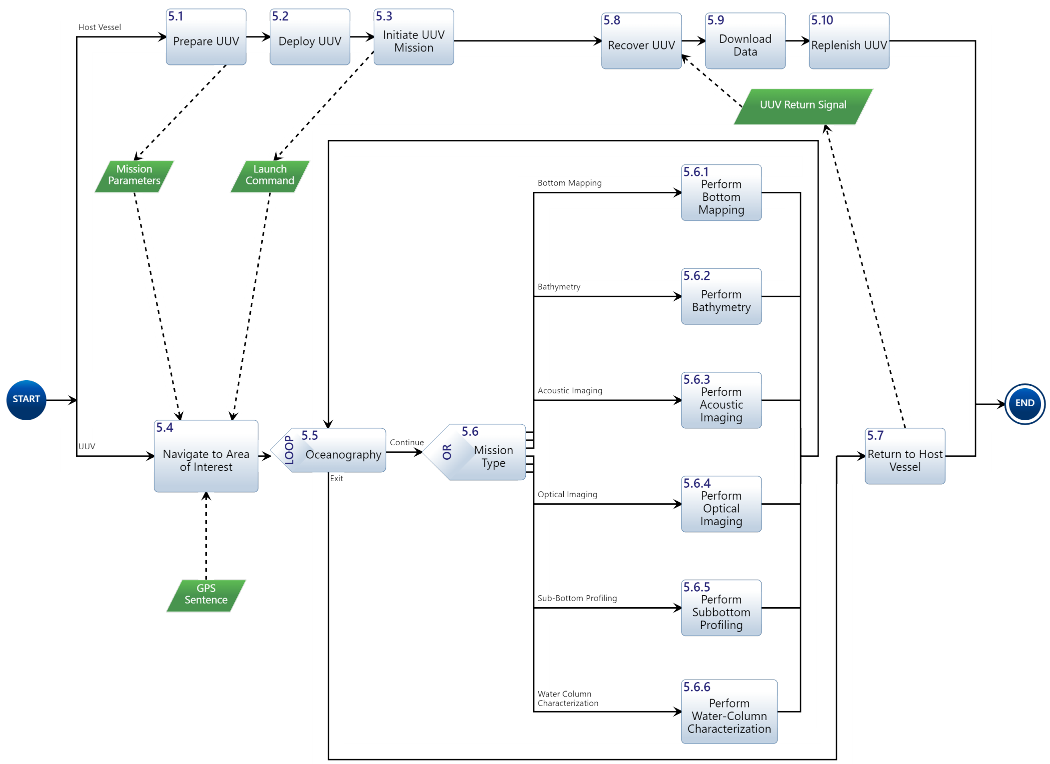


Diagram derived from the CONOPS in [3].

Figure A.10. OO Activity Diagram

A.1.6 Communication or Navigation Network Node

The following is the Communication or Navigation Network Node (CN3) Activity Diagram derived from the CONOPS in [3].

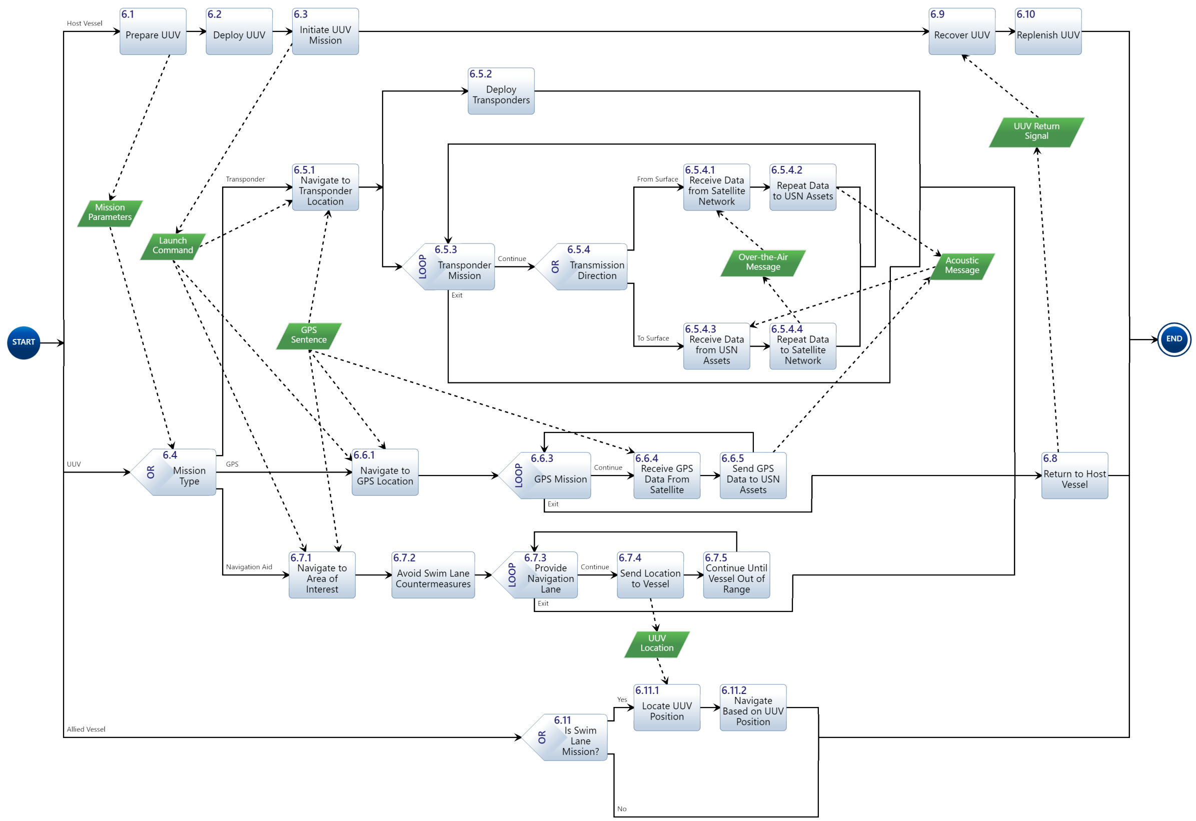


Diagram derived from the CONOPS in [3].

Figure A.11. CN3 Activity Diagram

A.1.7 Payload Delivery

The following are the Payload Delivery (PD) Activity Diagrams derived from the CONOPS in [3].

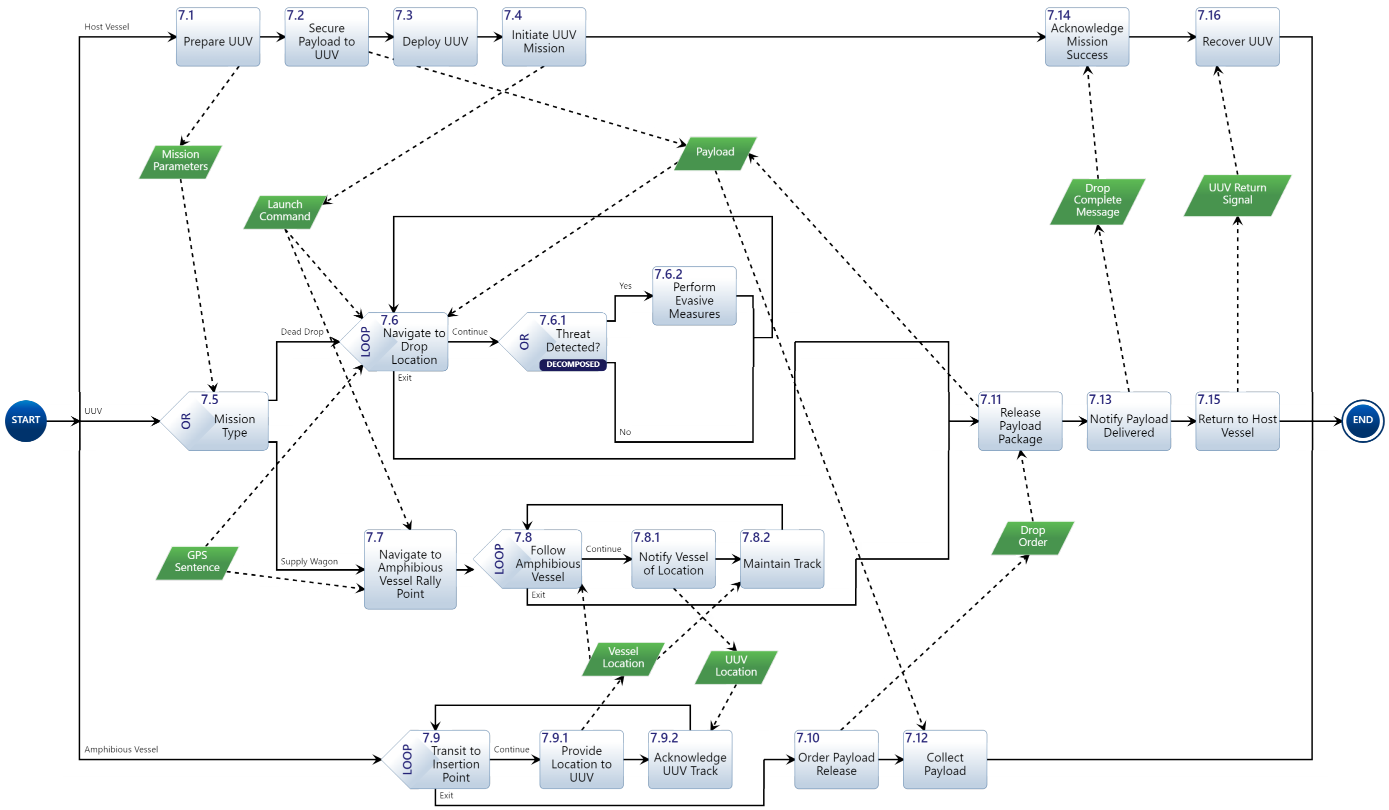


Diagram derived from the CONOPS in [3].

Figure A.12. PD Activity Diagram

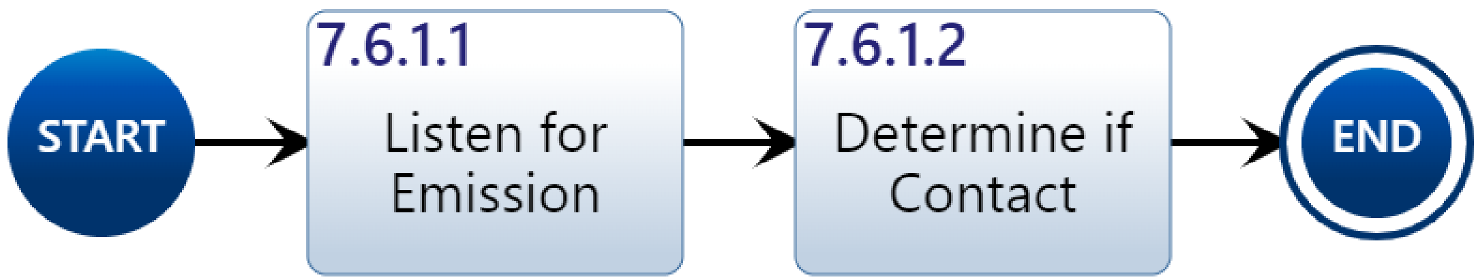


Diagram derived from the CONOPS in [3].

Figure A.13. PD Threat Detected Activity Decomposition Diagram

A.1.8 Information Operations

The following is the Information Operations (IO) Activity Diagram derived from the CONOPS in [3].

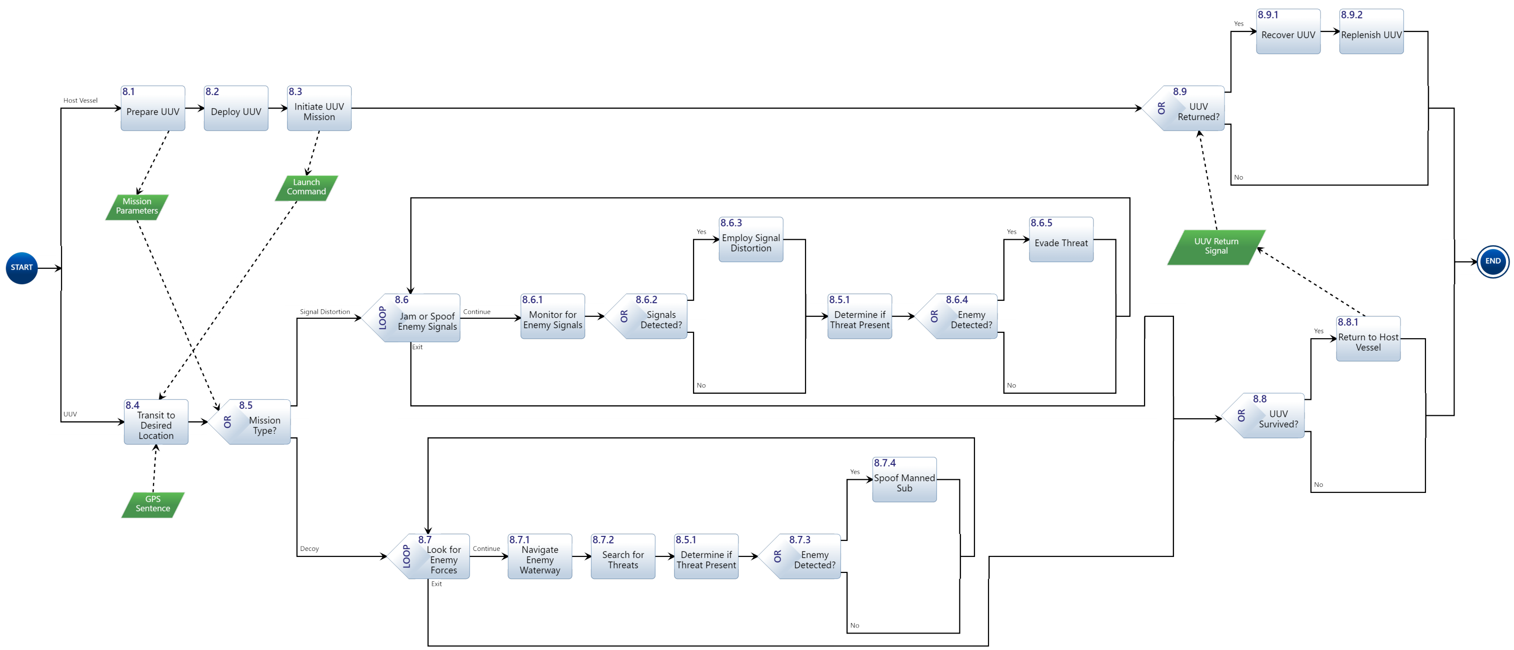


Diagram derived from the CONOPS in [3].

Figure A.14. IO Activity Diagram

A.1.9 Time Critical Strike

The following are the Time Critical Strike (TCS) Activity Diagrams derived from the CONOPS in [3].

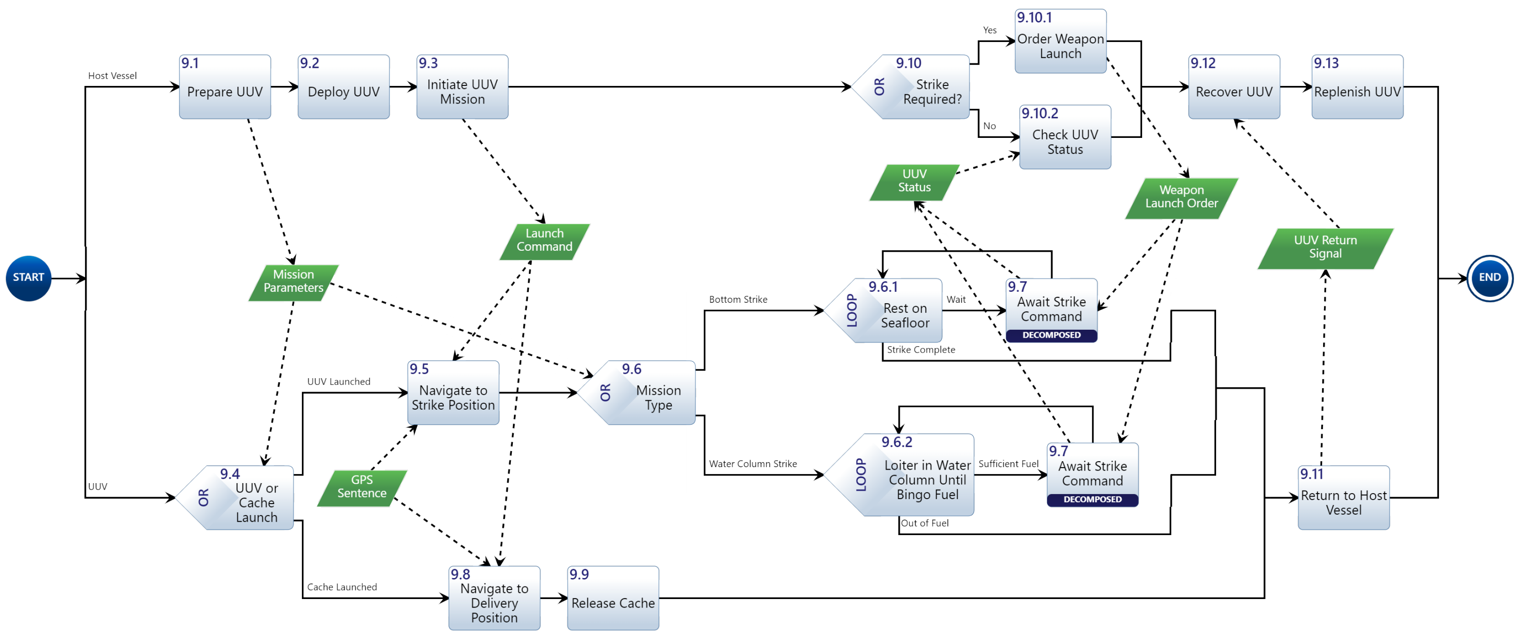


Diagram derived from the CONOPS in [3].

Figure A.15. TCS Activity Diagram

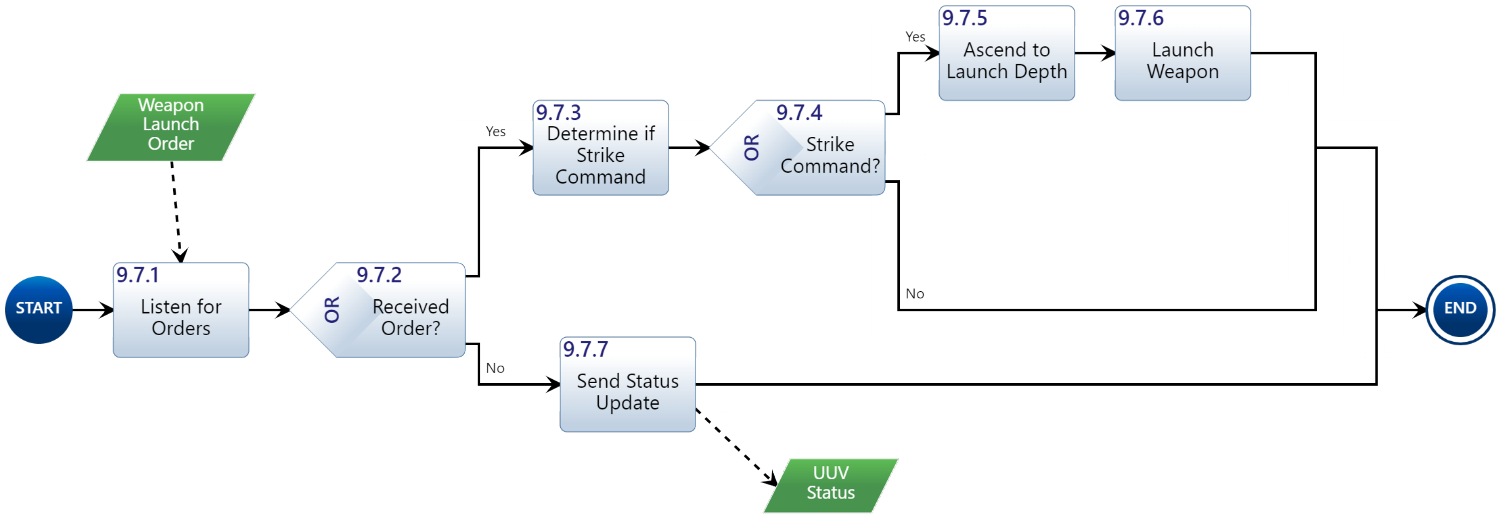


Diagram derived from the CONOPS in [3].

Figure A.16. TCS Await Strike Command Activity Decomposition Diagram

A.2 Interface Diagrams

The following are the Innoslate produced SysML Interface Diagrams derived from the Activity Diagrams in Appendix A.1 for the nine mission profiles.

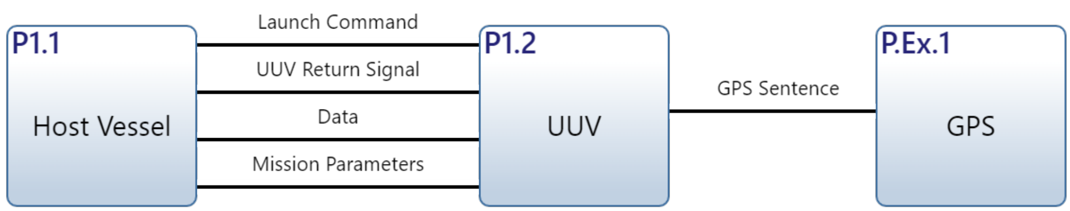


Figure A.17. ISR Interface Diagram

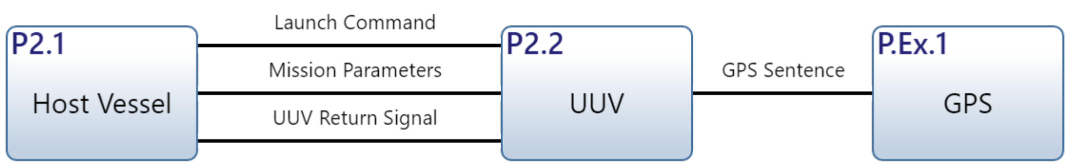


Figure A.18. MCM Interface Diagram

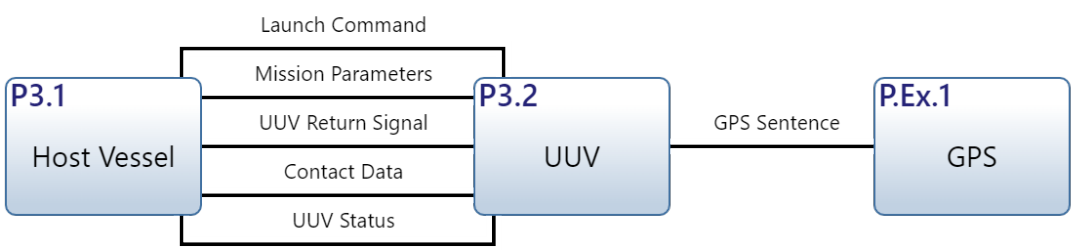


Figure A.19. ASW Interface Diagram

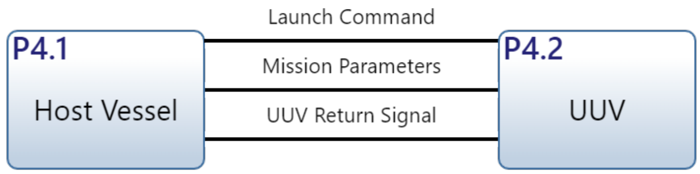


Figure A.20. INID Interface Diagram

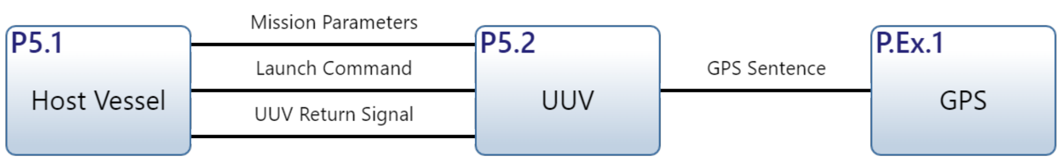


Figure A.21. OO Interface Diagram

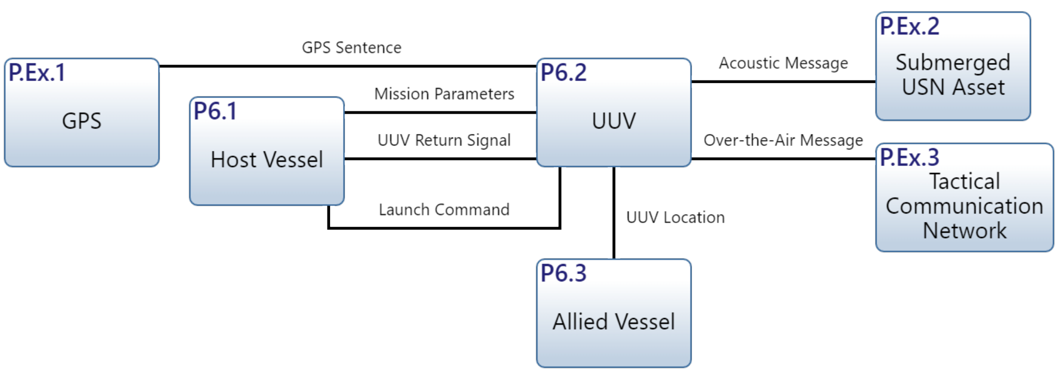


Figure A.22. CN3 Interface Diagram

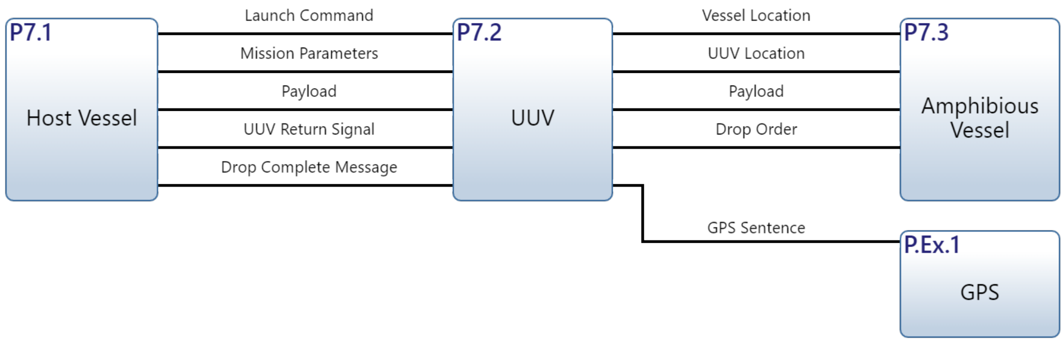


Figure A.23. PD Interface Diagram

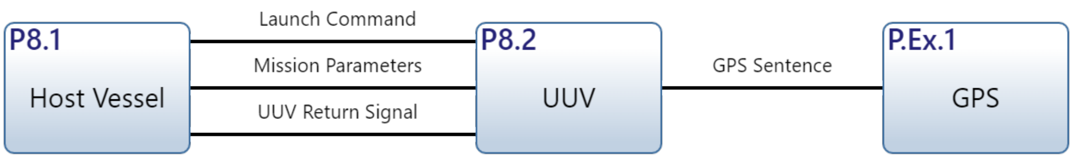


Figure A.24. IO Interface Diagram

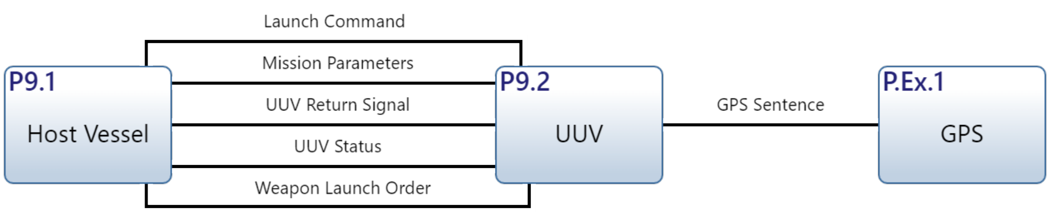


Figure A.25. TCS Interface Diagram

A.3 Requirement Diagrams

The following are the Innoslate produced SysML Requirement Diagrams for the nine mission profiles. Some diagrams contain decomposed nodes; where that is the case the child diagrams follow their parent.

A.3.1 Intelligence, Surveillance, and Reconnaissance

The following are the Intelligence, Surveillance, and Reconnaissance (ISR) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

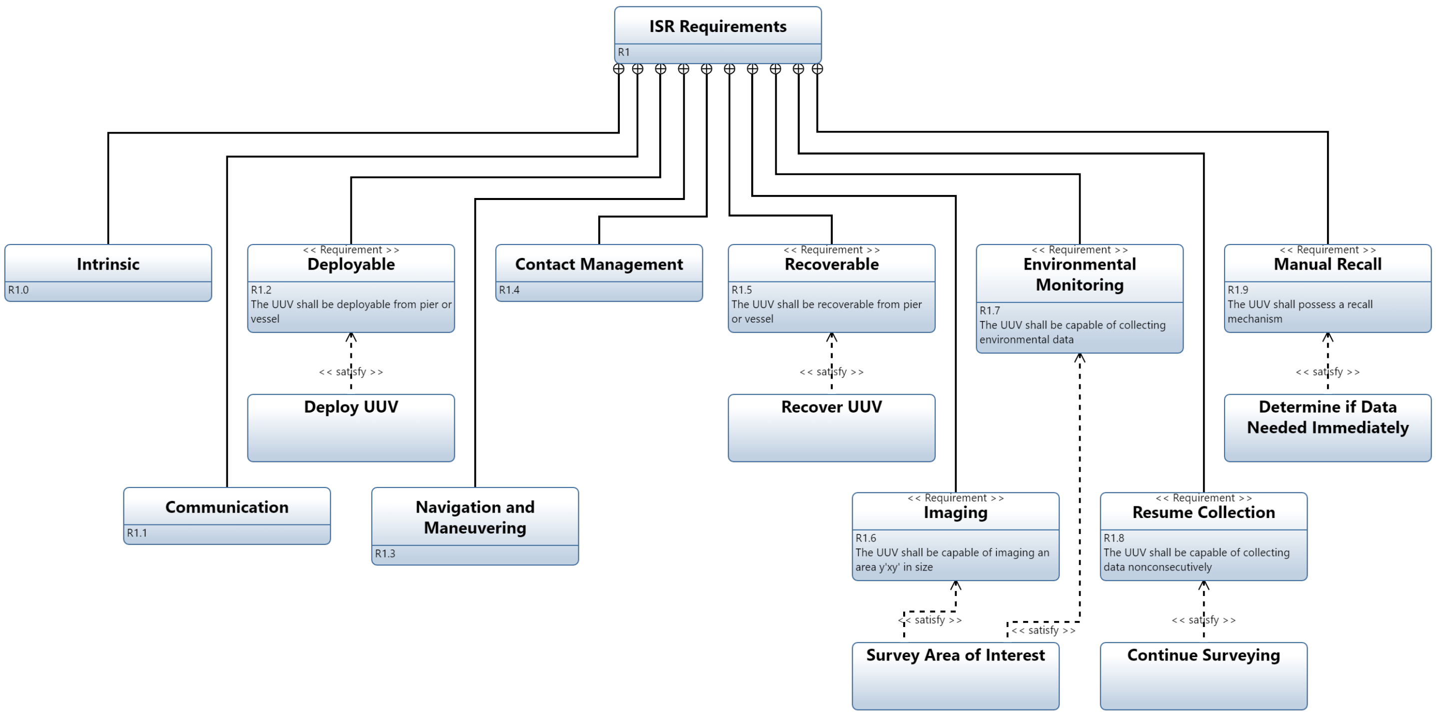


Figure A.26. ISR Requirement Diagram

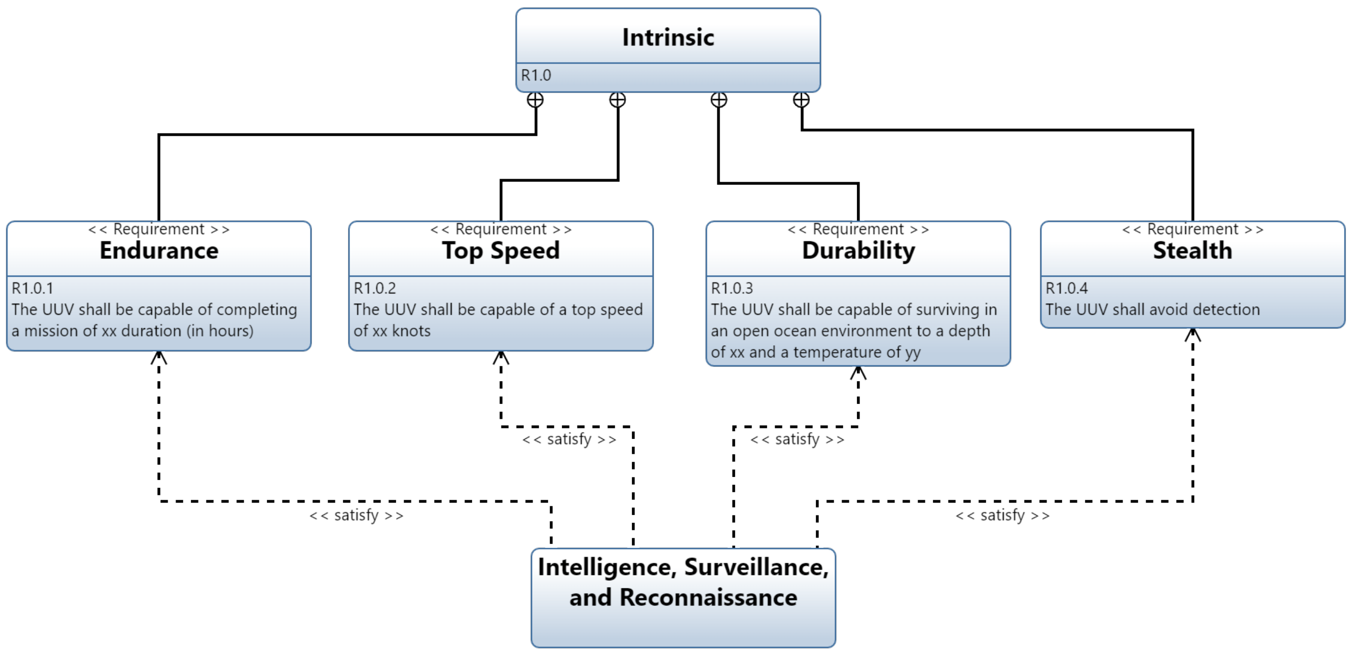


Figure A.27. ISR Intrinsic Requirement Decomposition Diagram

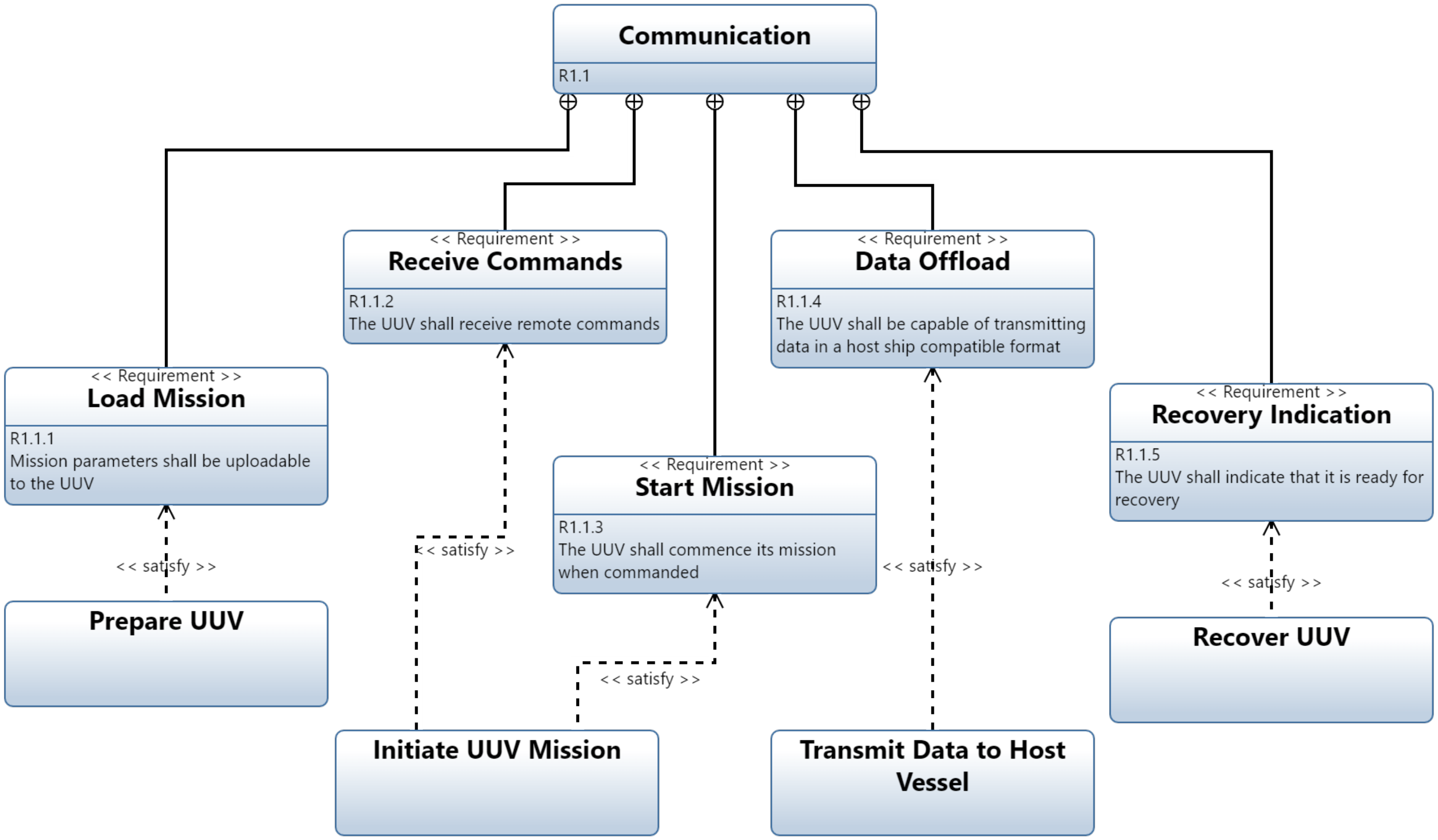


Figure A.28. ISR Communication Requirement Decomposition Diagram

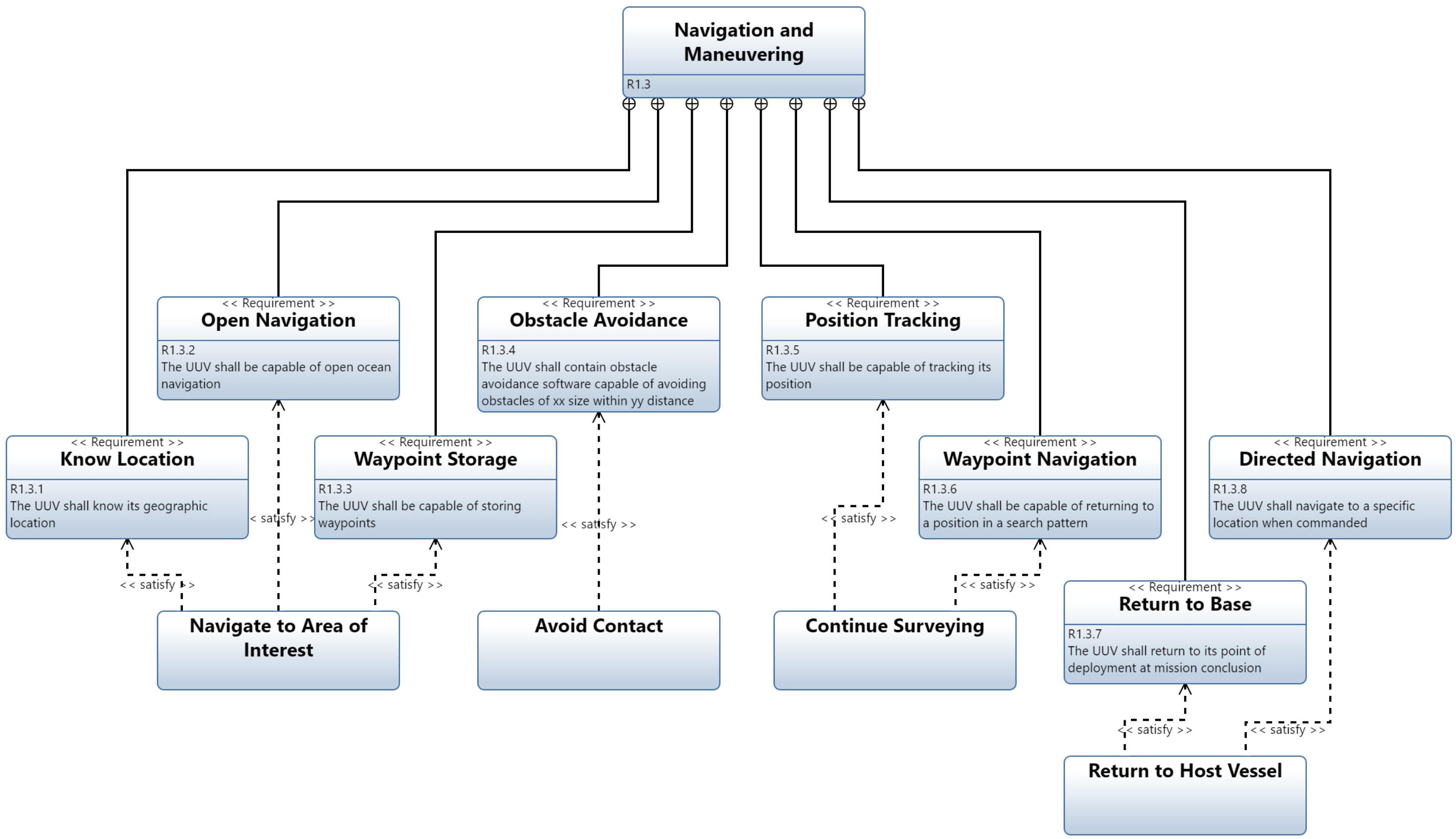


Figure A.29. ISR Navigation and Maneuvering Requirement Decomposition Diagram

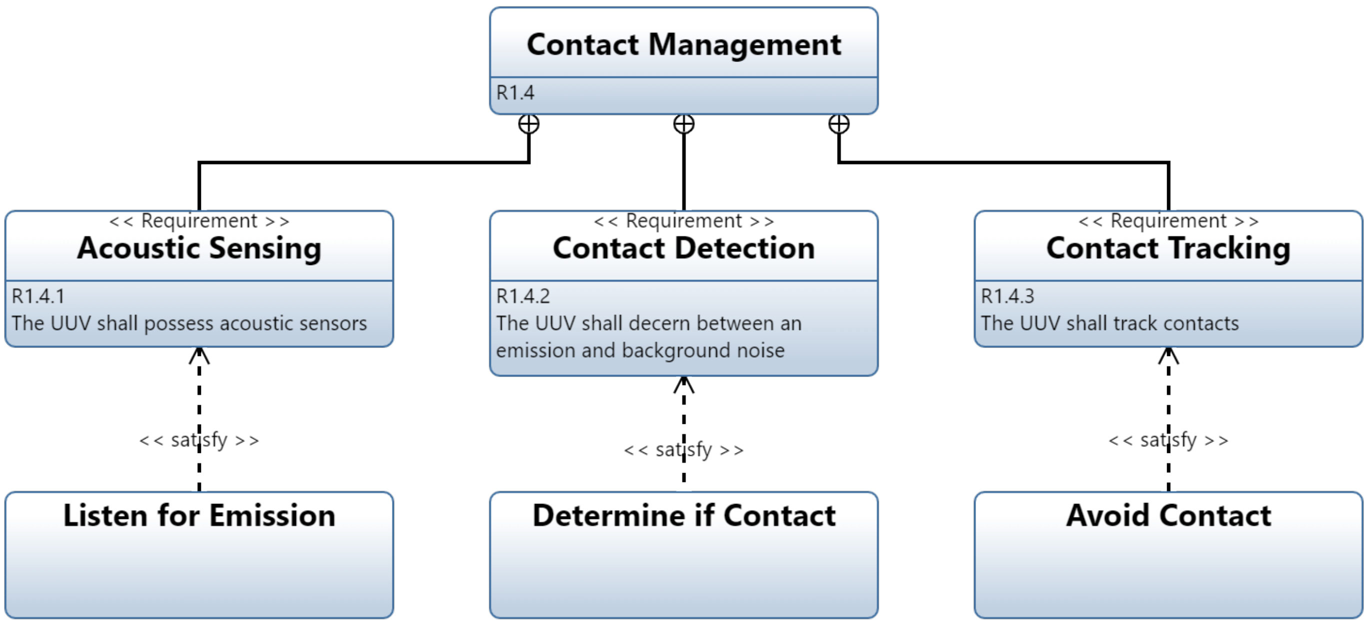


Figure A.30. ISR Contact Management Requirement Decomposition Diagram

A.3.2 Mine Countermeasures

The following are the Mine Countermeasures (MCM) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

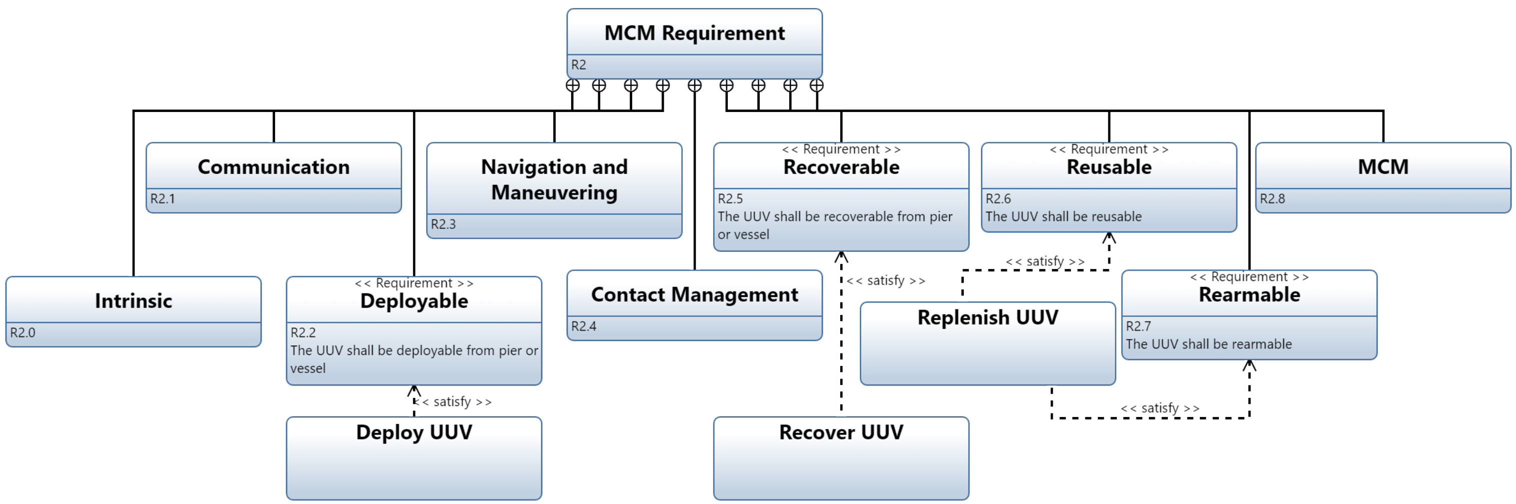


Figure A.31. MCM Requirement Diagram

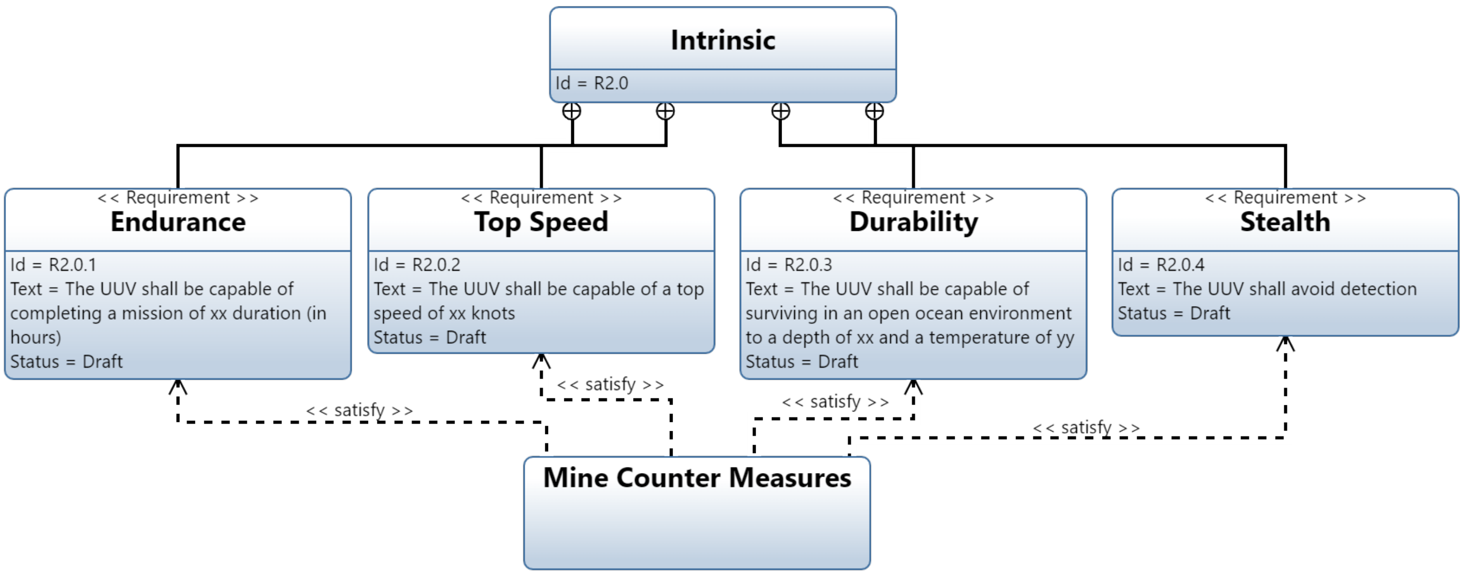


Figure A.32. MCM Intrinsic Requirement Decomposition Diagram

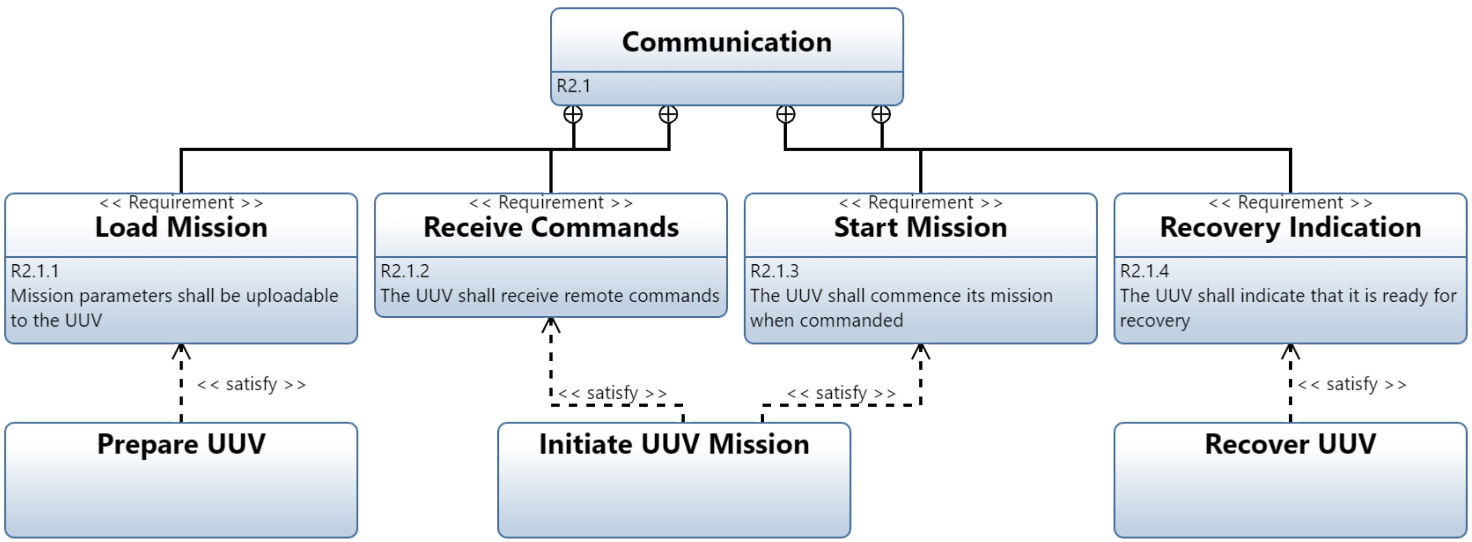


Figure A.33. MCM Communication Requirement Decomposition Diagram

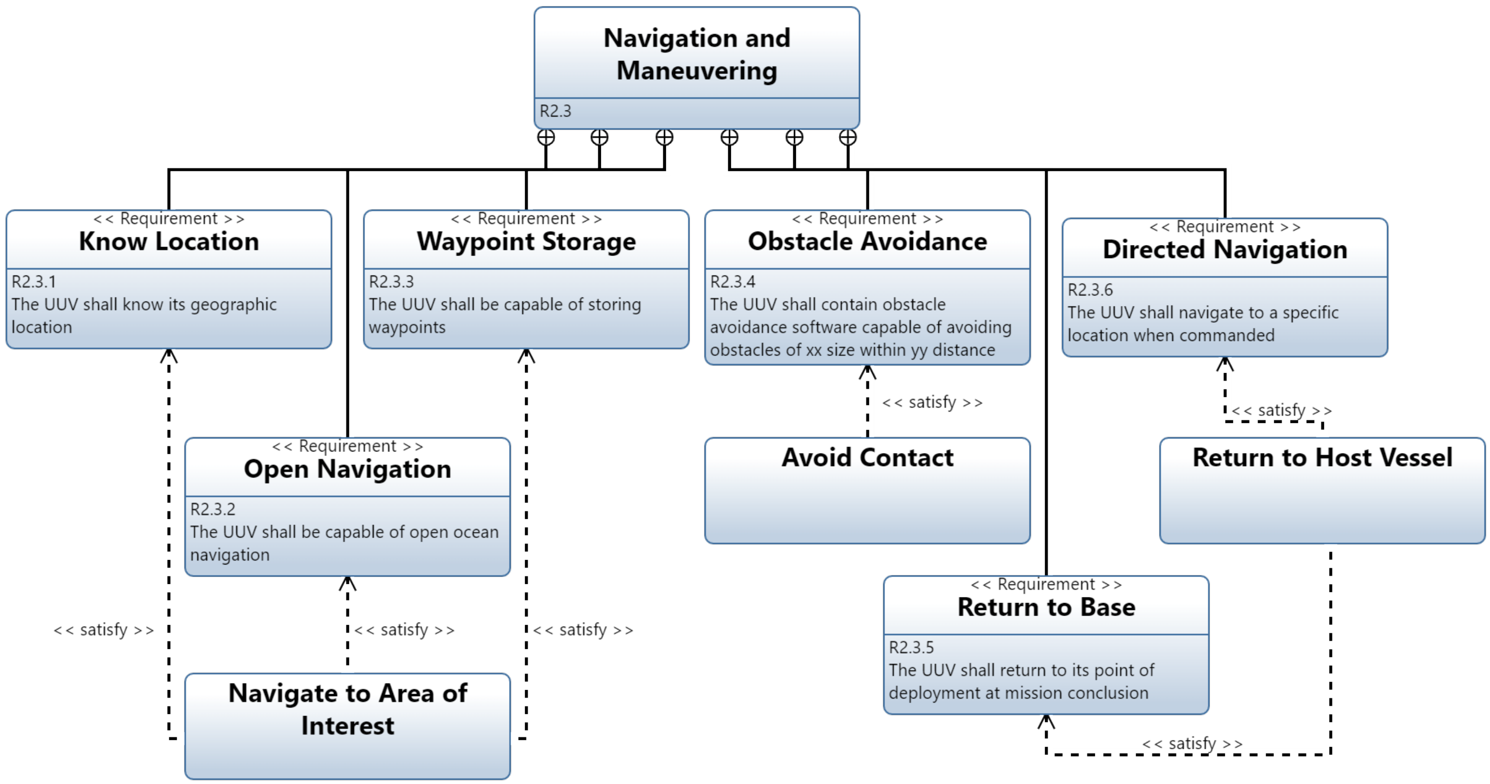


Figure A.34. MCM Navigation and Maneuvering Requirement Decomposition Diagram

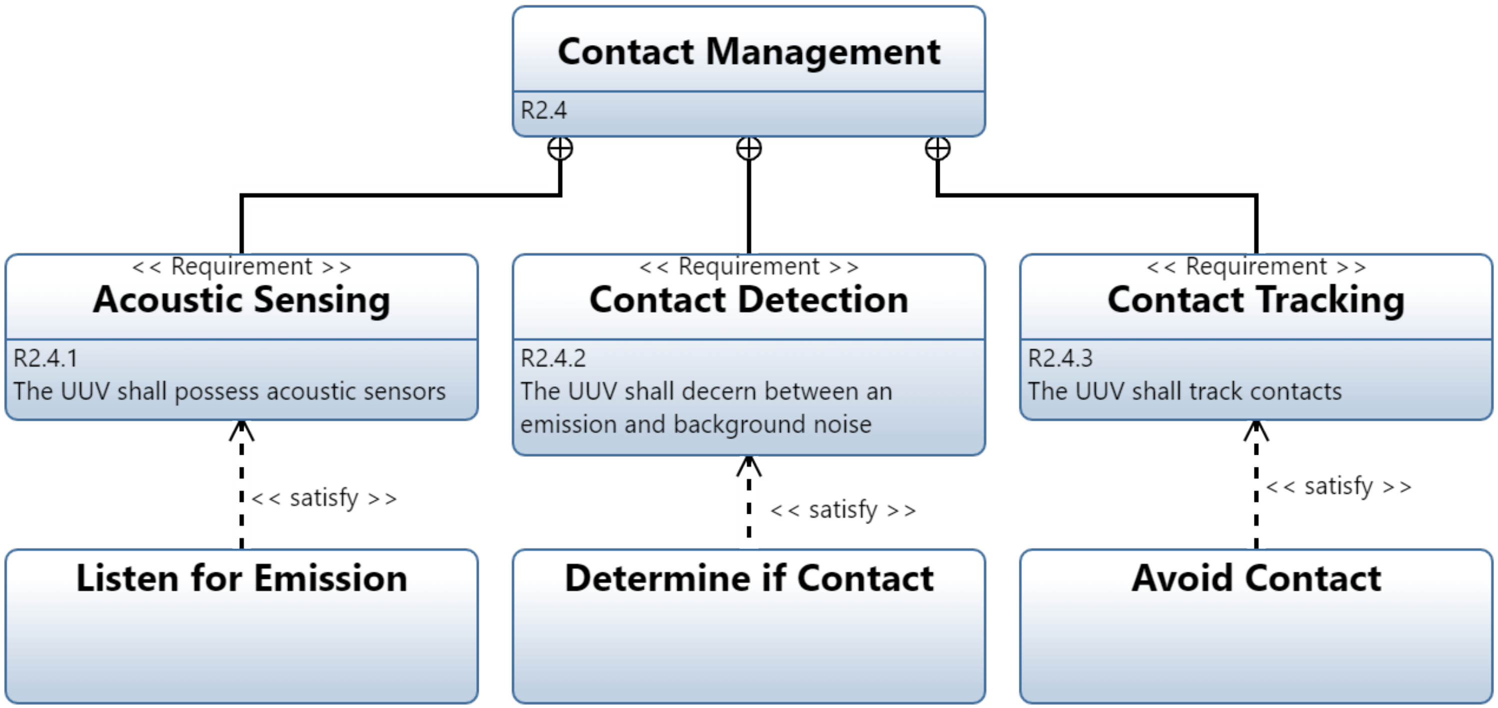


Figure A.35. MCM Contact Management Requirement Decomposition Diagram

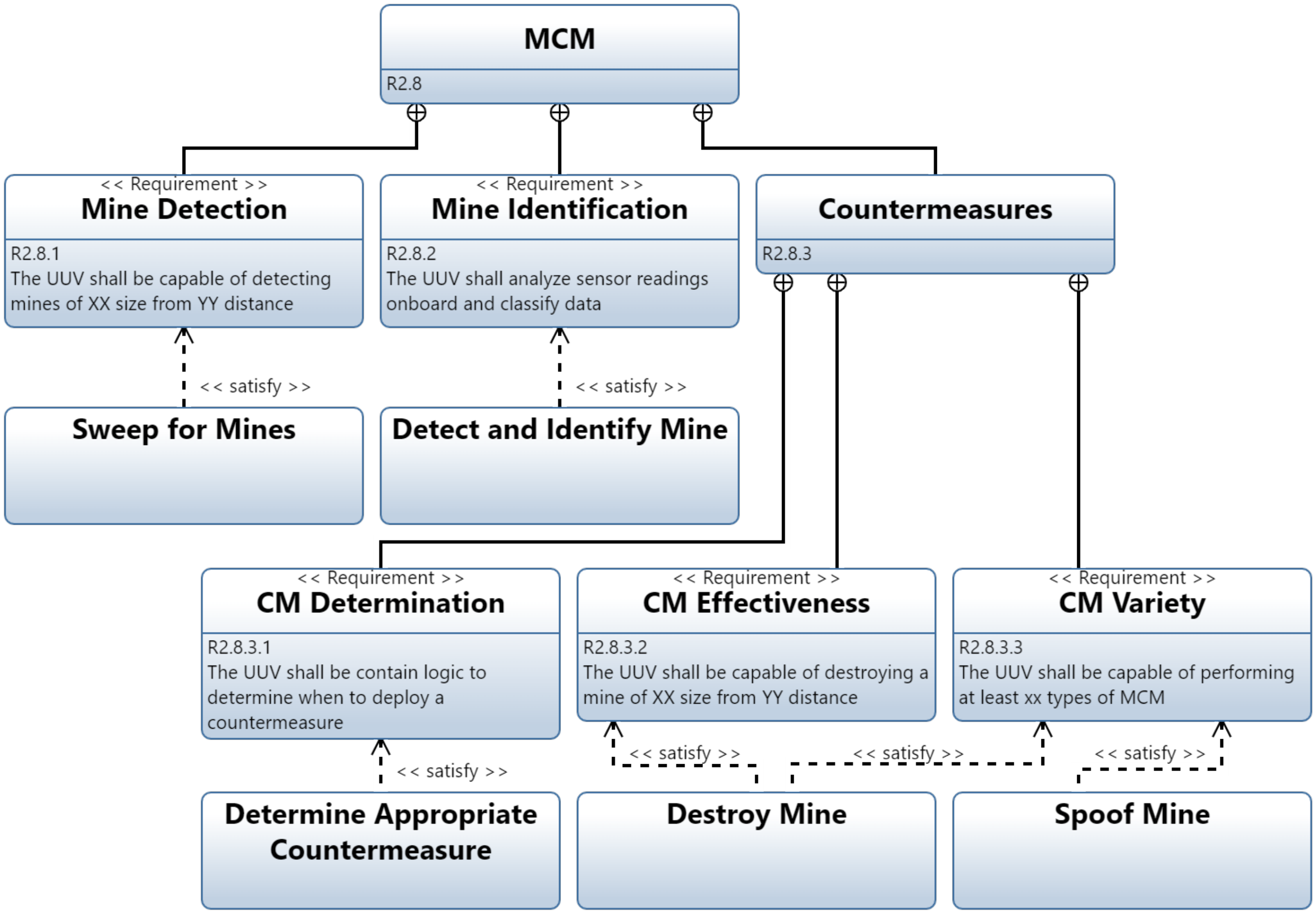


Figure A.36. MCM Requirement Decomposition Diagram

A.3.3 Anti-Submarine Warfare

The following are the Anti-Submarine Warfare (ASW) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

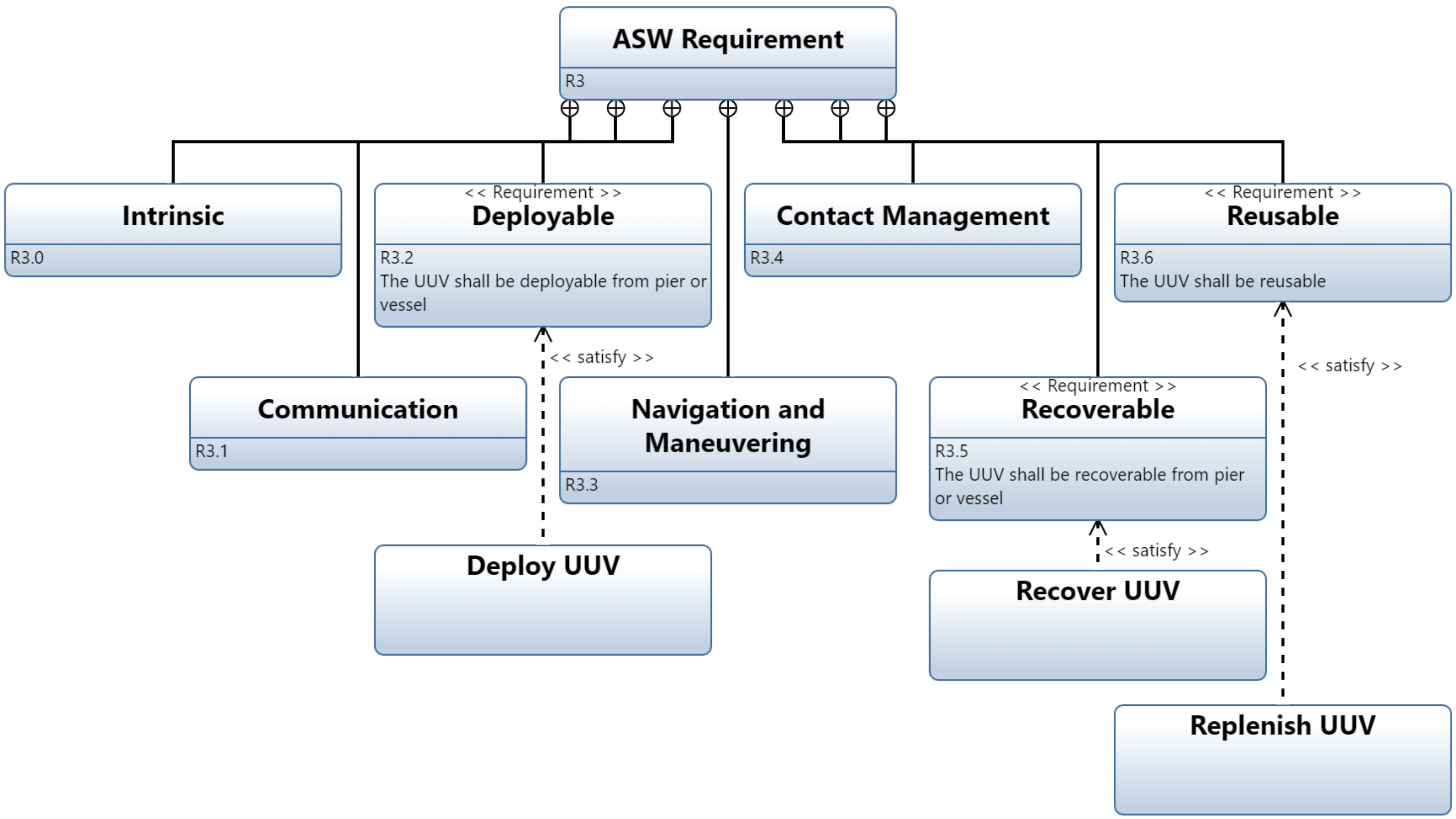


Figure A.37. ASW Requirement Diagram

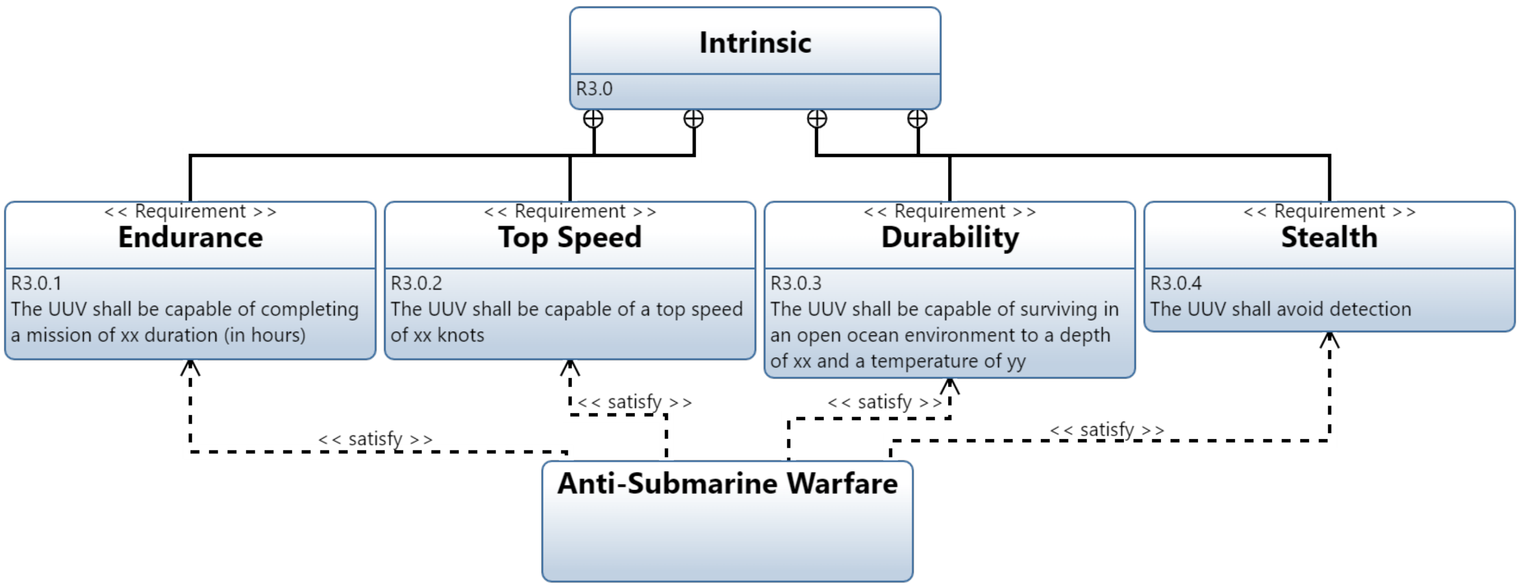


Figure A.38. ASW Intrinsic Requirement Decomposition Diagram

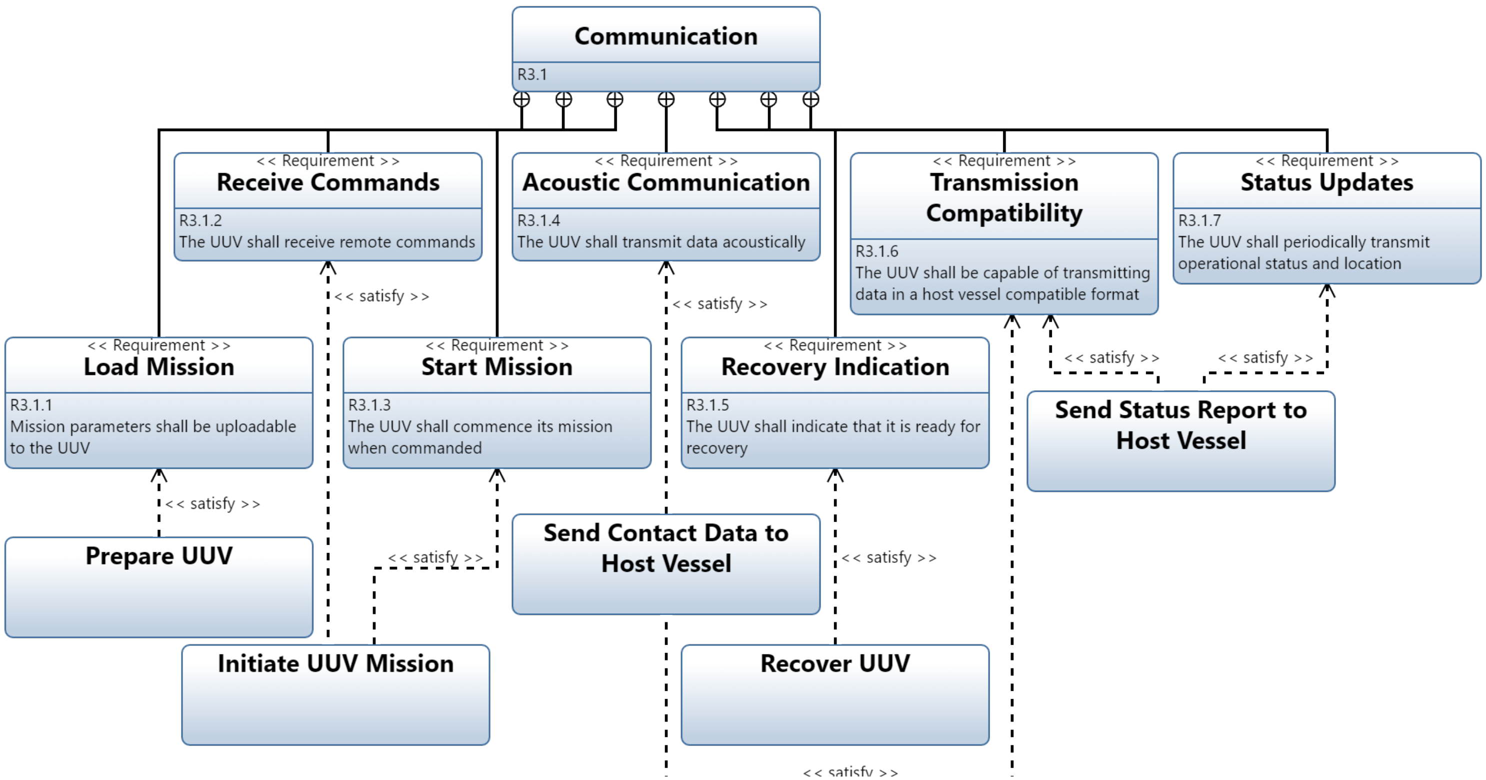


Figure A.39. ASW Communication Requirement Decomposition Diagram

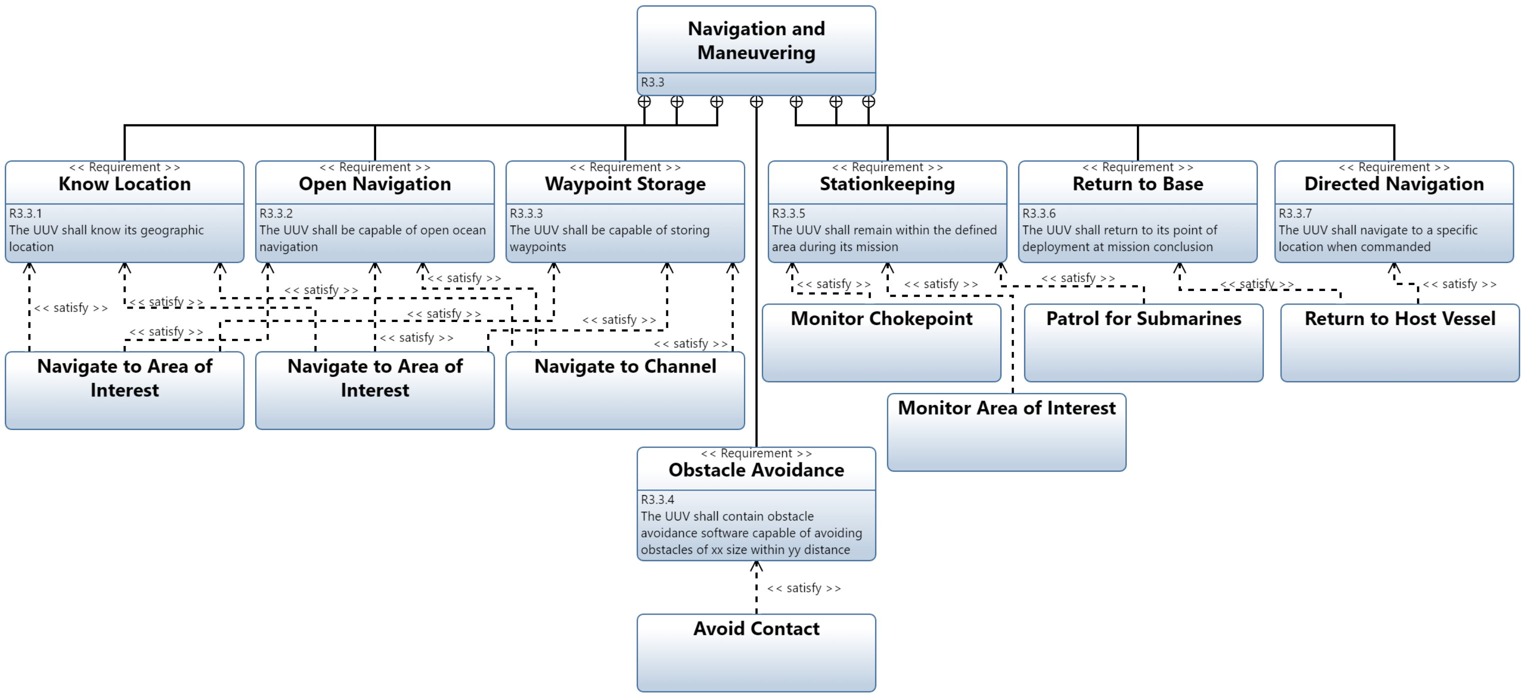


Figure A.40. ASW Navigation and Maneuvering Requirement Decomposition Diagram

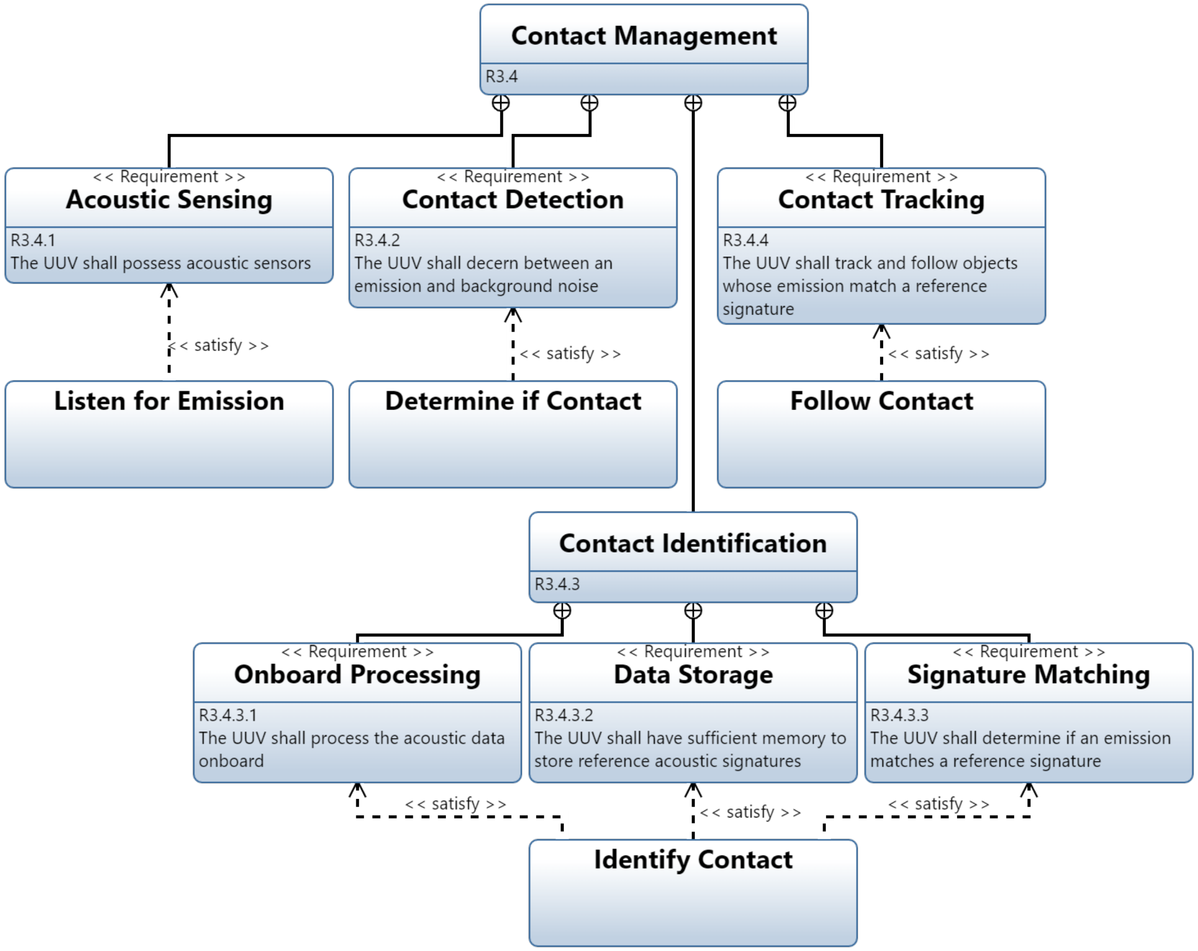


Figure A.41. ASW Contact Management Requirement Decomposition Diagram

A.3.4 Inspection and Identification

The following are the Inspection and Identification (INID) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

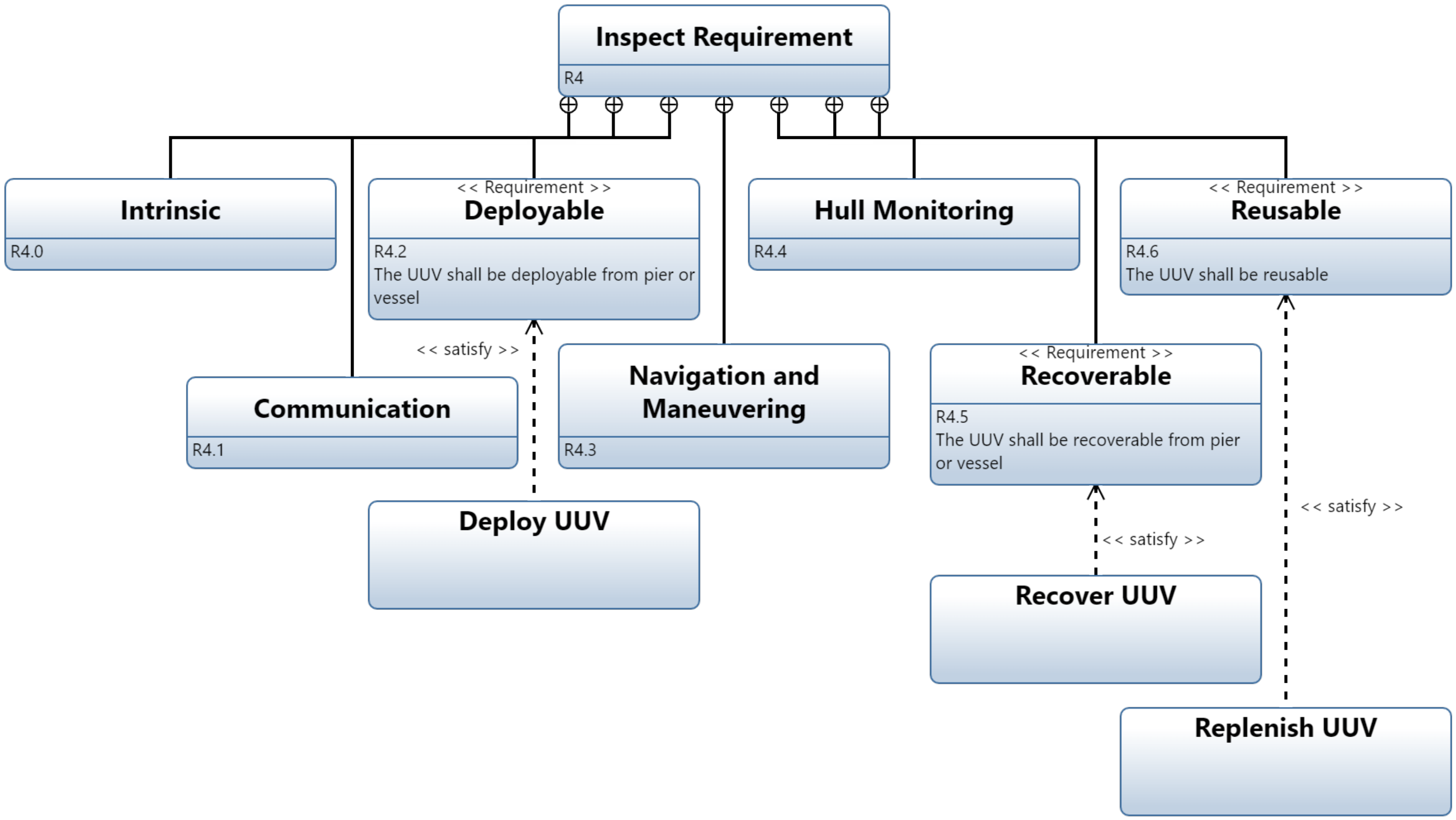


Figure A.42. INID Requirement Diagram

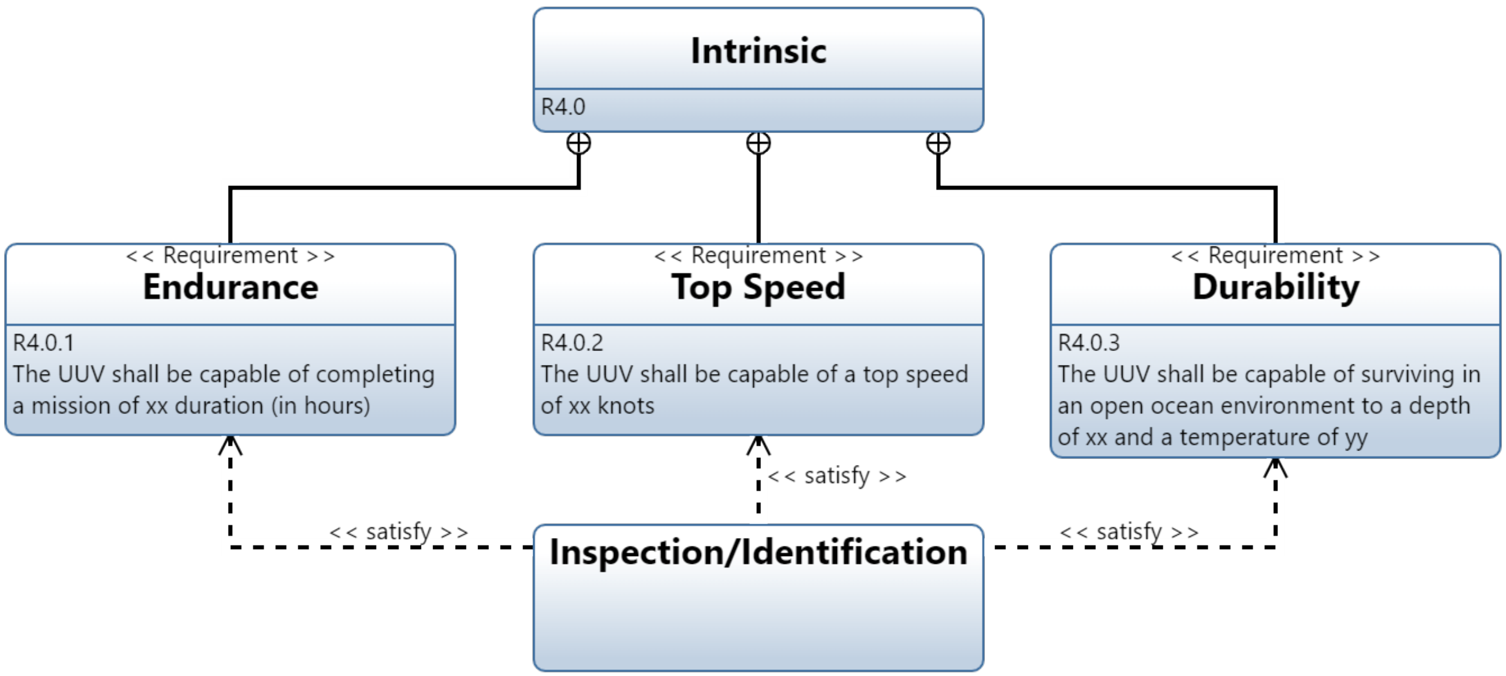


Figure A.43. INID Intrinsic Requirement Decomposition Diagram

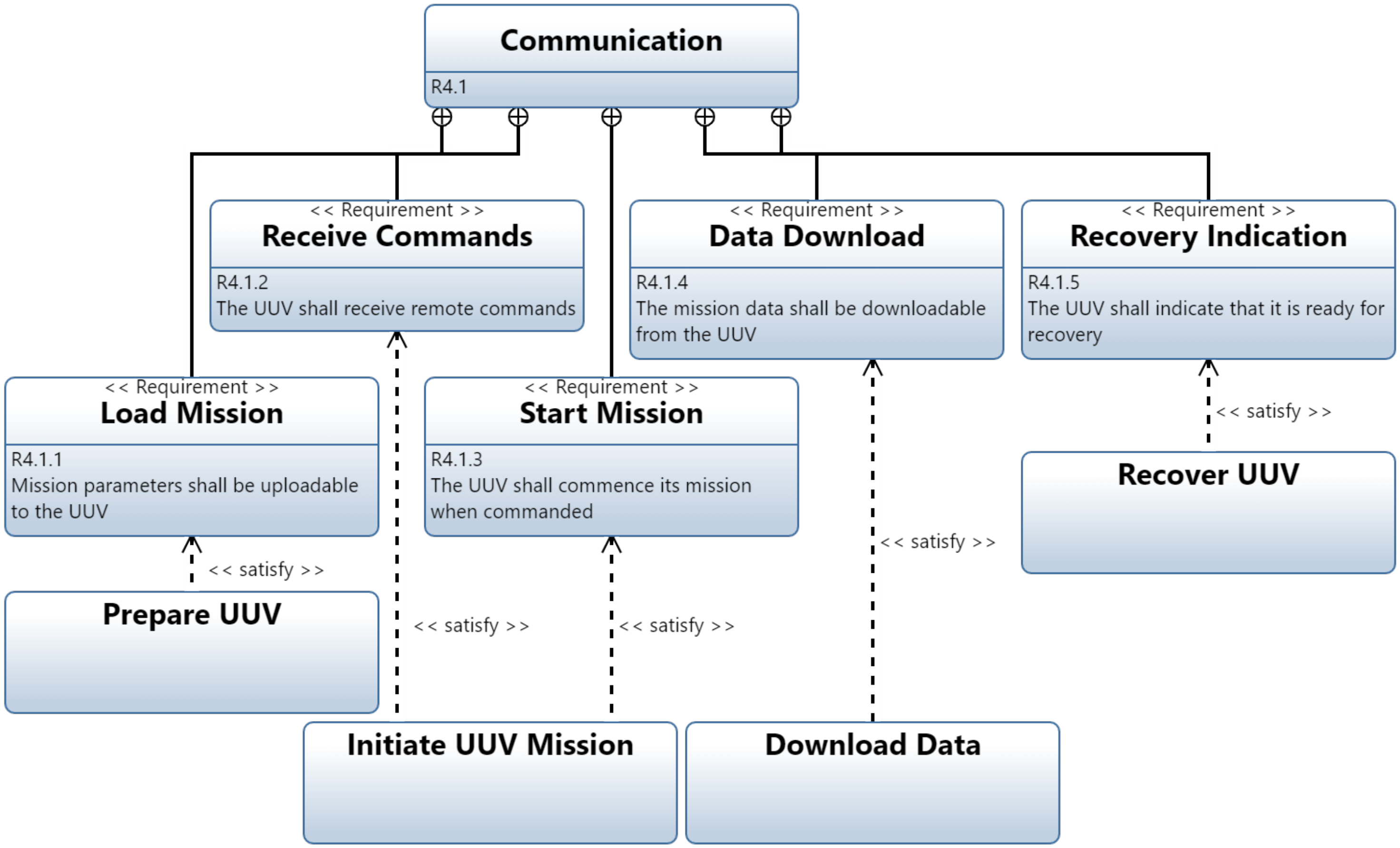


Figure A.44. INID Communication Requirement Decomposition Diagram

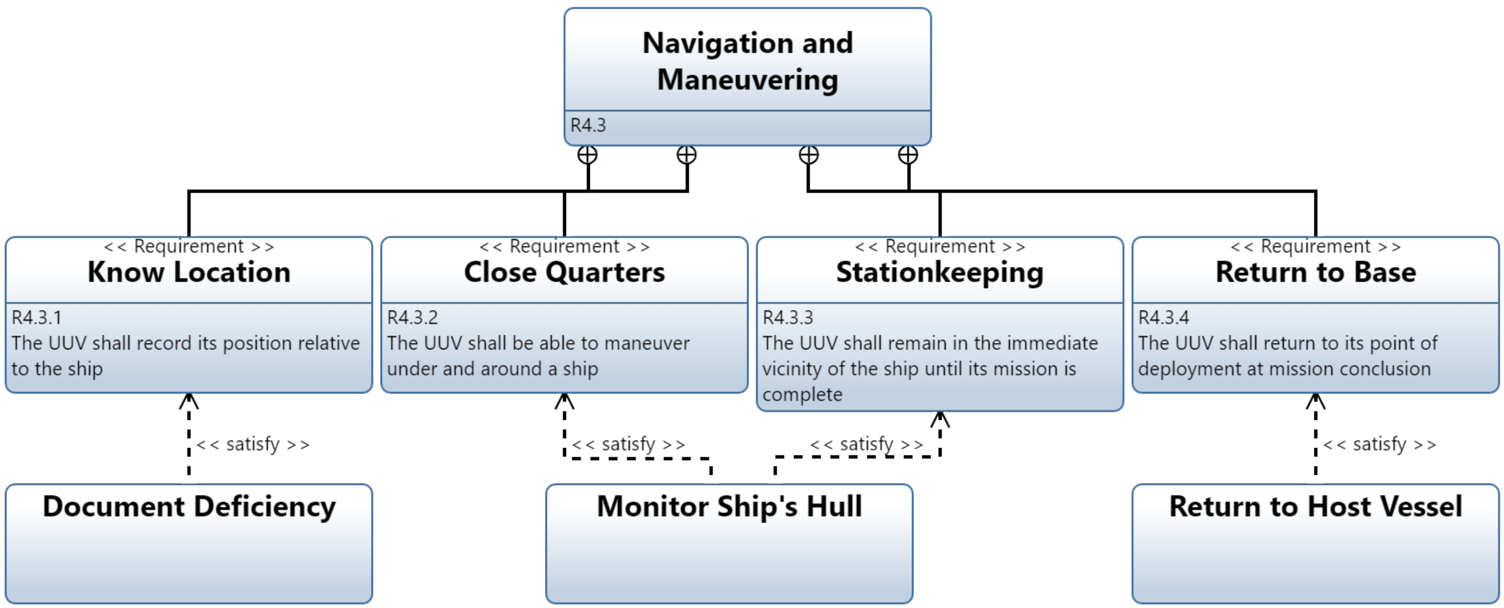


Figure A.45. INID Navigation and Maneuvering Requirement Decomposition Diagram

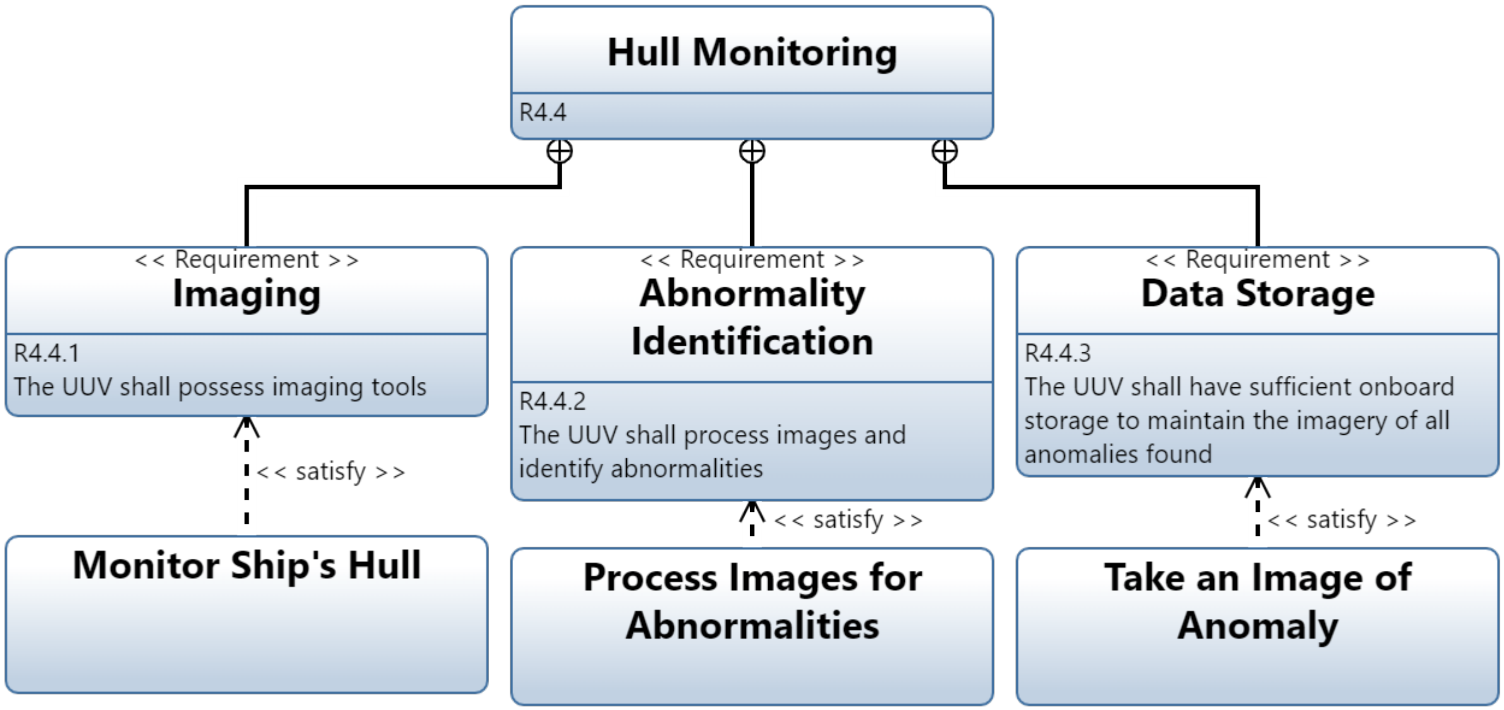


Figure A.46. INID Hull Monitoring Requirement Decomposition Diagram

A.3.5 Oceanography

The following are the Oceanography (OO) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

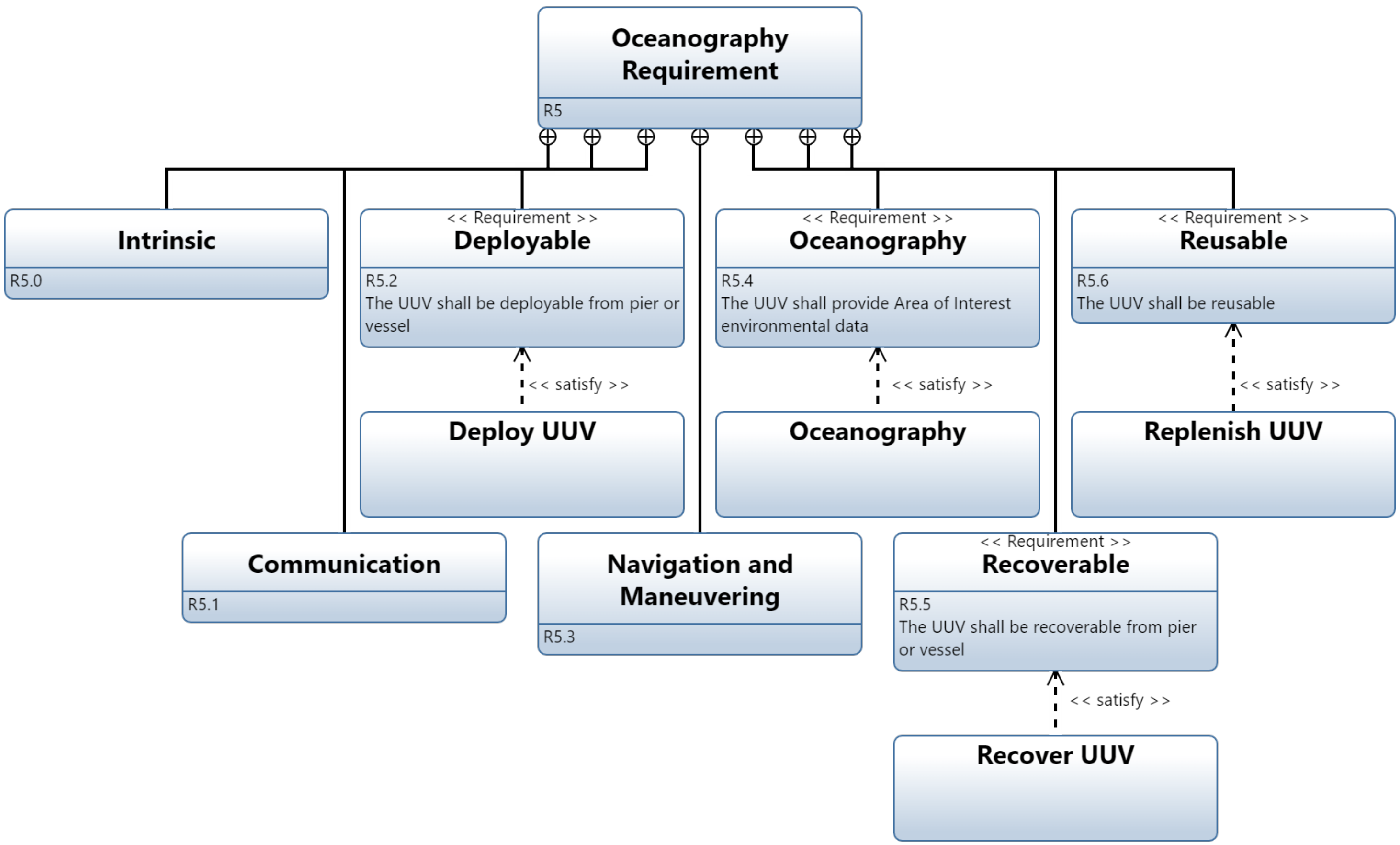


Figure A.47. OO Requirement Diagram

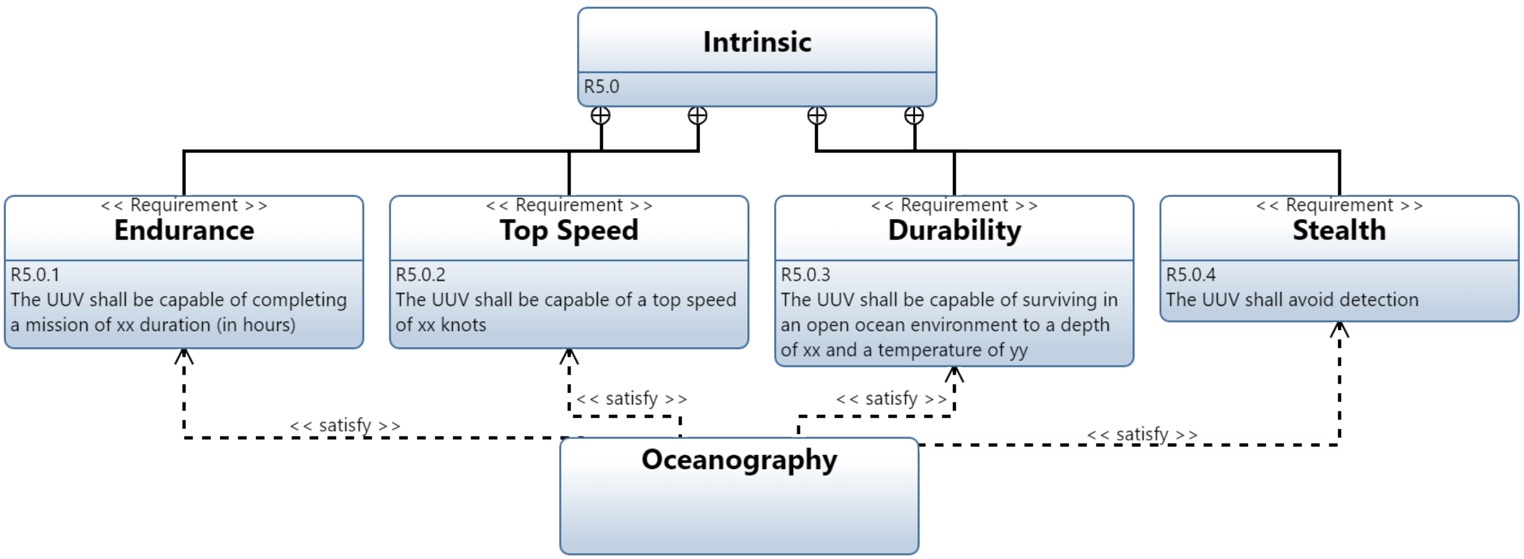


Figure A.48. OO Intrinsic Requirement Decomposition Diagram

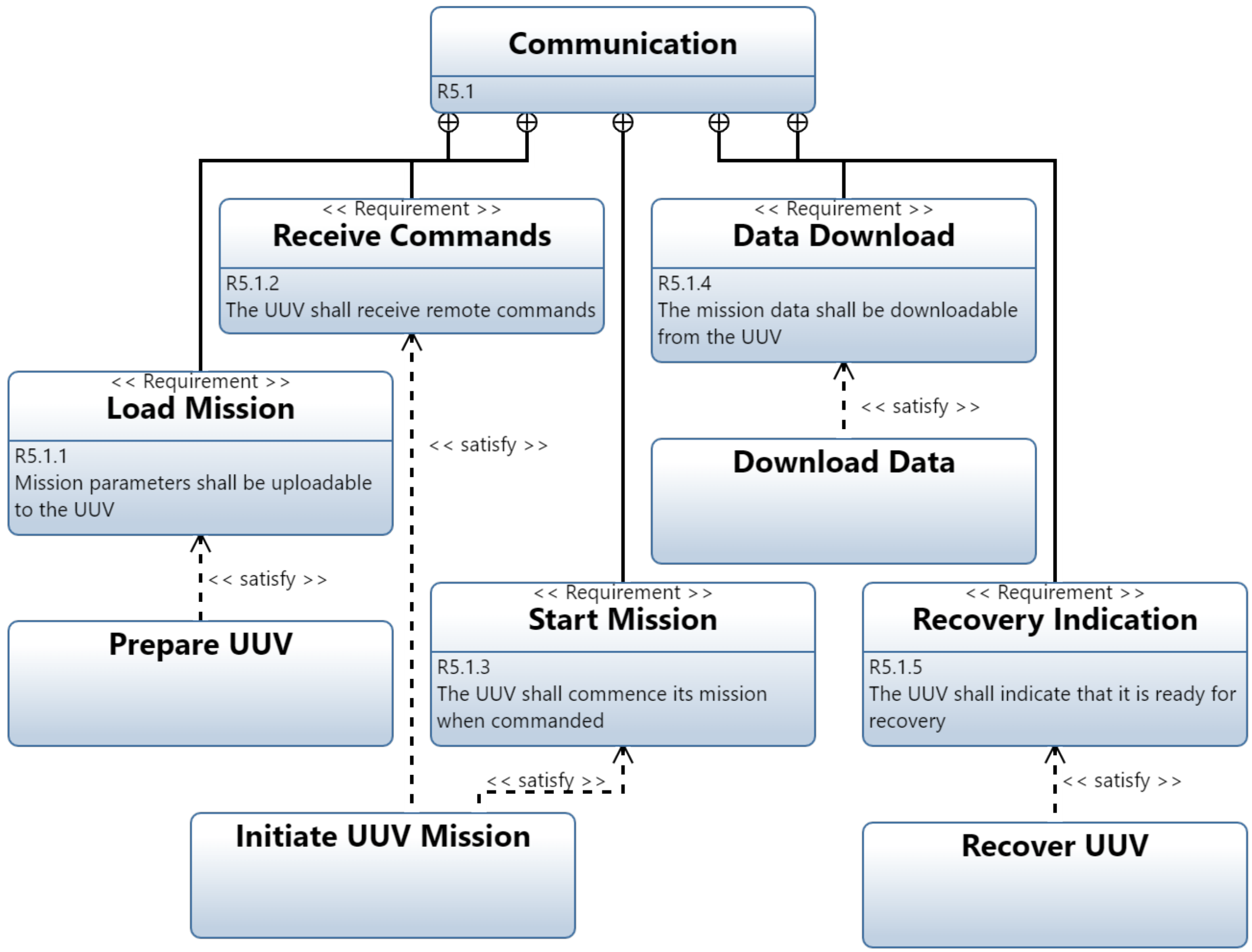


Figure A.49. OO Communication Requirement Decomposition Diagram

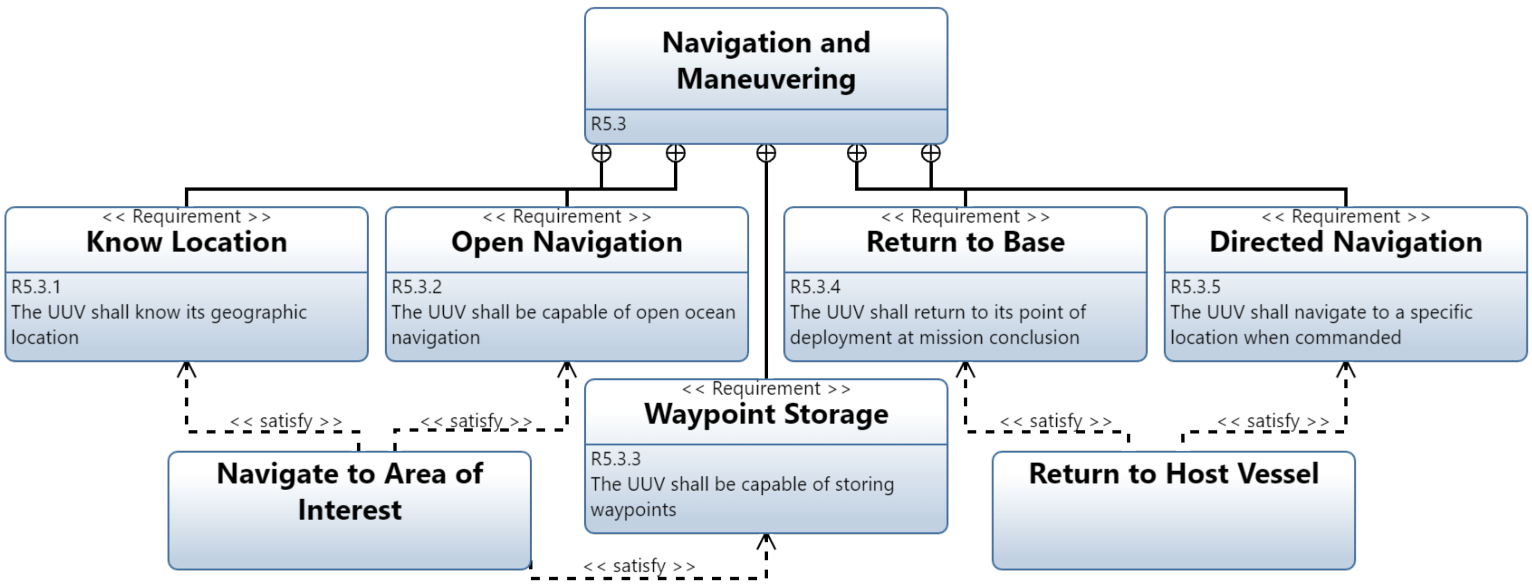


Figure A.50. OO Navigation and Maneuvering Requirement Decomposition Diagram

A.3.6 Communication or Navigation Network Node

The following are the Communication or Navigation Network Node (CN3) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

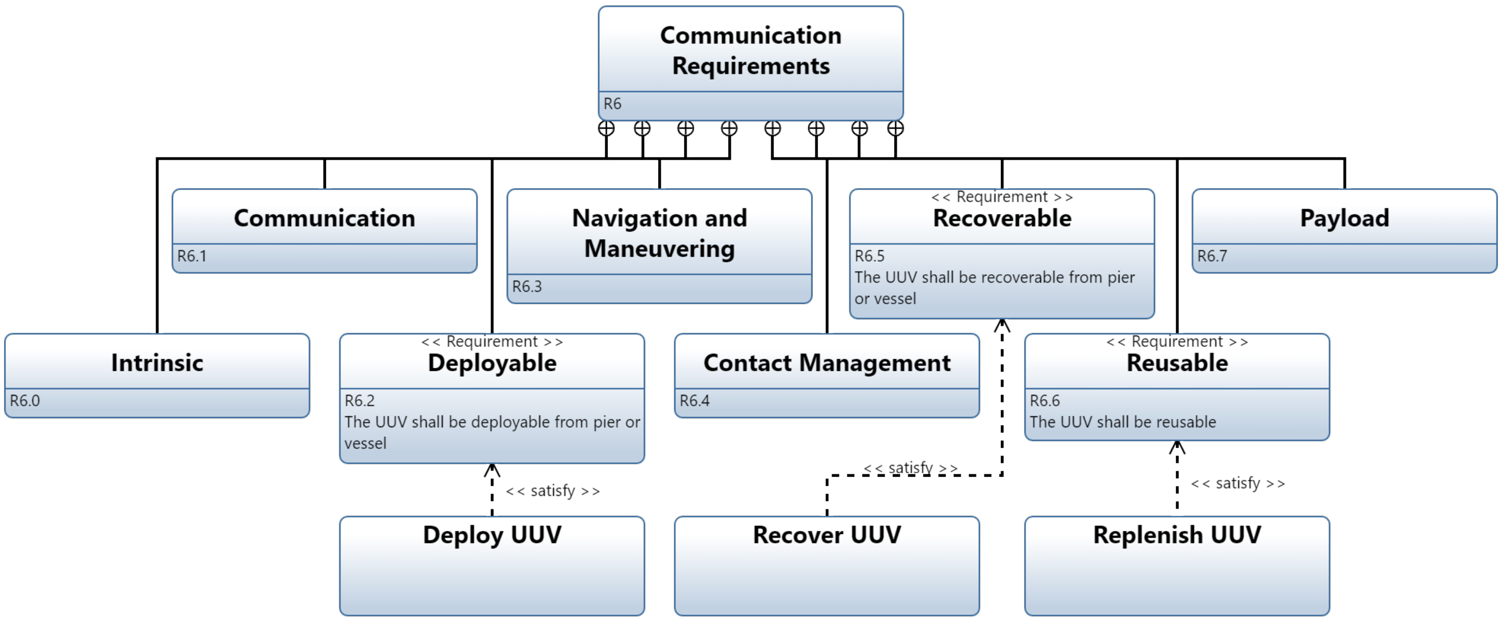


Figure A.51. CN3 Requirement Diagram

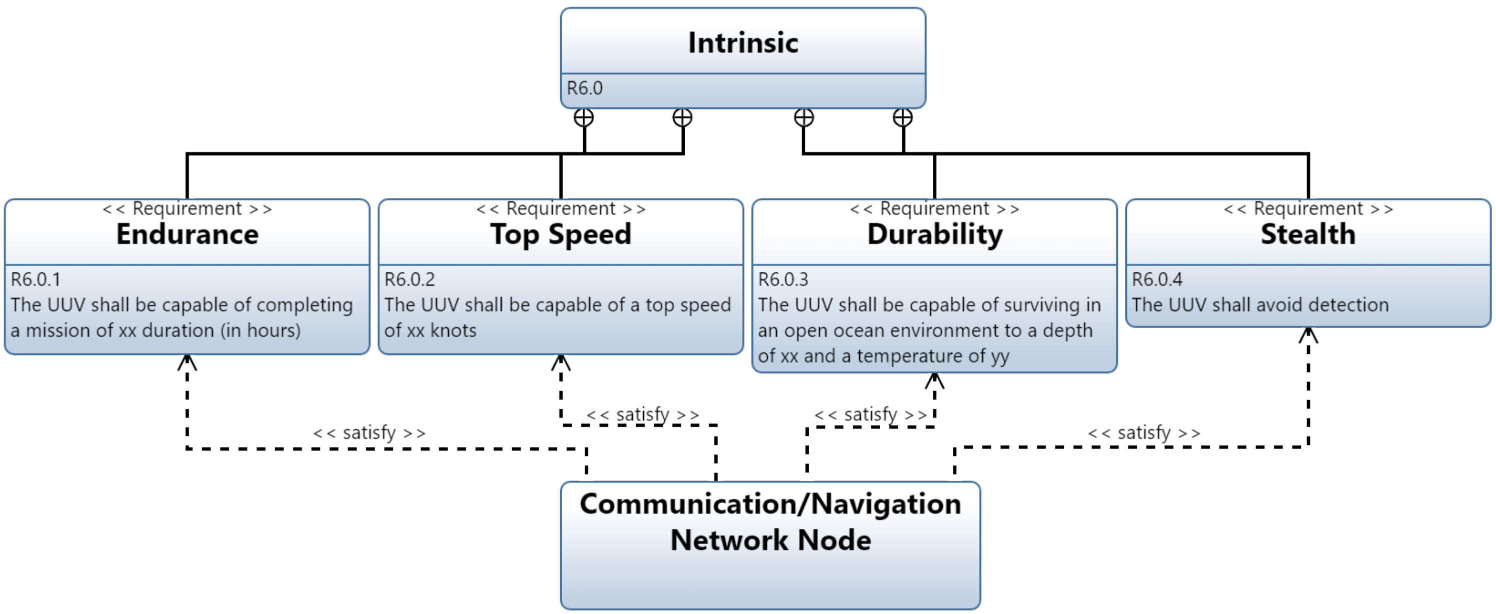


Figure A.52. CN3 Intrinsic Requirement Decomposition Diagram

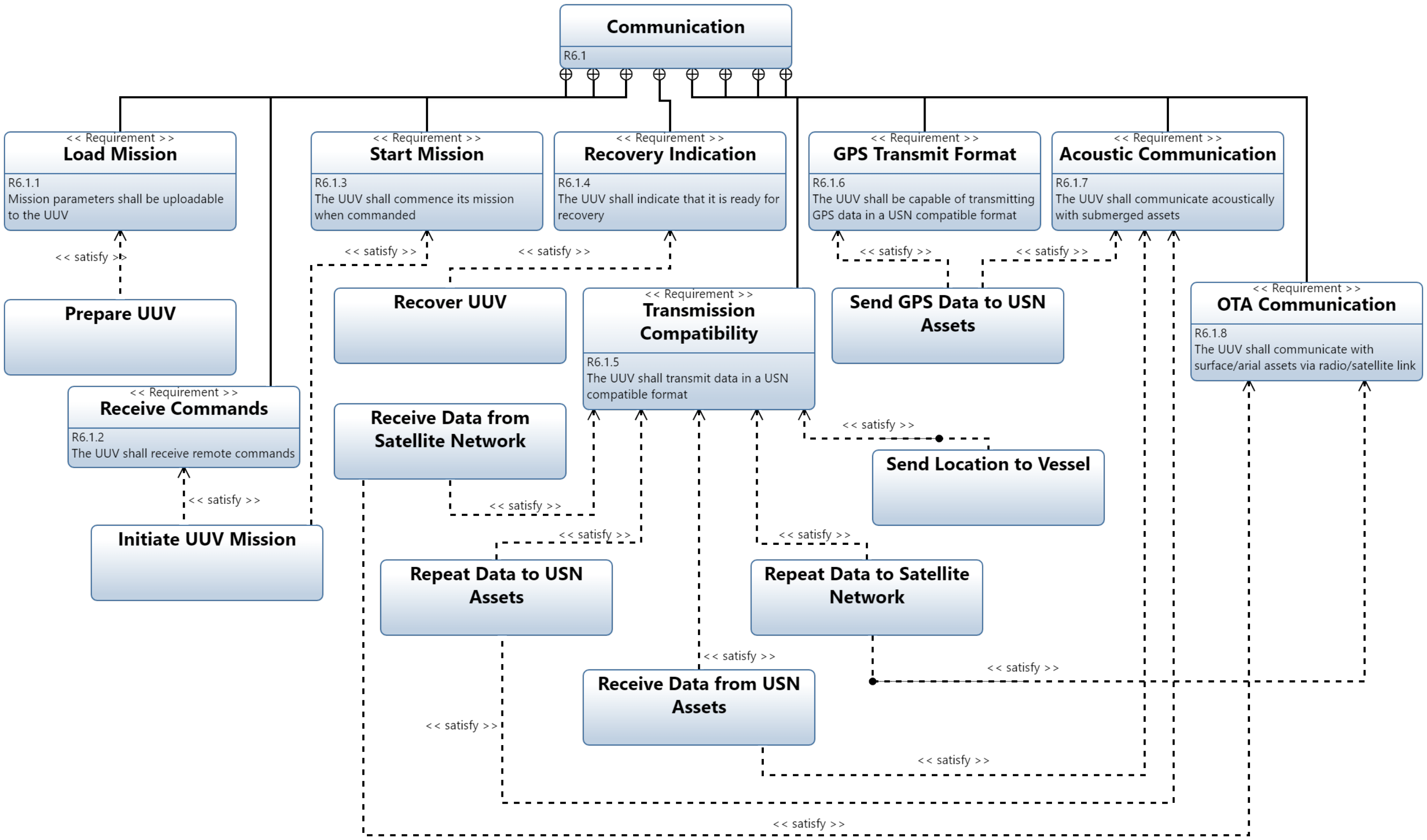


Figure A.53. CN3 Communication Requirement Decomposition Diagram

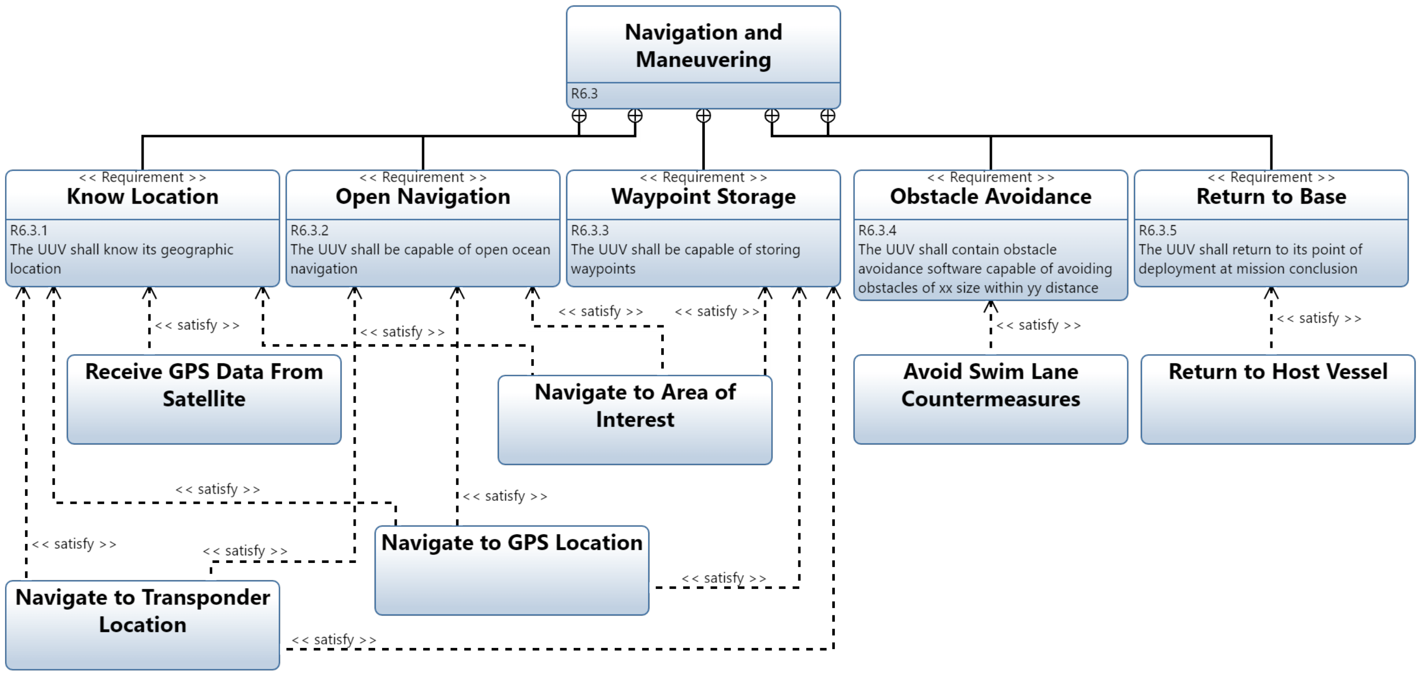


Figure A.54. CN3 Navigation and Maneuvering Requirement Decomposition Diagram

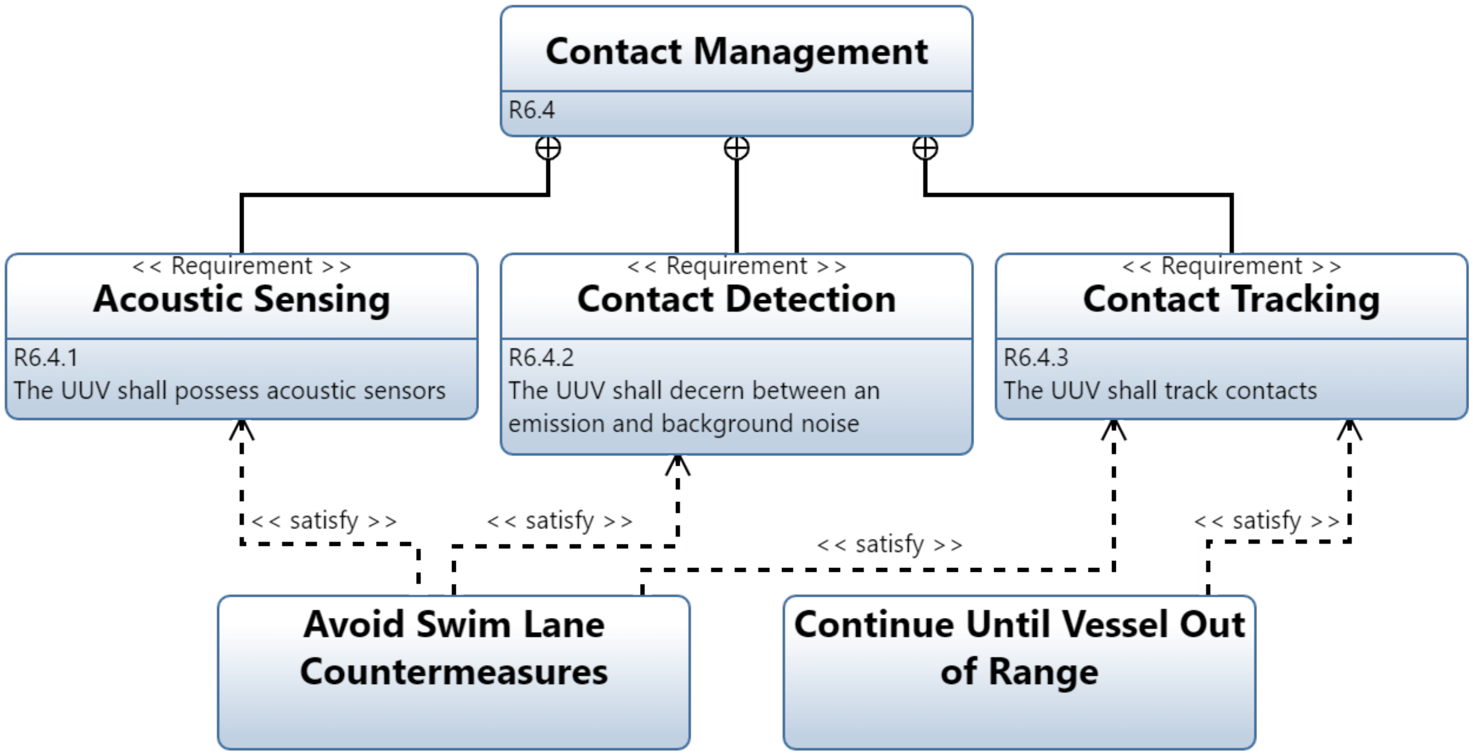


Figure A.55. CN3 Contact Management Requirement Decomposition Diagram

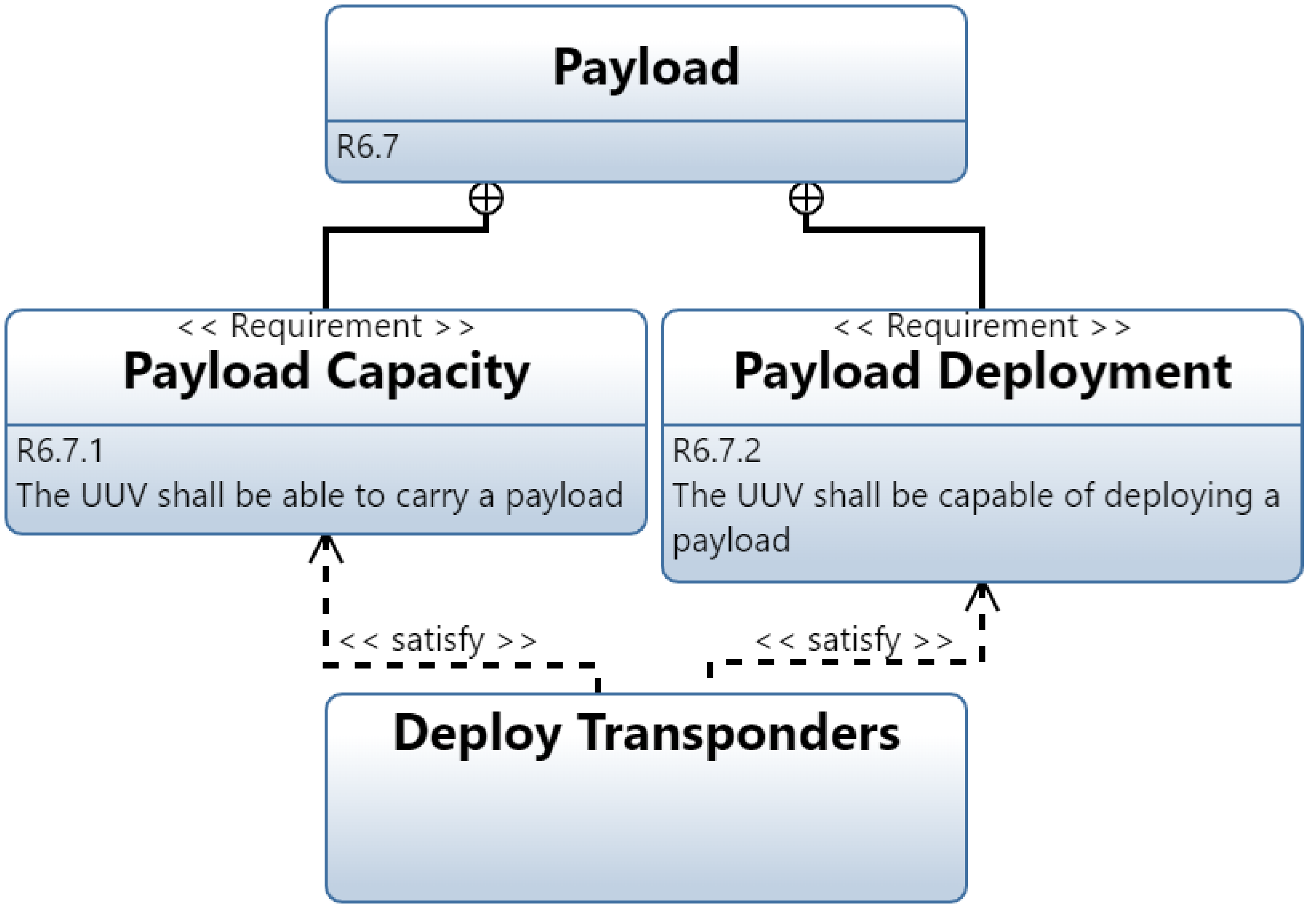


Figure A.56. CN3 Payload Requirement Decomposition Diagram

A.3.7 Payload Delivery

The following are the Payload Delivery (PD) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

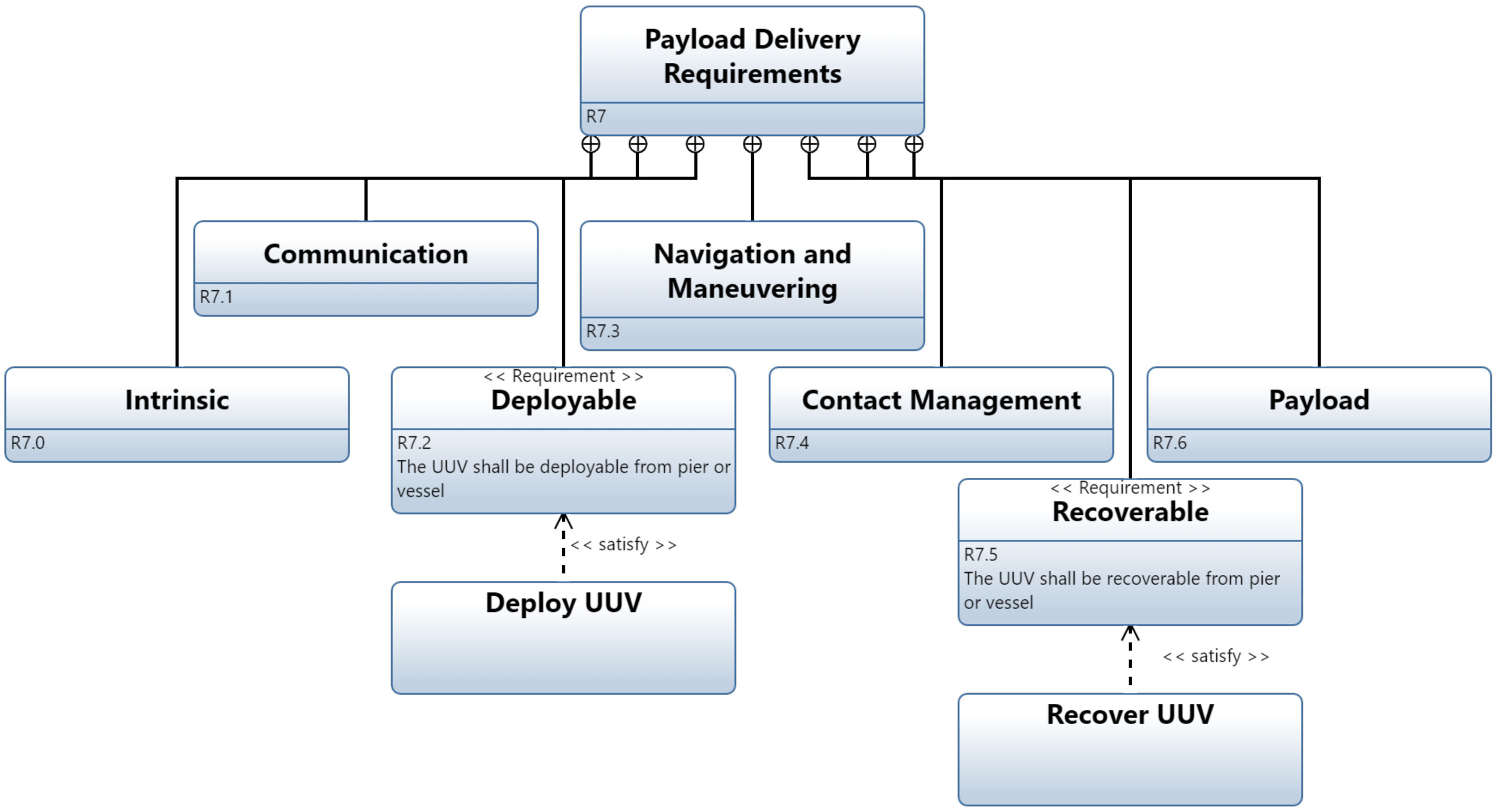


Figure A.57. PD Requirement Diagram

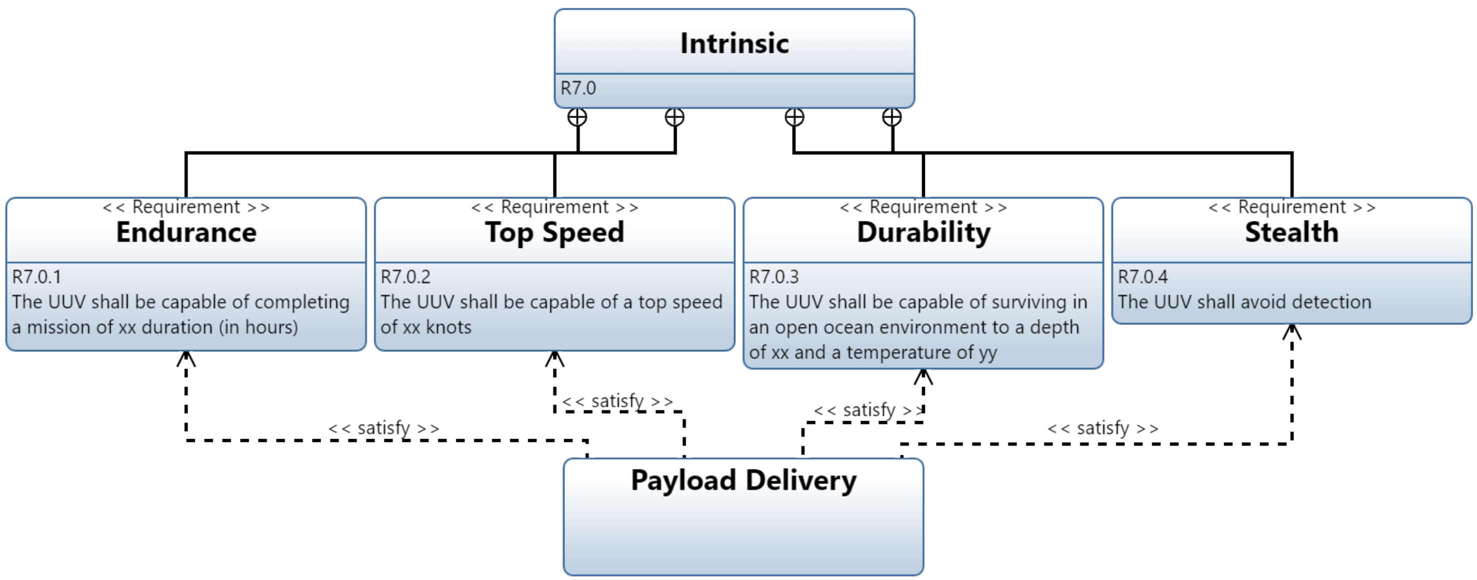


Figure A.58. PD Intrinsic Requirement Decomposition Diagram

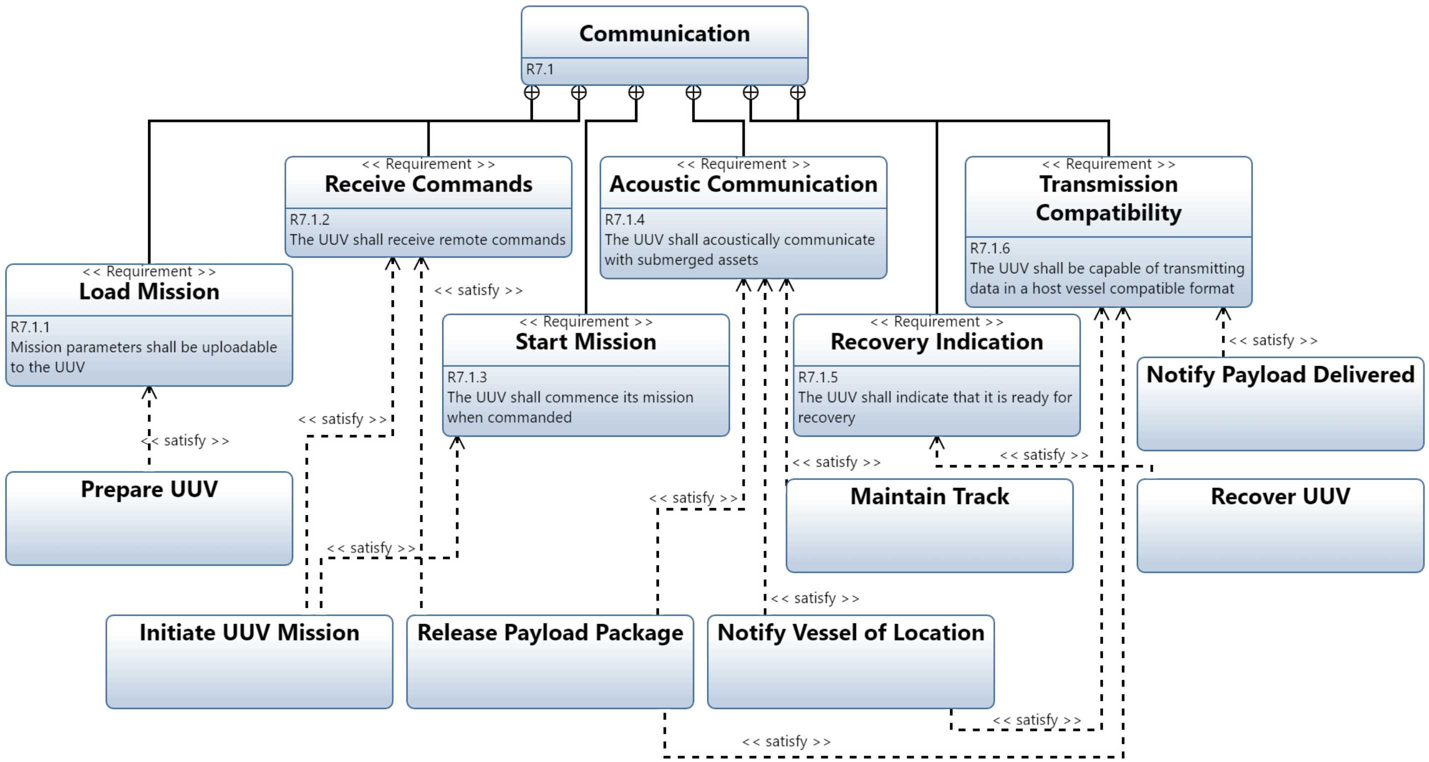


Figure A.59. PD Communication Requirement Decomposition Diagram

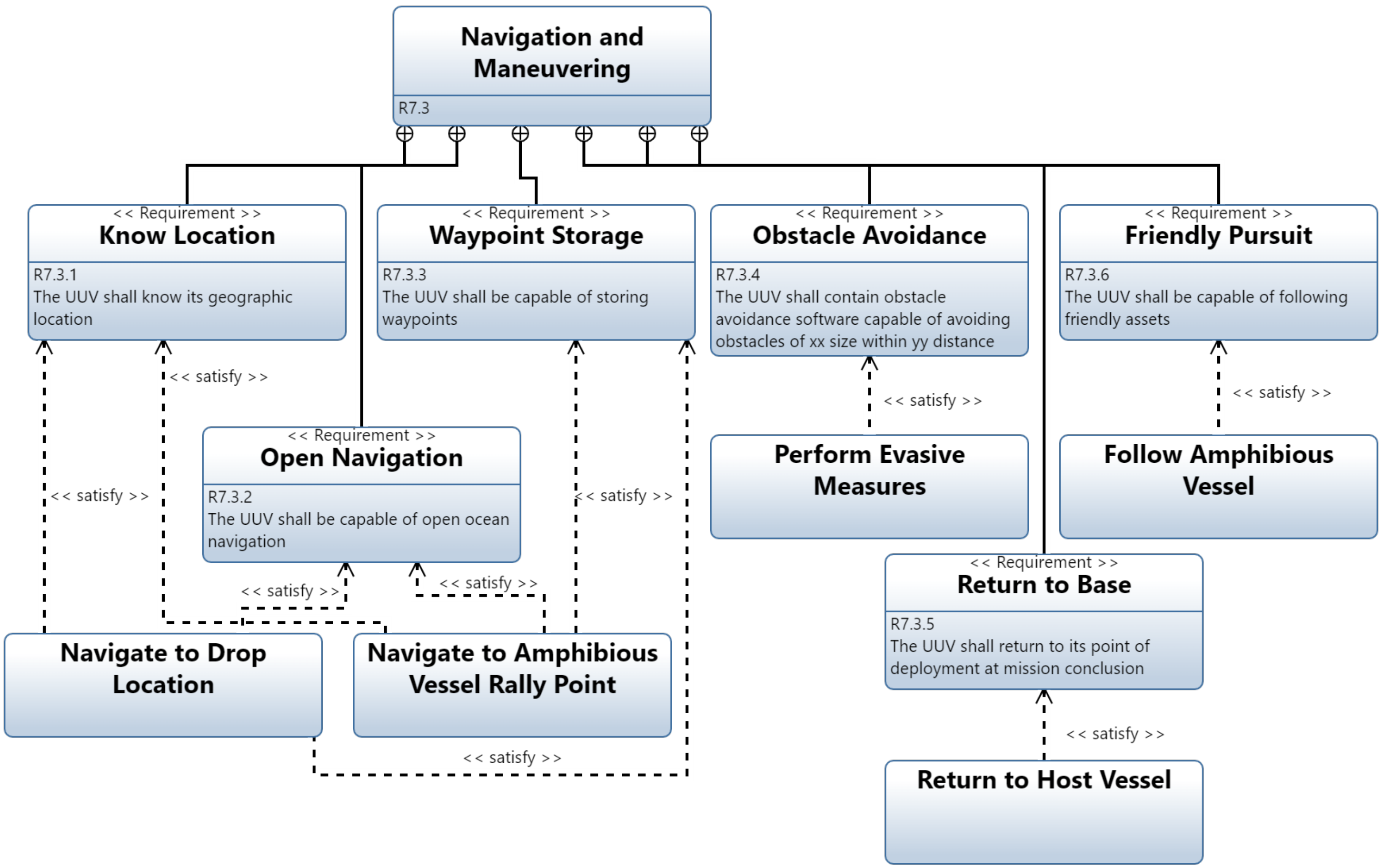


Figure A.60. PD Navigation and Maneuvering Requirement Decomposition Diagram

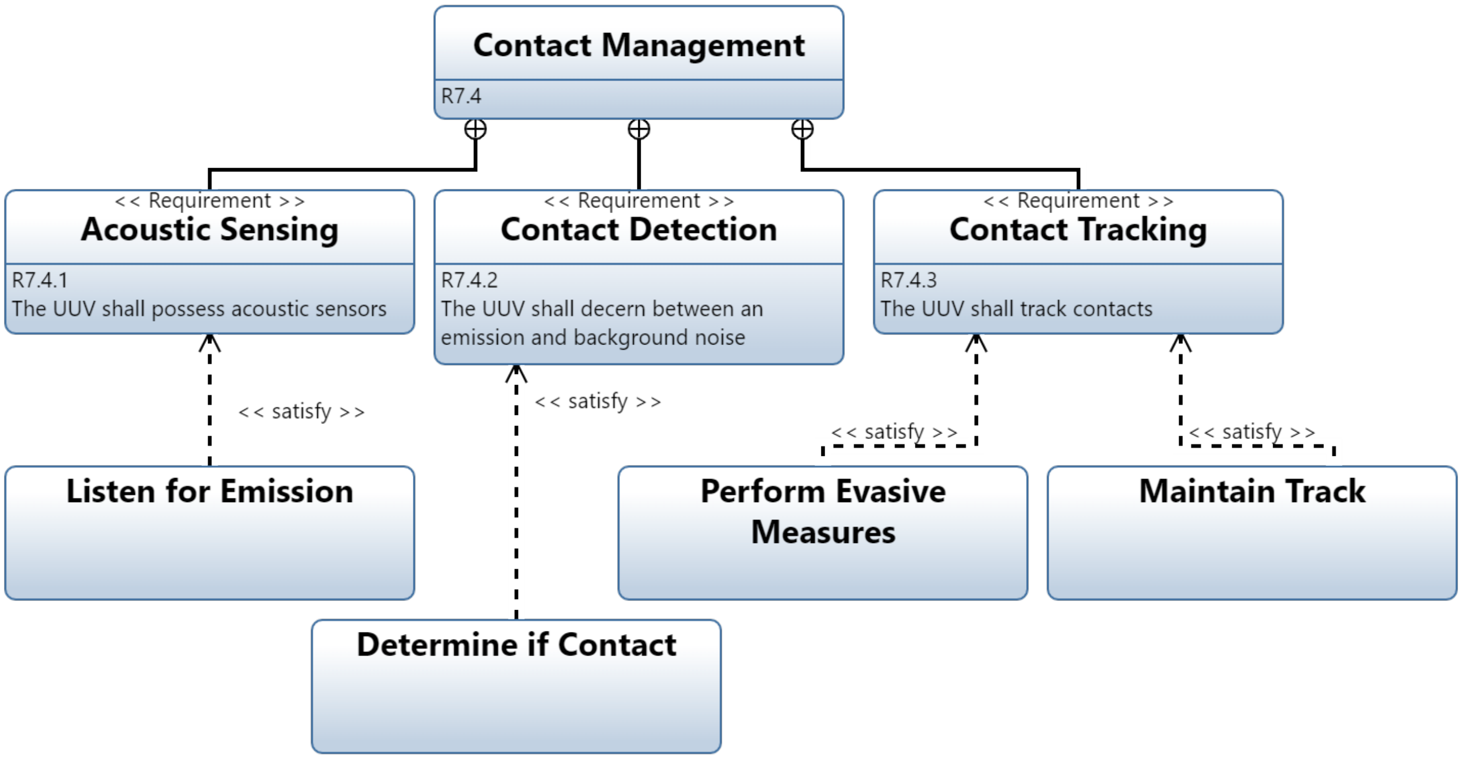


Figure A.61. PD Contact Management Requirement Decomposition Diagram

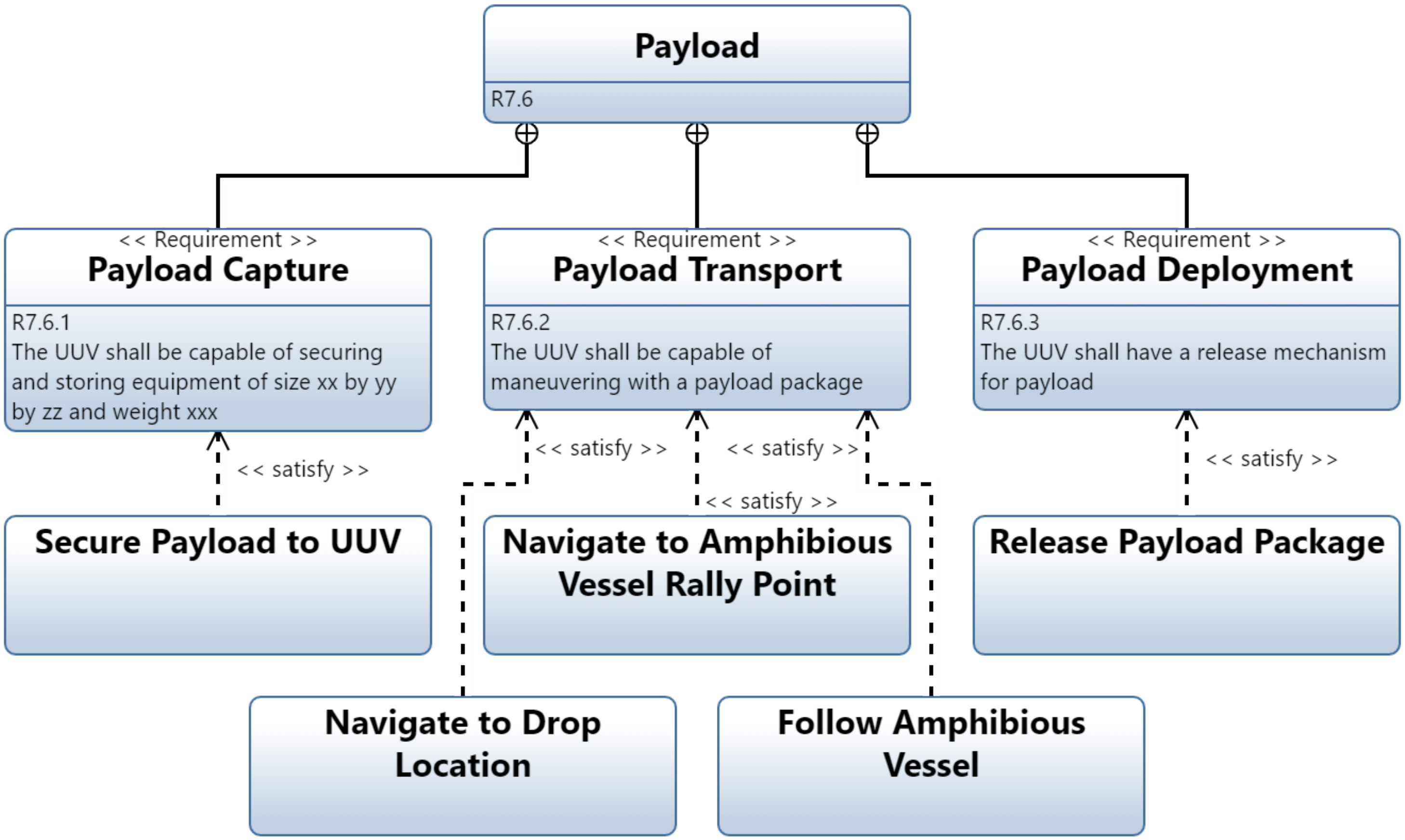


Figure A.62. PD Payload Requirement Decomposition Diagram

A.3.8 Information Operations

The following are the Information Operations (IO) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

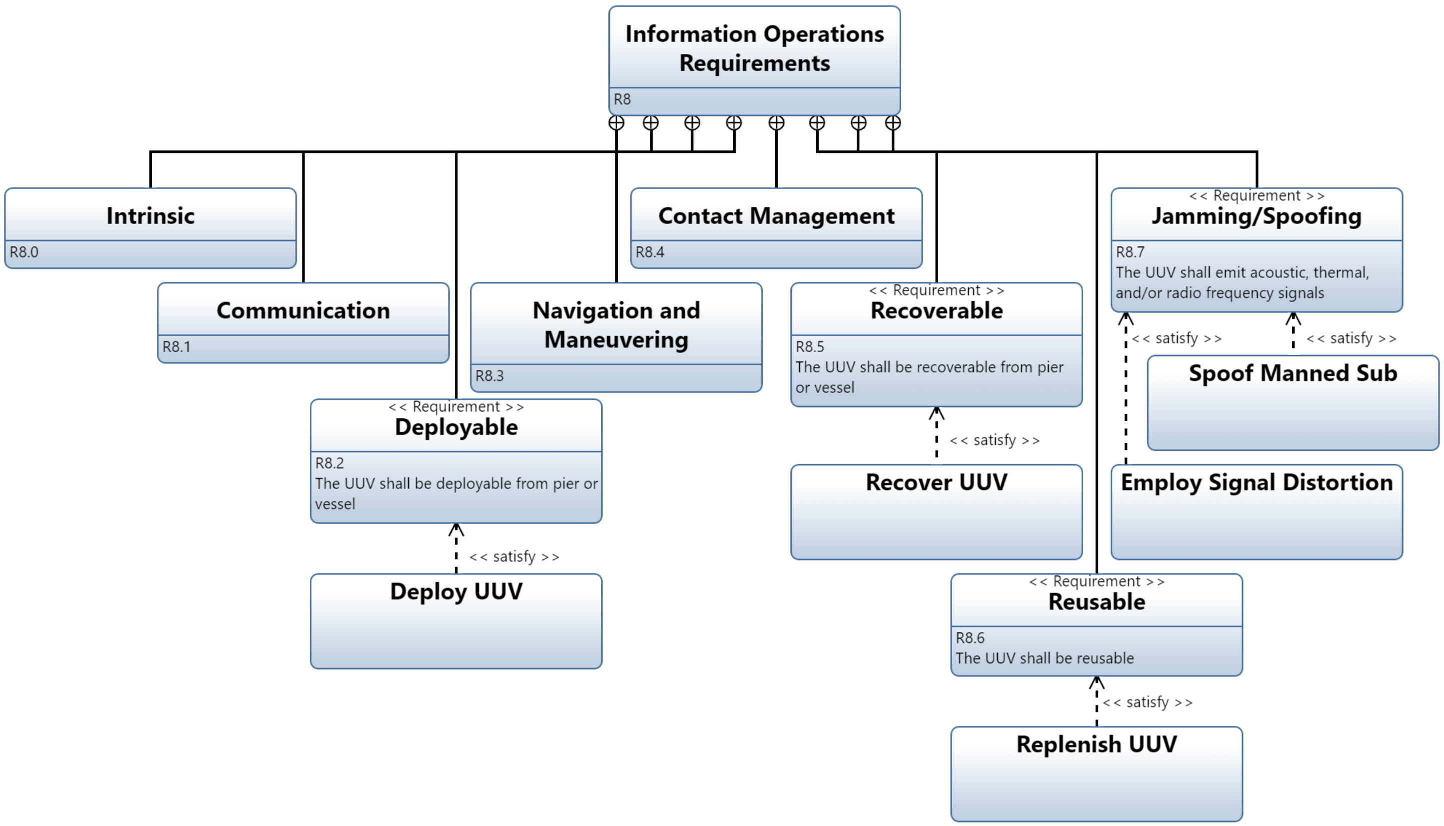


Figure A.63. IO Requirement Diagram

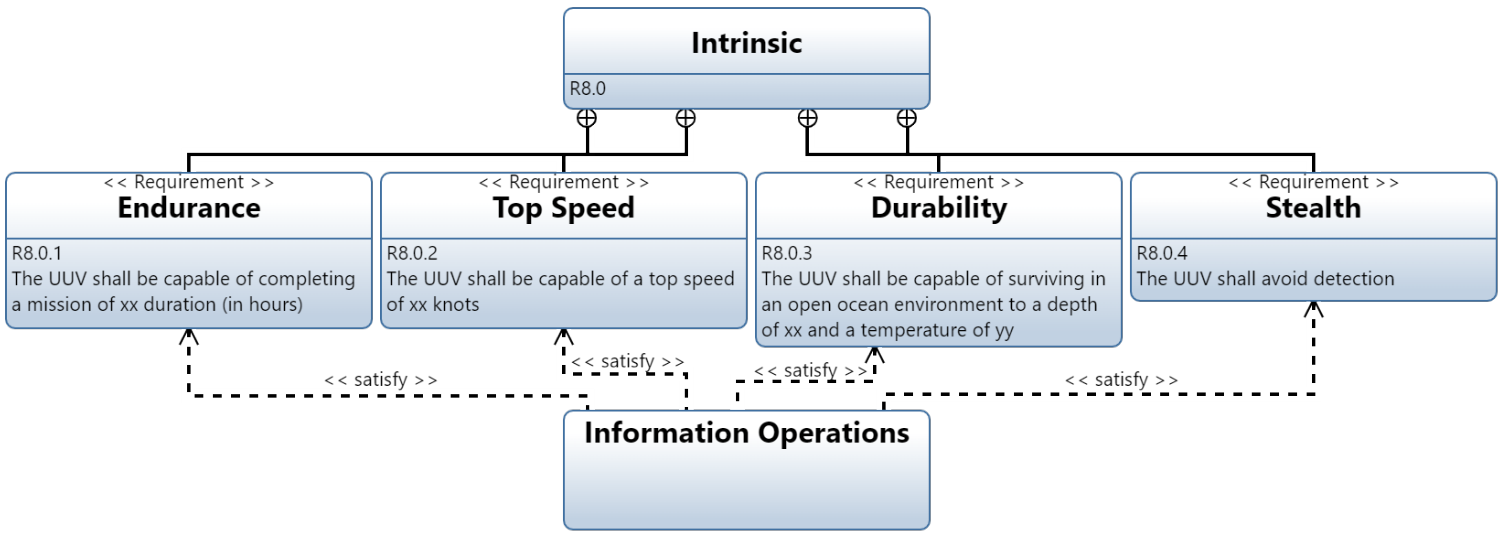


Figure A.64. IO Intrinsic Requirement Decomposition Diagram

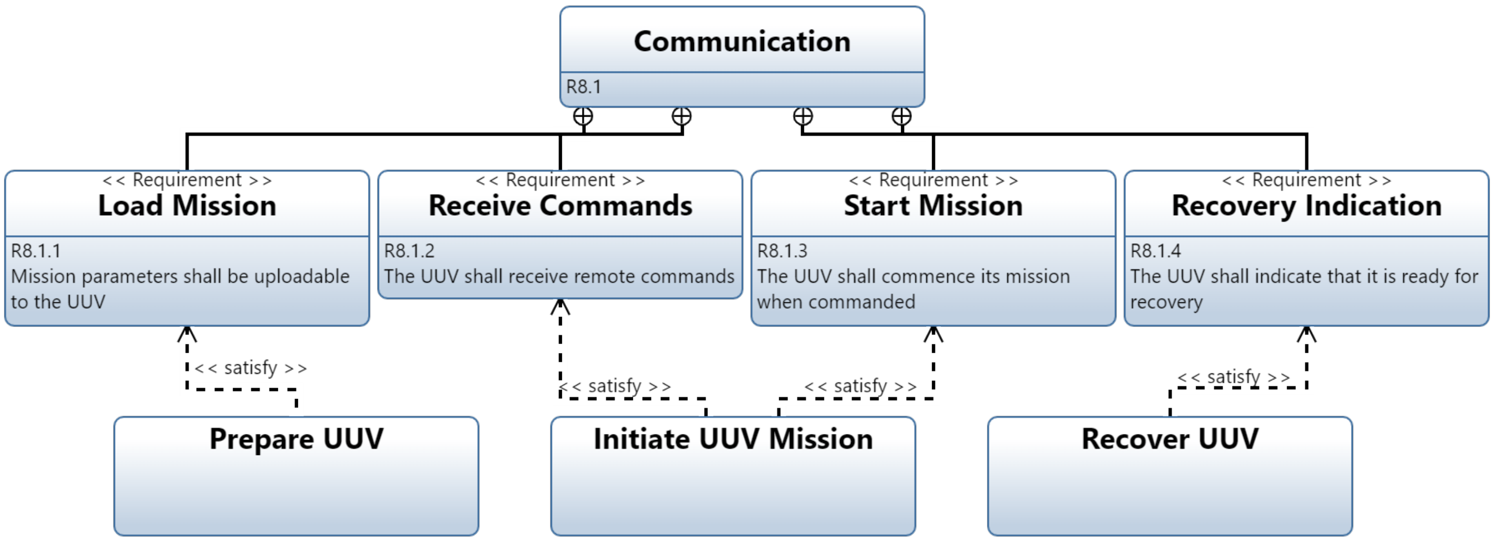


Figure A.65. IO Communication Requirement Decomposition Diagram

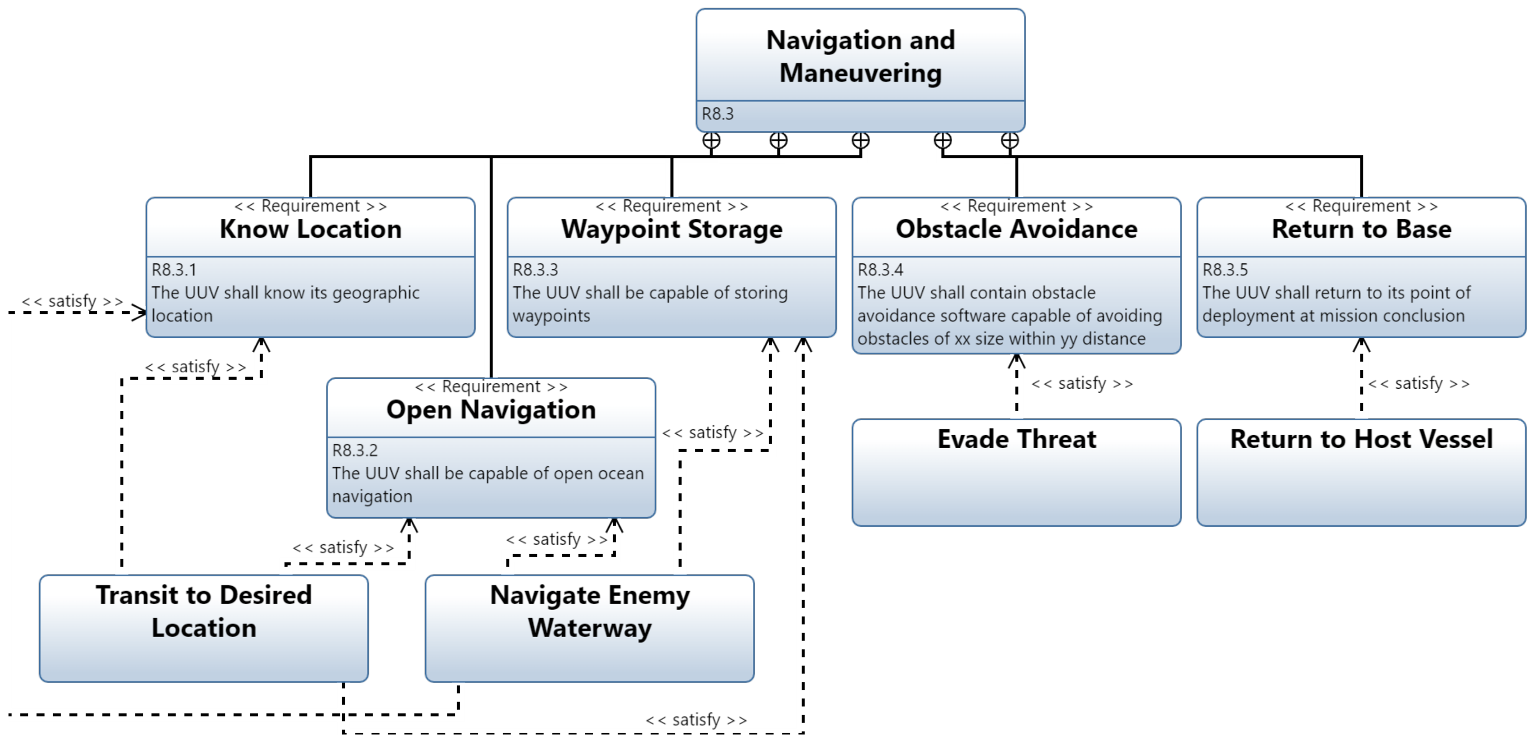


Figure A.66. IO Navigation and Maneuvering Requirement Decomposition Diagram

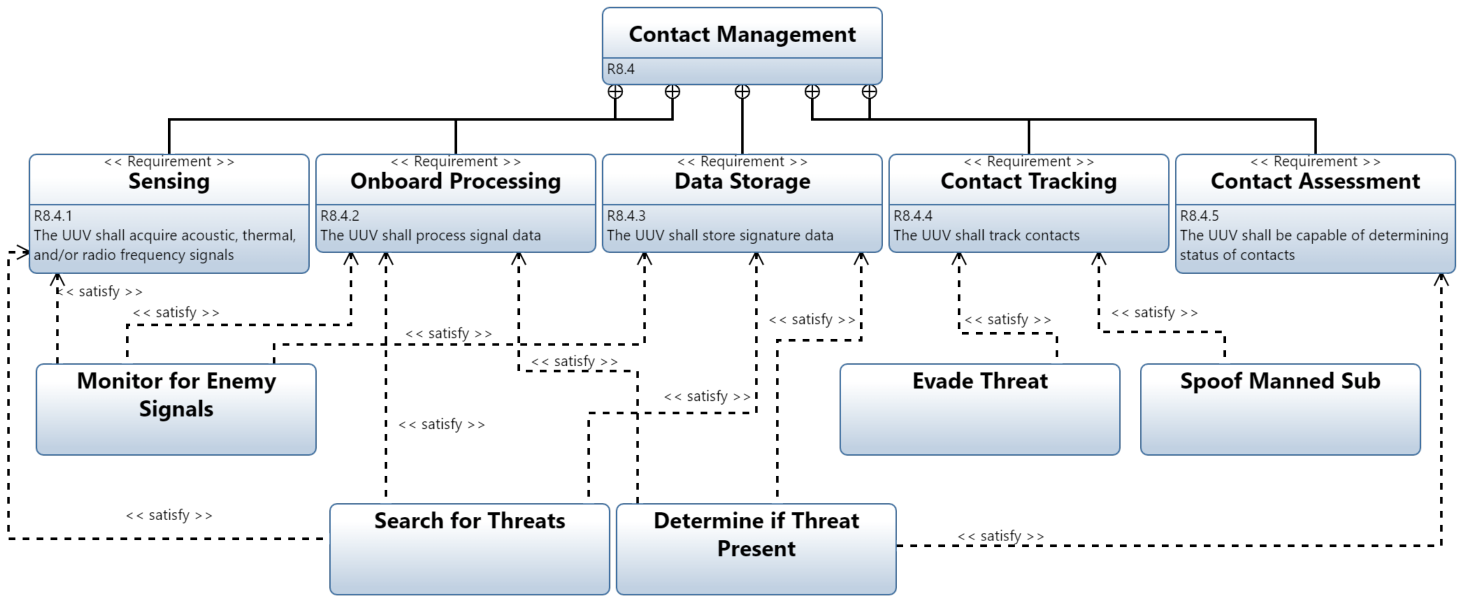


Figure A.67. IO Contact Management Requirement Decomposition Diagram

A.3.9 Time Critical Strike

The following are the Time Critical Strike (TCS) Requirement Diagrams derived from the Activity Diagrams in Section A.1.

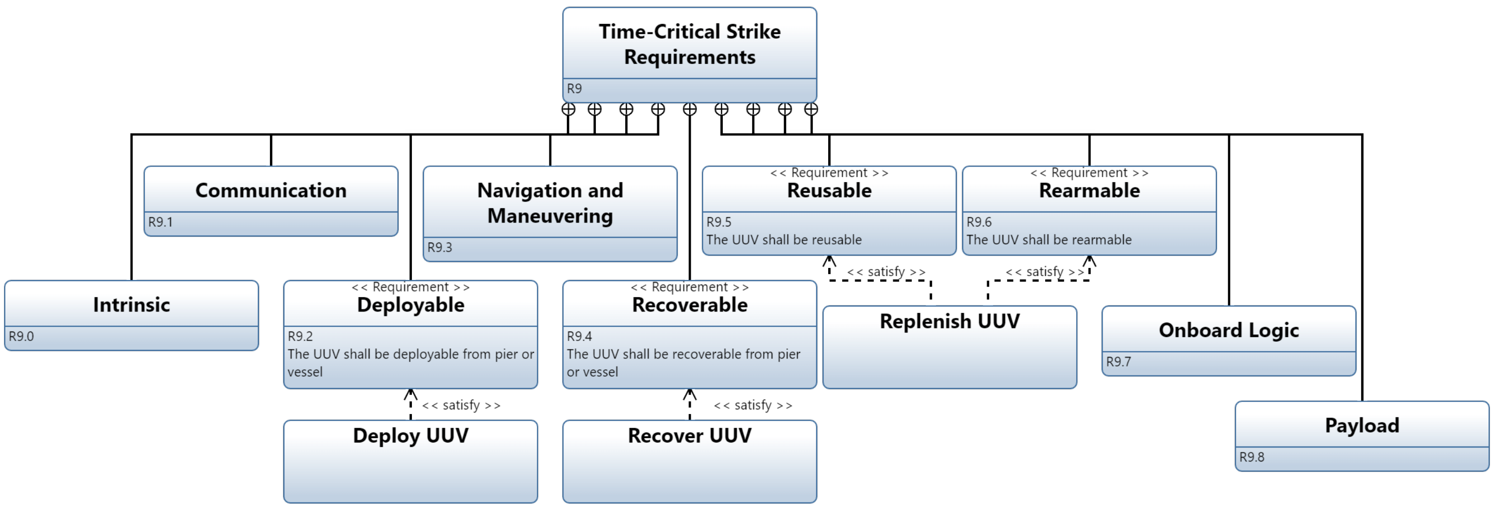


Figure A.68. TCS Requirement Diagram

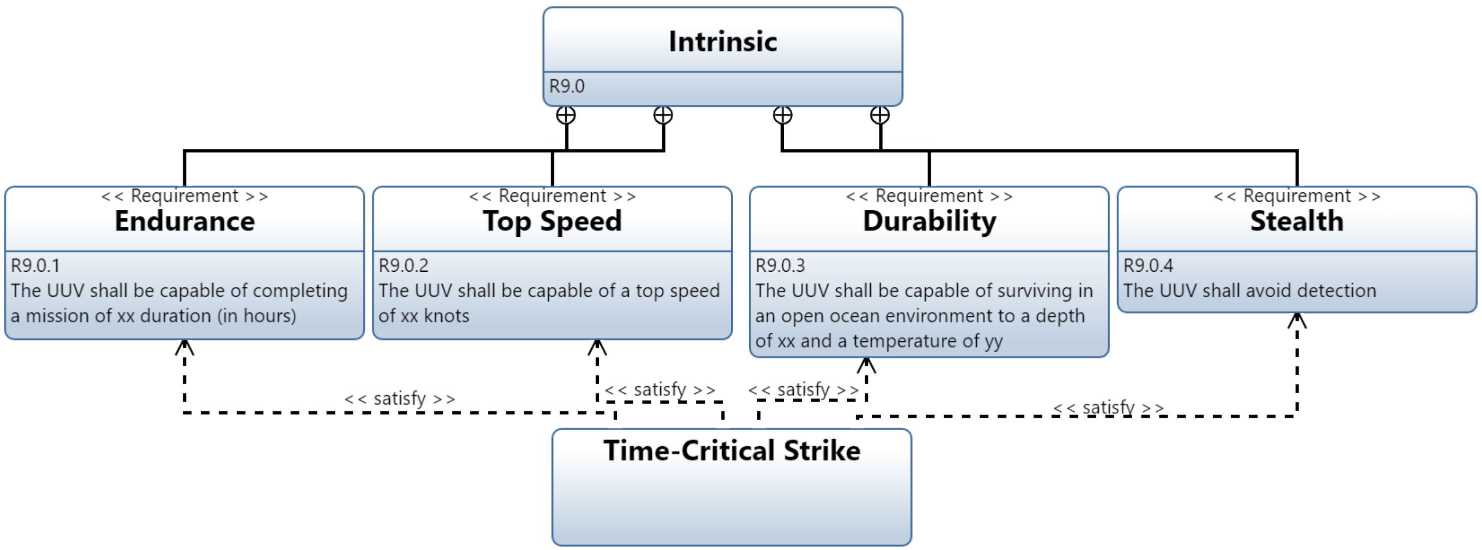


Figure A.69. TCS Intrinsic Requirement Decomposition Diagram

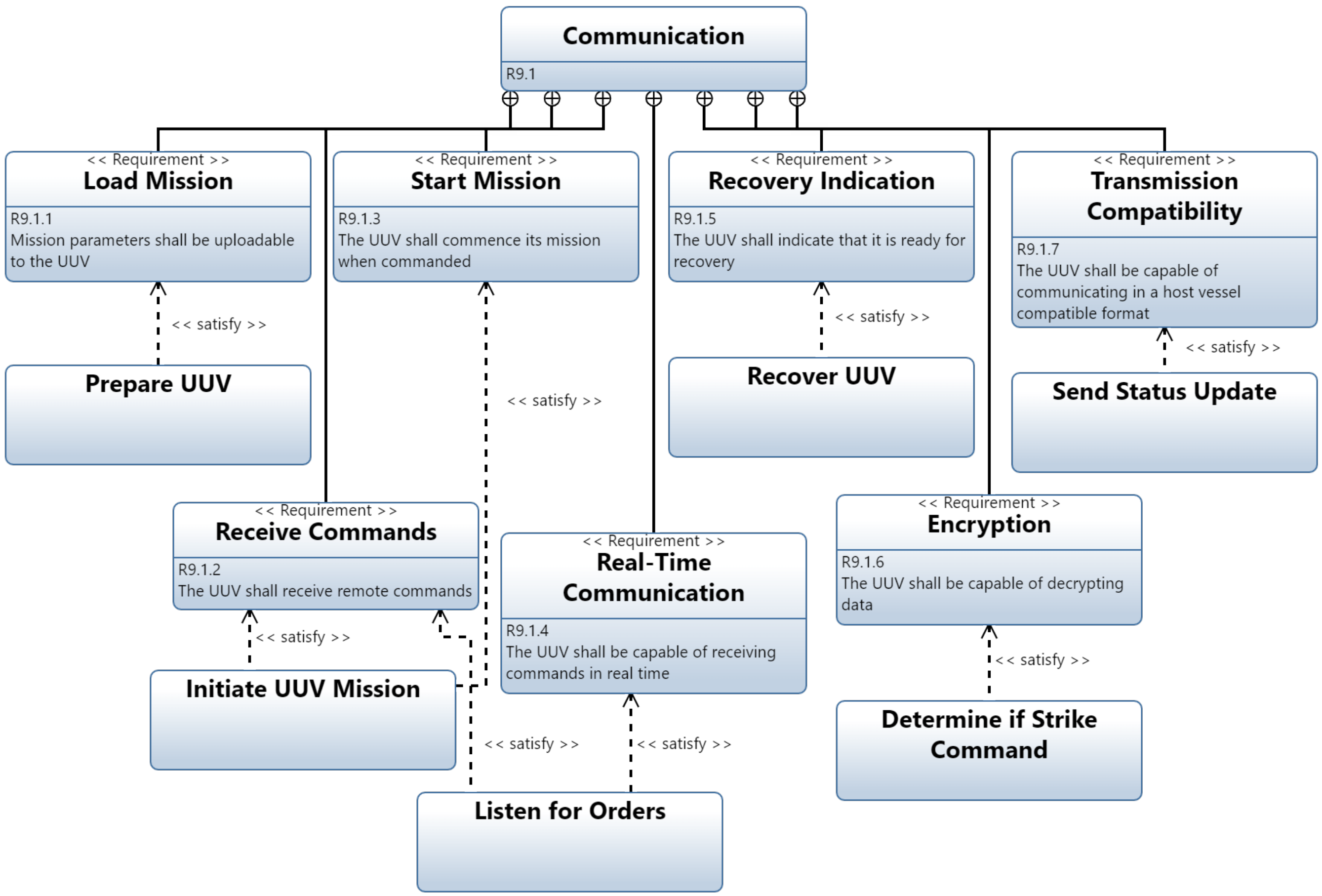


Figure A.70. TCS Communication Requirement Decomposition Diagram

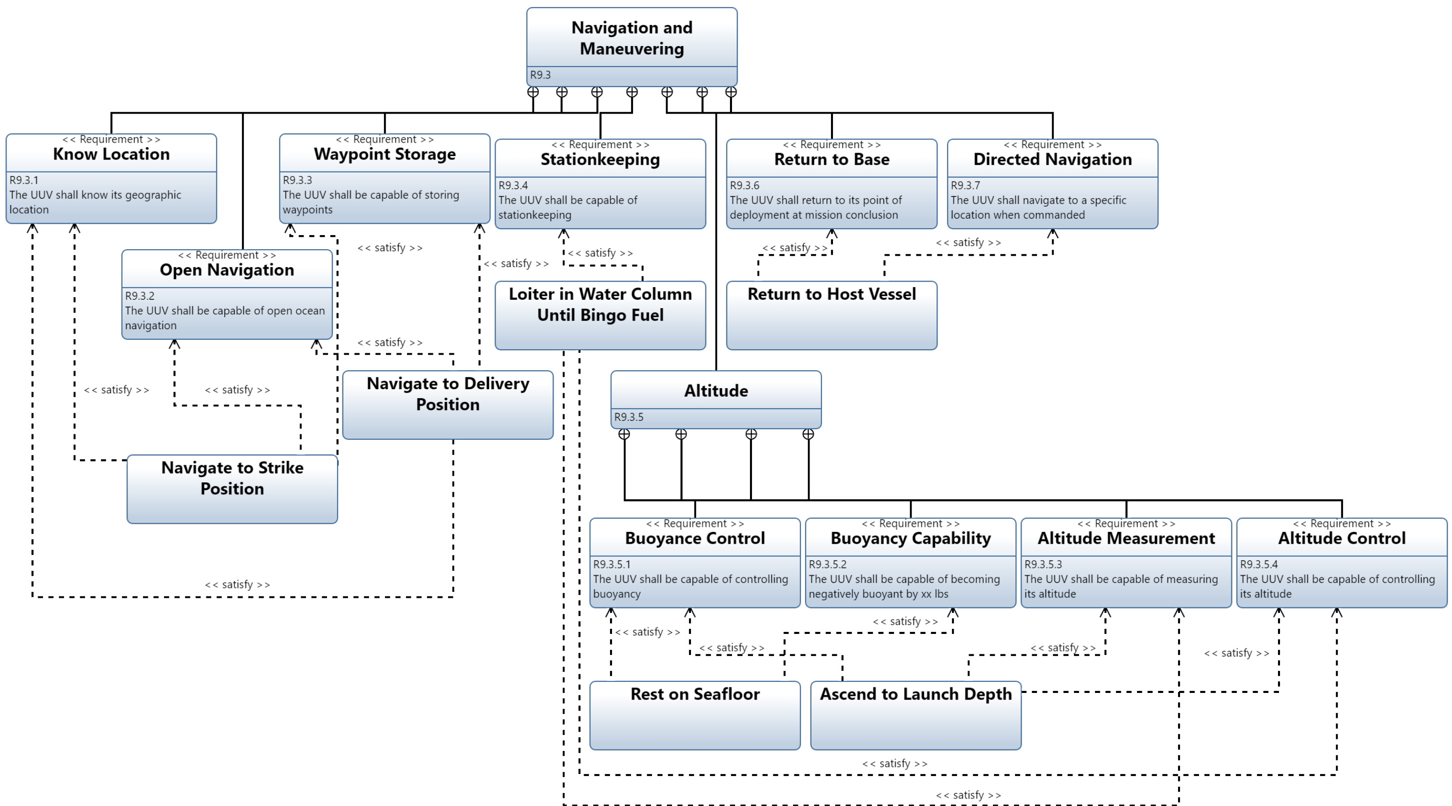


Figure A.71. TCS Navigation and Maneuvering Requirement Decomposition Diagram

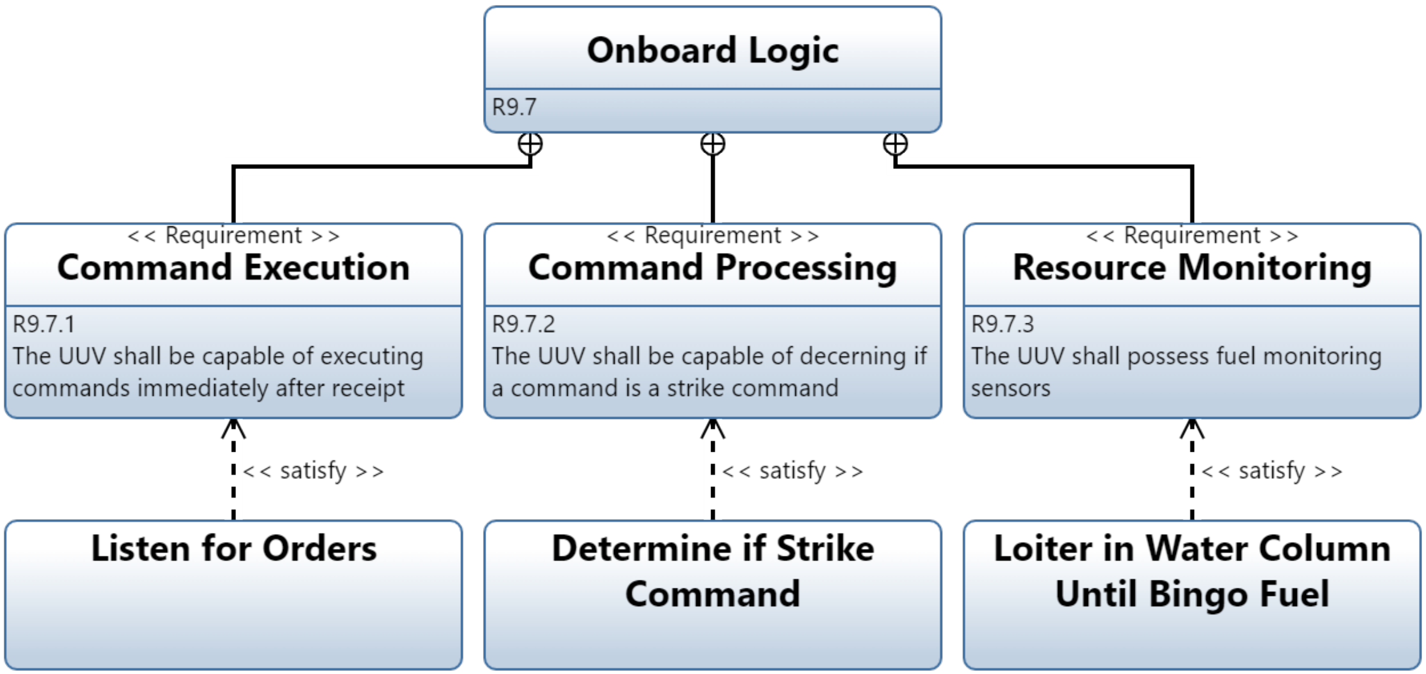


Figure A.72. TCS Onboard Logic Requirement Decomposition Diagram

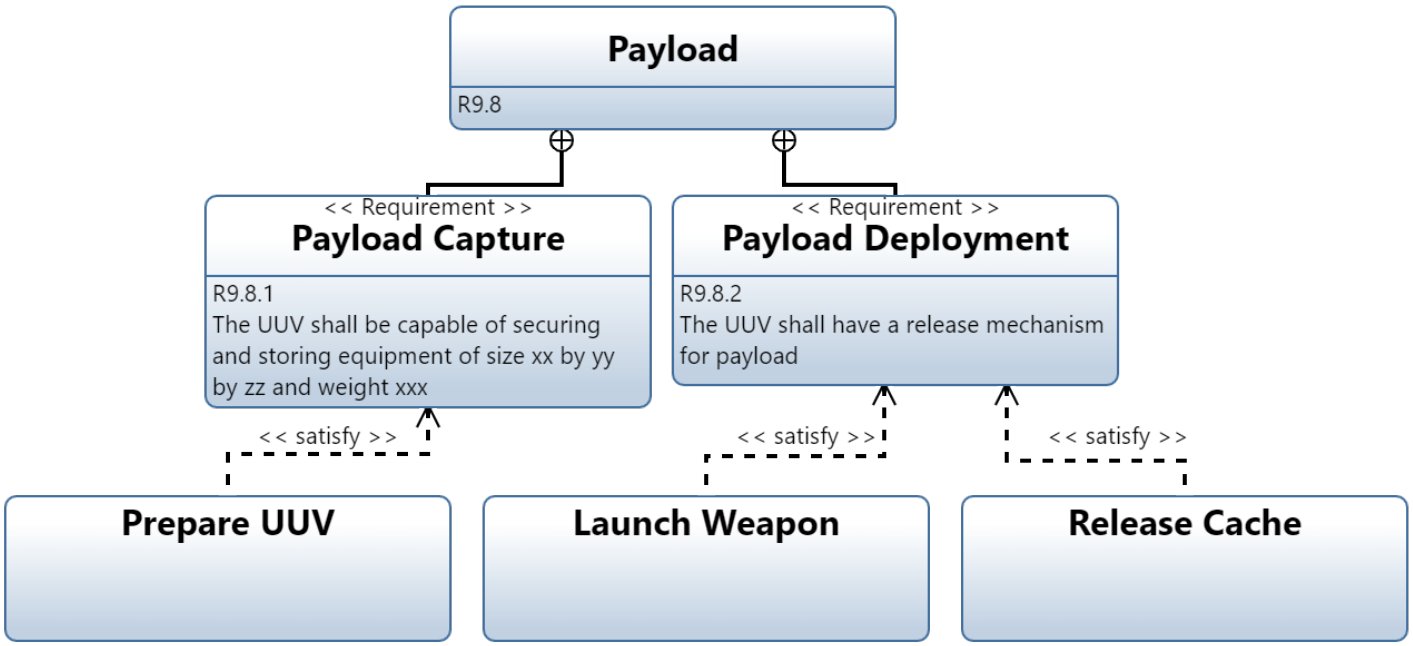


Figure A.73. TCS Payload Requirement Decomposition Diagram

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APPENDIX B: Mission Requirements Tables

This appendix contains the requirements tables for each of the nine missions derived from [3]. The development process began with the Requirements Diagrams from Appendix A.3. From the Requirement Diagrams, requirements were developed in tabular form and given a complexity rating, reuse rating, and rationale. Reused requirements are referenced for each subsequent mission beyond the baseline.

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Table B.1. Intelligence, Surveillance, and Reconnaissance (ISR) Requirements

	Requirement	Complexity	Reuse Category	Rationale
R1.0.1	The UUV shall be capable of completing a mission of xx duration (in hours)	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.0.2	The UUV shall be capable of a top speed of xx knots	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of xx and a temperature of yy	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.0.4	The UUV shall avoid detection	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.1.1	Mission requirements shall be uploadable to the UUV	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.1.2	The UUV shall receive remote commands	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.1.3	The UUV shall commence its mission when commanded	Easy	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.1.4	The UUV shall be capable of transmitting data in a host vessel compatible format	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.1.5	The UUV shall indicate that it is ready for recovery	Easy	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.2	The UUV shall be deployable from pier or vessel	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.1	The UUV shall know its geographic location	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.2	The UUV shall be capable of open ocean navigation	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.3	The UUV shall be capable of storing waypoints	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of xx size within yy distance	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.5	The UUV shall be capable of tracking its position	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.6	The UUV shall be capable of returning to a position in a search pattern	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.7	The UUV shall return to its point of deployment at mission conclusion	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.3.8	The UUV shall navigate to a specific location when commanded	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.4.1	The UUV shall possess acoustic sensors	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.4.2	The UUV shall discern between an emission and background noise	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.4.3	The UUV shall track contacts	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.5	The UUV shall be recoverable from pier or vessel	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.6	The UUV shall be capable of imaging an area $y'xy'$ in size	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.7	The UUV shall be capable of collecting environmental data	Difficult	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.8	The UUV shall be capable of collecting data nonconsecutively	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.
R1.9	The UUV shall possess a recall mechanism	Nominal	Designed for Reuse	Assuming all requirements in base case will be designed for reuse.

ISR was selected as the baseline mission for reuse, therefore all requirements were designated as *Designed for Reuse*.

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Table B.2. Mine Countermeasures (MCM) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R2.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R2.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R2.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R2.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R2.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R2.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R2.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R2.1.4	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R2.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Managed	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R2.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R2.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R2.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R2.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of *xx* size within *yy* distance	R1.3.4	Difficult	Modified	Contact tracking and avoidance is a common requirement across UUV mission types but the nature of the obstacles could be different.
R2.3.5	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R2.3.6	The UUV shall navigate to a specific location when commanded	R1.3.8	Nominal	Managed	Same requirement as responding to a host vessel command.
R2.4.1	The UUV shall possess acoustic sensors	R1.4.1	Nominal	Managed	Acoustic sensors are a basic requirement with consistent definitions.
R2.4.2	The UUV shall discern between an emission and background noise	R1.4.2	Difficult	Managed	Discerning between emissions and background noise is a basic requirement with consistent definitions.
R2.4.3	The UUV shall track contacts	R1.4.3	Difficult	Adopted	Contacts could be of a different nature between missions.
R2.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R2.6	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.
R2.7	The UUV shall be rearmable	None	Easy	New	ISR does not have munitions or armed countermeasures.
R2.8.1	The UUV shall be capable of detecting mines of *xx* size from *yy* distance	None	Difficult	New	Requirement not defined in ISR mission. Unique to MCM mission.
R2.8.2	The UUV shall analyze sensor readings onboard and classify data	None	Difficult	New	Analysis and classification is beyond scope of ISR data processing requirements.

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Table B.2. Continued

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R2.8.3.1	The UUV shall be contain logic to determine when to deploy a countermeasure	None	Difficult	New	ISR does not have countermeasures.
R2.8.3.2	The UUV shall be capable of destroying a mine of *xx* size from *yy* distance	None	Difficult	New	Requirement not defined in ISR mission. Unique to MCM mission.
R2.8.3.3	The UUV shall be capable of performing at least *xx* types of MCM	None	Difficult	New	Requirement not defined in ISR mission. Unique to MCM mission.

Table B.3. Anti-Submarine Warfare (ASW) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R3.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R3.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R3.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R3.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R3.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R3.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R3.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R3.1.4	The UUV shall transmit data acoustically	None	Nominal	New	Basic requirement not defined in ISR mission.
R3.1.5	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R3.1.6	The UUV shall be capable of transmitting data in a host vessel compatible format	R1.1.4	Nominal	Adopted	Host communication is a basic requirement but specific formats may differ between mission types.
R3.1.7	The UUV shall periodically transmit operational status and location	None	Nominal	New	Requirement beyond scope of ISR communication requirements.
R3.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Managed	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R3.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R3.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R3.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R3.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of *xx* size within *yy* distance	R1.3.4	Difficult	Modified	Contact tracking and avoidance is a common requirement across UUV mission types but the nature of the obstacles could be different.
R3.3.5	The UUV shall remain within the defined area during its mission	None	Nominal	New	Requirement exists in ISR for commanding UUV to a location, but to loiter within defined bounds does not.
R3.3.6	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R3.3.7	The UUV shall navigate to a specific location when commanded	R1.3.8	Nominal	Managed	Same requirement as responding to a host vessel command.
R3.4.1	The UUV shall possess acoustic sensors	R1.4.1	Nominal	Managed	Acoustic sensors are a basic requirement with consistent definitions.
R3.4.2	The UUV shall discern between an emission and background noise	R1.4.2	Difficult	Managed	Discerning between emissions and background noise is a basic requirement with consistent definitions.
R3.4.3.1	The UUV shall process the acoustic data onboard	None	Difficult	New	Onboard acoustic data processing is beyond scope of ISR data requirements.
R3.4.3.2	The UUV shall have sufficient memory to store reference acoustic signatures	None	Nominal	New	Storing acoustic data to identify possible contacts/threats is beyond scope of ISR data requirements.

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Table B.3. Continued

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R3.4.3.3	The UUV shall determine if an emission matches a reference signature	None	Difficult	New	Signature matching is beyond scope of ISR data requirements.
R3.4.4	The UUV shall track and follow objects whose emission match a reference signature	None	Difficult	New	Following a specific contact is beyond scope of general contact tracking requirements.
R3.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R3.6	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.

Table B.4. Inspection and Identification (INID) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R4.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R4.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R4.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R4.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R4.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R4.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R4.1.4	The mission data shall be downloadable from the UUV	None	Nominal	New	Basic requirement not defined in ISR mission.
R4.1.5	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R4.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Managed	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R4.3.1	The UUV shall record its position relative to the ship	None	Nominal	New	Ship-relative positioning is beyond scope of ISR navigation requirements.
R4.3.2	The UUV shall be able to maneuver under and around a ship	None	Difficult	New	Ship-relative positioning is beyond scope of ISR navigation requirements.
R4.3.3	The UUV shall remain in the immediate vicinity of the ship until its mission is complete	None	Nominal	New	Ship-relative positioning is beyond scope of ISR navigation requirements.
R4.3.4	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R4.4.1	The UUV shall possess imaging tools	R1.6	Difficult	Modified	Extension of requirement to image a fixed area.
R4.4.2	The UUV shall process images and identify abnormalities	None	Difficult	New	Image processing is beyond scope of ISR data requirements.
R4.4.3	The UUV shall have sufficient onboard storage to maintain the imagery of all anomalies found	None	Nominal	New	Imagery storage is beyond scope of ISR data requirements.
R4.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R4.6	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.

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Table B.5. Oceanography (OO) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R5.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R5.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R5.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R5.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R5.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R5.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R5.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R5.1.4	The mission data shall be downloadable from the UUV	None	Nominal	New	Basic requirement not defined in ISR mission.
R5.1.5	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R5.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Managed	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R5.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R5.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R5.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R5.3.4	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R5.3.5	The UUV shall navigate to a specific location when commanded	R1.3.8	Nominal	Managed	Same requirement as responding to a host vessel command.
R5.4	The UUV shall provide Area of Interest environmental data	R1.7	Difficult	Modified	Mapping environment is an enhancement of ISR type missions. Data collection is similar, but quality of sensor/data and location is more specific.
R5.4.1	The UUV shall provide seabed scans	R1.7	Difficult	Modified	Mapping environment is an enhancement of ISR type missions. Data collection is similar, but quality of sensor/data and location is more specific.
R5.4.2	The UUV shall be capable of creating topographical maps of the seafloor in real-time	R1.7	Difficult	Modified	Mapping environment is an enhancement of ISR type missions. Data collection is similar, but quality of sensor/data and location is more specific.
R5.4.3	The UUV shall use ultrasound to produce images of the bottom of oceans, seas, or lakes	R1.7	Difficult	Modified	Mapping environment is an enhancement of ISR type missions. Data collection is similar, but quality of sensor/data and location is more specific.
R5.4.4	The UUV shall possess imaging tools	R1.6	Nominal	Modified	Extension of requirement to image a fixed area.
R5.4.5	The UUV shall be capable of taking geotechnical data	None	Difficult	New	Requirement to take geotechnical data from the seafloor not defined in ISR mission. Unique to OO missions.
R5.4.6	The UUV shall provide water column characterization (depth, current, temperature, salinity, and obstructions)	None	Difficult	New	Specific water column data is a new requirement beyond scope of ISR mission.

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Table B.5. Continued

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R5.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R5.6	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.

Table B.6. Communication or Navigation Network Node (CN3) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R6.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R6.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R6.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R6.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R6.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R6.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R6.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R6.1.4	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R6.1.5	The UUV shall transmit data in a USN compatible format	R1.1.4	Nominal	Adopted	Host communication is a basic requirement but specific formats may differ between mission types. Transmitting in USN format falls within this scope.
R6.1.6	The UUV shall be capable of transmitting GPS data in a USN compatible format	R1.1.4	Nominal	Adopted	Host communication is a basic requirement but specific formats may differ between mission types. Transmitting in USN format falls within this scope.
R6.1.7	The UUV shall communicate acoustically with submerged assets	None	Difficult	New	Communication with submerged assets is beyond scope of ISR communication requirements.
R6.1.8	The UUV shall communicate with surface/arial assets via radio/satellite link	None	Difficult	New	Communication with surface assets is beyond scope of ISR communication requirements.
R6.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Adopted	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R6.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R6.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R6.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R6.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of *xx* size within *yy* distance	R1.3.4	Difficult	Modified	Contact tracking and avoidance is a common requirement across UUV mission types but the nature of the obstacles could be different.
R6.3.5	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R6.4.1	The UUV shall possess acoustic sensors	R1.4.1	Nominal	Managed	Acoustic sensors are a basic requirement with consistent definitions.
R6.4.2	The UUV shall discern between an emission and background noise	R1.4.2	Difficult	Managed	Discerning between emissions and background noise is a basic requirement with consistent definitions.
R6.4.3	The UUV shall track contacts	R1.4.3	Difficult	Adopted	Contacts could be of a different nature between missions.
R6.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.

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Table B.6. Continued

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R6.6	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.
R6.7.1	The UUV shall be able to carry a payload	None	Difficult	New	Payload requirements not defined in ISR mission.
R6.7.2	The UUV shall be capable of deploying a payload	None	Difficult	New	Payload requirements not defined in ISR mission.

Table B.7. Payload Delivery (PD) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R7.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R7.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R7.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R7.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R7.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R7.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R7.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R7.1.4	The UUV shall acoustically communicate with submerged assets	None	Difficult	New	Communication with submerged assets is beyond scope of ISR communication requirements.
R7.1.5	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R7.1.6	The UUV shall be capable of transmitting data in a host vessel compatible format	R1.1.4	Nominal	Adopted	Host communication is a basic requirement but specific formats may differ between mission types.
R7.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Adopted	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R7.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R7.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R7.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R7.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of *xx* size within *yy* distance	R1.3.4	Difficult	Modified	Contact tracking and avoidance is a common requirement across UUV mission types but the nature of the obstacles could be different.
R7.3.5	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R7.3.6	The UUV shall be capable of following friendly assets	None	Difficult	New	Following friendly assets is a new requirement beyond scope of ISR tracking and navigation requirements.
R7.4.1	The UUV shall possess acoustic sensors	R1.4.1	Nominal	Managed	Acoustic sensors are a basic requirement with consistent definitions.
R7.4.2	The UUV shall discern between an emission and background noise	R1.4.2	Difficult	Managed	Discerning between emissions and background noise is a basic requirement with consistent definitions.
R7.4.3	The UUV shall track contacts	R1.4.3	Difficult	Adopted	Contacts could be of a different nature between missions.
R7.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R7.6.1	The UUV shall be capable of securing and storing equipment of size *xx* by *yy* by *zz* and weight *xxx*	None	Difficult	New	Payload requirements not defined in ISR mission.

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Table B.7. Continued

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R7.6.2	The UUV shall be capable of maneuvering with a payload package	None	Difficult	New	Requirement is beyond scope of ISR maneuvering requirements.
R7.6.3	The UUV shall have a release mechanism for payload	None	Difficult	New	Payload requirements not defined in ISR mission.

Table B.8. Information Operations (IO) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R8.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R8.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R8.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R8.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R8.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R8.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R8.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R8.1.4	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R8.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Adopted	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R8.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R8.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R8.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R8.3.4	The UUV shall contain obstacle avoidance software capable of avoiding obstacles of *xx* size within *yy* distance	R1.3.4	Difficult	Modified	Contact tracking and avoidance is a common requirement across UUV mission types but the nature of the obstacles could be different.
R8.3.5	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R8.4.1	The UUV shall acquire acoustic, thermal, and/or radio frequency signals	None	Difficult	New	Requirement is beyond scope of ISR data collection requirements.
R8.4.2	The UUV shall process signal data	None	Difficult	New	Requirement is beyond scope of ISR data processing requirements.
R8.4.3	The UUV shall store signature data	None	Nominal	New	Requirement is beyond scope of ISR data storage requirements.
R8.4.4	The UUV shall track contacts	R1.4.3	Difficult	Adopted	Contacts could be of a different nature between missions.
R8.4.5	The UUV shall be capable of determining status of contacts	R1.4.2	Difficult	Modified	UUV for IO mission type will need more contact determining capability than for ISR mission.
R8.5	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R8.6	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.
R8.7	The UUV shall emit acoustic, thermal, and/or radio frequency signals	None	Difficult	New	Requirement beyond scope of ISR transmission requirements.

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Table B.9. Time Critical Strike (TCS) Requirements

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R9.0.1	The UUV shall be capable of completing a mission of *xx* duration (in hours)	R1.0.1	Difficult	Modified	Mission length can vary between mission types.
R9.0.2	The UUV shall be capable of a top speed of *xx* knots	R1.0.2	Difficult	Modified	Mission length can vary between mission types.
R9.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of *xx* and a temperature of *yy*	R1.0.3	Nominal	Modified	Mission depth and environmental conditions can vary between mission types.
R9.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Mission location and payloads may differ between mission types.
R9.1.1	Mission requirements shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Should use the same hardware and software interfaces across mission types.
R9.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; processing is covered by separate requirements.
R9.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	*Begin Mission* command should not change from mission to mission.
R9.1.4	The UUV shall be capable of receiving commands in real time	None	Difficult	New	Real-time command reception is beyond scope of ISR communication requirements.
R9.1.5	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R9.1.6	The UUV shall be capable of decrypting data	None	Easy	New	Decryption is beyond scope of ISR data requirements.
R9.1.7	The UUV shall be capable of communicating in a host vessel compatible format	R1.1.4	Nominal	Modified	Expansion of data transmission compatibility to full communication compatibility.
R9.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Adopted	UUV will need to be deployed pierside or from a vessel, similar to ISR.
R9.3.1	The UUV shall know its geographic location	R1.3.1	Nominal	Adopted	GPS recognition and inertial navigation systems should be similar across all platforms.
R9.3.2	The UUV shall be capable of open ocean navigation	R1.3.2	Nominal	Managed	Open ocean navigation is a basic requirement with consistent definitions.
R9.3.3	The UUV shall be capable of storing waypoints	R1.3.3	Nominal	Managed	Waypoint storage is a basic requirement with consistent definitions.
R9.3.4	The UUV shall be capable of stationkeeping	None	Nominal	New	Stationkeeping is beyond scope of ISR maneuvering requirements.
R9.3.5.1	The UUV shall be capable of controlling buoyancy	None	Nominal	New	Buoyancy control is beyond scope of ISR maneuvering requirements.
R9.3.5.2	The UUV shall be capable of becoming negatively buoyant by *xx* lbs	None	Nominal	New	Buoyancy control is beyond scope of ISR maneuvering requirements.
R9.3.5.3	The UUV shall be capable of measuring its altitude	None	Easy	New	Altitude measurement is beyond scope of ISR sensing requirements.
R9.3.5.4	The UUV shall be capable of controlling its altitude	None	Difficult	New	Altitude control is beyond scope of ISR maneuvering requirements.
R9.3.6	The UUV shall return to its point of deployment at mission conclusion	R1.3.7	Nominal	Managed	UUV will be recovered across all missions.
R9.3.7	The UUV shall navigate to a specific location when commanded	R1.3.8	Nominal	Managed	Functionally same requirement as responding to a host vessel command.
R9.4	The UUV shall be recoverable from pier or vessel	R1.5	Nominal	Adopted	UUV will be recovered across all missions but nature of recovery could be different.
R9.5	The UUV shall be reusable	None	Easy	New	Basic requirement not defined in ISR mission.
R9.6	The UUV shall be rearmable	None	Nominal	New	ISR does not have munitions.

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Table B.9. Continued

	Requirement	Reused ISR Requirement	Complexity	Reuse Category	Rationale
R9.7.1	The UUV shall be capable of executing commands immediately after receipt	None	Nominal	New	Real-time command processing is beyond scope of ISR communication/data requirements.
R9.7.2	The UUV shall be capable of discerning if a command is a strike command	None	Nominal	New	Combat system specific requirement; not in-scope for ISR.
R9.7.3	The UUV shall possess fuel monitoring sensors	None	Easy	New	Onboard resource monitoring requirements not defined in ISR mission.
R9.8.1	The UUV shall be capable of securing and storing equipment of size xx by yy by zz and weight xxx	None	Difficult	New	Payload requirements not defined in ISR mission.
R9.8.2	The UUV shall have a release mechanism for payload	None	Difficult	New	Payload requirements not defined in ISR mission.

APPENDIX C:
Mission Interfaces Tables

This appendix contains the interface tables for each of the nine missions derived from [3]. The tables were derived from the Interface Diagrams in Appendix A.2. From the Interface Diagrams, interfaces and their directionality were developed in tabular form and given a complexity rating, reuse rating, and rationale.

Table C.1. Intelligence, Surveillance, and Reconnaissance (ISR) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Designed for Reuse	Nominal	Assuming interfaces in base case will be designed for reuse.
Host Vessel	Data	Out	Designed for Reuse	Difficult	Assuming interfaces in base case will be designed for reuse.
Host Vessel	Launch Command	In	Designed for Reuse	Easy	Assuming interfaces in base case will be designed for reuse.
Host Vessel	Mission Parameters	In	Designed for Reuse	Nominal	Assuming interfaces in base case will be designed for reuse.
Host Vessel	UUV Return Signal	Out	Designed for Reuse	Easy	Assuming interfaces in base case will be designed for reuse.

Table C.2. Mine Countermeasures (MCM) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Data	Out	Deleted	Difficult	No in-mission host link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.

Table C.3. Anti-Submarine Warfare (ASW) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Contact Data	Out	Modified	Difficult	Tailoring of ISR UUV-host data link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.
Host Vessel	UUV Status	Out	Modified	Difficult	Tailoring of ISR UUV-host data link.

Table C.4. Inspection and Identification (INID) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Deleted	Nominal	No GPS data needed.
Host Vessel	Data	Out	Deleted	Difficult	No in-mission host link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.

Table C.5. Oceanography (OO) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Data	Out	Deleted	Difficult	No in-mission host link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.

Table C.6. Communication or Navigation Network Node (CN3) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
Allied Vessel	UUV Location	Out	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Data	Out	Deleted	Difficult	No in-mission host link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.
Submerged USN Asset	Acoustic Message	Bidirectional	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.
Tactical Communication Network	Over-the-Air Message	Bidirectional	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.

Table C.7. Payload Delivery (PD) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
Amphibious Vessel	Drop Order	In	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.
Amphibious Vessel	Payload	Out	New	Difficult	Physical interaction with payload to be delivered will be specific to each node.
Amphibious Vessel	UUV Location	Out	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.
Amphibious Vessel	Vessel Location	In	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Drop Complete Message	Out	Modified	Difficult	Tailoring of ISR UUV-host data link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	Payload	In	New	Difficult	Physical interaction with payload to be delivered will be specific to each node.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.

Table C.8. Information Operations (IO) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Data	Out	Deleted	Difficult	No in-mission host link.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.

Table C.9. Time Critical Strike (TCS) Interfaces

Node	Item	Direction	Reuse Category	Complexity	Rationale
GPS	GPS Sentence	In	Managed	Nominal	Universal GPS sync method.
Host Vessel	Launch Command	In	Managed	Easy	Mission begin mechanism same and requires minimal qualification.
Host Vessel	Mission Parameters	In	Adopted	Nominal	Mission loading is the same, but parameters vary.
Host Vessel	UUV Return Signal	Out	Adopted	Easy	Mechanism same but needs to be validated for specific mission environment.
Host Vessel	UUV Status	Out	Modified	Difficult	Tailoring of ISR UUV-host data link.
Host Vessel	Weapon Launch Order	In	New	Difficult	In-theater communication requires significant testing and must meet stringent requirements.

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