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SYSTEMS ENGINEERING CAPSTONE REPORT

**CONDITION-BASED UNMANNED UNDERSEA
VEHICLE MAINTENANCE MONITORING
AND PREDICTION SYSTEM (C-BUMMPS)**

by

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MONITORING AND PREDICTION SYSTEM (C-BUMMPS)**

Dana C. Colegrove, Jason M. Delisser, Corey D. Johnson, and John R. Stebe

Submitted in partial fulfillment of the
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ABSTRACT

As the Navy introduces its large displacement and extra-large class Unmanned Undersea Vehicles (UUVs), the need and desire grows for increased endurance on the order of weeks to months. Extended endurance is a necessary capability to enable UUVs to take on some of the mission areas of nuclear submarines. Energy efficiency and storage capacity are some of the first factors to be considered for extending the endurance of unmanned vehicles. However, a secondary and more challenging factor is UUV system reliability, and the ability to tolerate or avoid system failures. The intent of this project is to capture the stakeholder needs for improving UUV reliability, maintainability, and availability, then transform those needs into system requirements for a Condition-Based UUV Maintenance Monitoring and Prediction System (C-BUMMPS). Specifically, this project will develop and identify stakeholder, system functional, and system non-functional requirements. A C-BUMMPS architecture is developed to address the stakeholders' needs. The developed architecture will consist of on-board sensing, monitoring, and processing elements on the UUV, in addition to ashore testing, data analytics, and maintenance activities needed to support the maturation of the C-BUMMPS. This project will utilize a model based systems engineering (MBSE) approach, and Innoslate was chosen as the desired MBSE tool. As such, certain views will be developed to depict the C-BUMMPS architecture from various perspectives.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
CBM	Condition Based Maintenance
C-BUMMPS	Condition-Based UUV Maintenance Monitoring and Prediction System
CONOPS	Concept of Operations
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
DAG	Defense Acquisition Guidebook
DAU	Defense Acquisition University
DOD	Department of Defense
DODAF	Department of Defense Architecture Framework
DODI	Department of Defense Instruction
EMD	Engineering and Manufacturing Development
FMDA	Failure Mode and Detection Analysis
FPR	Final Project Review
INCOSE	International Council on Systems Engineering
IPR	Interim Project Review
IPS	Integrated Product Support
ISEA	In-Service Engineering Agent
LDUUV	Large Displacement Unmanned Undersea Vehicle
MBSE	Model-Based Systems Engineering
MOE	Measure of Effectiveness
MSA	Materiel Solution Analysis
MTBF	Mean Time Between Failures
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NIST	National Institute of Standards and Technology
NSWCCD	Naval Surface Warfare Center Carderock Division
NTA	Navy Tactical Task

OPSIT	Operational Situation
PMP	Program Management Plan
POA&M	Plan of Actions and Milestones
Pre-MDD	Pre-Materiel Development Decision
PRSO	Project Review Scope Outline
SATCOM	Satellite Communications
SE	Systems Engineering
SME	Subject Matter Experts
TGIF	Thank Goodness it's Friday
TMRR	Technology Maturation and Risk Reduction
UMAA	Unmanned Maritime Autonomy Architecture
UNTL	Universal Naval Task List
UUV	Unmanned Undersea Vehicle
UUVRON-1	Unmanned Undersea Vehicle Squadron
WBS	Work Breakdown Structure
XLUUV	Extra Large Unmanned Undersea Vehicle

EXECUTIVE SUMMARY

As the Navy introduces its Large Displacement and Extra-Large class Unmanned Undersea Vehicles (UUVs), LDUUV and XLUUV, respectively, the need and desire grow for increased endurance on the order of weeks to months. Extended endurance is a necessary capability to enable UUVs to begin to take on some of the mission areas of nuclear submarines. Energy efficiency and storage capacity are some of the first factors to be considered for extending the endurance of unmanned vehicles. However, a secondary, and more challenging factor is UUV system reliability and its ability to tolerate or avoid system failures. The Navy needs to increase the endurance of its UUVs beyond improvements to energy capacity, efficiency of energy consumption, and reliability of critical components. Addressing the issue of UUV system reliability through condition-based maintenance (CBM) will improve the mean time between failures (MTBF) rate of UUVs. Increasing the MTBF of UUVs to support mission durations of weeks to months is a critical capability gap.

The intent of this project is to capture the stakeholders' need for improving UUV reliability, maintainability, and availability, then transform those needs into system requirements for a conceptual system that aims to improve UUV system reliability, a condition-based UUV maintenance monitoring and prediction system (C-BUMMPS). The C-BUMMPS architecture, UUV interfaces, and system requirements will be presented and shown to meet the stakeholders' needs. Specifically, this project will develop stakeholder, system functional, and system non-functional requirements. The developed architecture will consist of onboard sensing, monitoring, and processing elements on the UUV as well as the ashore testing, data analytics, and maintenance activities to support the maturation of the C-BUMMPS.

Figure 1 depicts a high-level operational view of the C-BUMMPS concept. As it is envisioned, the C-BUMMPS will monitor and record UUV system, subsystem, and component performance parameters. Initial data collection will form a baseline performance profile for the onboard equipment. The In-Service Engineering Agent (ISEA) will collect, analyze, and use the data to form maintenance and failure prediction

algorithms. As the UUV performs missions, and other test and training operations, the C-BUMMPS will continuously monitor and record equipment performance in relation to the environmental conditions and UUV command and control. As anomalies and off nominal performance are sensed, the C-BUMMPS will detect potential issues and failure modes and communicate alert message along with UUV health assessments. These messages will be communicated to the UUV controller and relayed to the Operations Center via Satellite Communications (SATCOM). The Operations Center will make decisions on whether to continue or abort the mission and relay the UUV Health data to the ISEA. The ISEA will then analyze the data and determine appropriate maintenance actions to be performed when the UUV returns. These maintenance actions are communicated to the Maintenance Activity as Maintenance Instructions. Early information provided by the C-BUMMPS while the UUV is still underway allows the Maintenance Activity additional time to plan and resource the maintenance actions in advance, for immediate execution upon UUV return to port. When maintenance actions are complete, the UUV will be tested to verify repair and the C-BUMMPS will monitor the UUV to append the life cycle performance profile as a result of the repaired or replaced equipment.

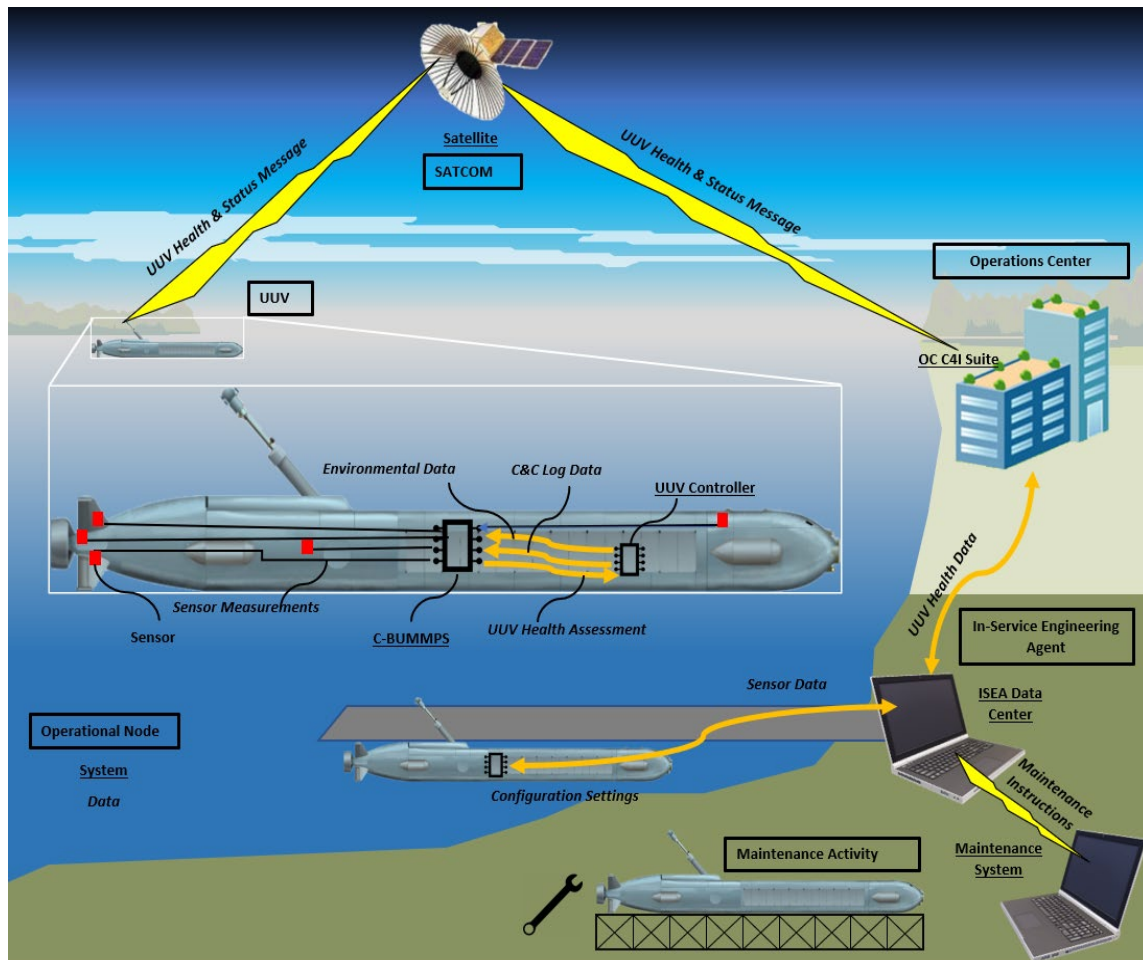


Figure 1. C-BUMMPS Operational Concept Diagram. Adapted from Sutton (2019).

A systems engineering approach was used to guide this project. A mission analysis helped to shape the mission of the C-BUMMPS within the context of normal UUV operations. The team collected data and information through a review of literature and interactions with stakeholders. An evaluation of the stakeholder needs resulted in a list of stakeholder requirements. Then a requirements analysis and UUV subsystem failure mode analysis was performed to identify potential C-BUMMPS system requirements.

This project employed digital modeling tools and utilized a model-based systems engineering (MBSE) approach to present the C-BUMMPS architecture from system, operational, and capability viewpoints. This includes a high-level operational concept

diagram (OV-1), resource flow (SV-2), operational activities (OV-5b/6c), functional block diagrams, and data and information flow diagrams. Finally, a set of system requirements will be presented, and can be used as recommendations for engineering the C-BUMMPS in the future. In addition, the MBSE model used for this project, developed in Innoslate, will be provided. The systems engineering products from this project can serve as an engineering framework for future development and implementation of the C-BUMMPS onto UUVs.

References

Sutton, H I. 2019. "USN XLUUV." Covert Shores. October 20, 2019.
http://www.hisutton.com/USN_XLUUV.html

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This report is dedicated to Stephen Ebner, who pushed each of us to strive for integrity, honor, and excellence in what we do, as engineers, teammates, and individuals. He encouraged us to pursue a systems engineering degree at NPS, to advance our careers as well as our division's collective knowledge. Furthermore, his ideas and leadership have contributed greatly to the advancement of this project and the development of unmanned systems for the Navy at large.

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I. INTRODUCTION

A. BACKGROUND

As the Navy introduces its Large Displacement and Extra-Large class Unmanned Undersea Vehicles (UUVs), LDUUV and XLUUV, respectively, the need and desire grow for increased endurance on the order of weeks to months. Extended endurance is a necessary capability to enable UUVs to begin to take on some of the mission areas of nuclear submarines. Energy efficiency and storage capacity are some of the first factors to be considered for extending the endurance of unmanned vehicles. However, a secondary, and more challenging factor is UUV system reliability and its ability to tolerate or avoid system failures. System and subsystem redundancies can improve fault tolerance, but also increase system size, cost, and logistics footprint. Assessing the past and current UUV operating conditions helps to predict the likelihood of failure occurrence. This information is used to inform preventative and corrective maintenance activities which ensure system reliability prior to a long endurance mission and reduce the number of unnecessary maintenance activities for components that show little to no degradation beyond their prescribed maintenance cycles.

B. CAPABILITY NEED STATEMENT

The United States Navy needs to increase the endurance of its Unmanned Undersea Vehicles (UUVs) beyond improvements to energy capacity, efficiency of energy consumption, and reliability of critical components. Addressing the issue of UUV system reliability through Condition-Based Maintenance (CBM) will improve the Mean Time Between Failures (MTBF) rate of UUVs. Increasing the MTBF of UUVs to support mission durations of weeks to months is a critical capability gap.

C. PURPOSE

The intent of this project is to capture the stakeholders need for improving UUV reliability, maintainability, and availability, then transform those needs into system requirements for a Condition-Based UUV Maintenance Monitoring and Prediction

System (C-BUMMPS) architecture that addresses the stakeholders' needs. Specifically, this project will develop stakeholder, system functional, and system non-functional requirements. The developed architecture will consist of on-board sensing, monitoring, and processing elements on the UUV, in addition to the ashore testing, data analytics, and maintenance activities to support the maturation of the C-BUMMPS. The objectives of this project are:

- Identify and address stakeholder concerns from system, operational, and capability viewpoints
- Architect the C-BUMMPS
- Develop requirements to inform future C-BUMMPS development and integration
- Employ digital modeling of the C-BUMMPS system to help develop system views and requirements

D. SCOPE

This project will be focused on large-displacement UUVs (LDUUVs) and the extra-large UUVs (XLUUVs) as the platforms for integrating C-BUMMPS.

II. LITERATURE REVIEW

This section presents a review of the literature which guided this project and previously conducted research on UUVs and Condition Based Maintenance (CBM) methods. Each subsection will detail the different research topics, including Department of Defense (DOD) and Navy acquisition documents, UUV design and UUV operations, failure analysis techniques, and a comparison of CBM employed in other systems to UUVs. Various technical reports, acquisition documents, systems engineering reports, NPS thesis papers, and journal articles were reviewed and informed the project. This literature review identifies and presents the relevant topics that provide the basis of understanding for the project and aims to elicit further research questions for future work in CBM in UUVs.

A. COMPARISON OF EXISTING CBM SYSTEMS TO UUVS

CBM and data collection for predictive maintenance algorithms exists in many other types of systems which have mission needs for extended durations of weeks to years and must maintain high reliability. Both military and commercial applications in aerospace and aeronautical industries use this capability in high-maturity engineering systems (Iverson 2017). The application of CBM in UUVs is unique in that it must integrate into a relatively low-level of “human-in-the-loop” interaction to the vehicles autonomy and decision-making system, and the degraded communications environment that are inherent to military UUV missions. A precursory study of other systems which employ CBM was conducted to understand possible benefits or requirements which may also be useful for C-BUMMPS. Some examples of companies and systems found to include CBM, system monitoring, and predictive maintenance are Boeing, General Electric, Airbus, NASA, Navy submarines and aircraft, Nuclear Power Plants, commercial shipping vessels, and even software systems.

Research has shown there as some common characteristics and techniques of systems that employ CBM and monitoring. Some examples of these characteristics include:

- Vibration analysis
- Temperature measurements via infrared cameras
- Ultrasonic
- Acoustic
- Oil analysis
- Electrical measurements (voltage and current)
- Operational measurements (pressure, flow, density)

B. NAVAL UUV DESIGN, OPERATIONS, AND ACQUISITION PRACTICES AND PROCESSES

Previous work and research in DOD acquisition of UUVs within the Navy significantly impacted the development of the project. Various Navy stakeholders (identified in Section 5) and the work performed under their purview contributes to the general knowledge of UUVs which established the basis for the project. Navy acquisition documentation was extensively researched in the lead up to the project. Numerous overarching documents helped to shape the vision and inspiration for this project. Some documents include, but are not limited to:

- The National Defense Strategy
- The Navy UUV Master Plan (2004)
- Unmanned Maritime Systems (PMS406) Strategic Plan
- Navy/DOD CBM Policy
- NAVSEA Engineering and Technical Authority Documents for Engineering Agents
- Navy Submarine Maintenance Engineering, Planning and Procurement Activity (SUBMEPP) Reliability Centered Maintenance (RCM) Process

- Various Acoustic Monitoring Systems Requirements Documents
- MIL-STD-881D – Work Breakdown Structures for Defense Materiel Items

C. OTHER CBM RESEARCH

Several NPS theses were reviewed to see what work has been completed on CBM. The first thesis reviewed was “A methodical development of measures of effectiveness for a condition-based maintenance management system” by Hector A. Ojeda. Ojeda (2014) presents several measures of effectiveness (MOEs) for evaluating Condition-Based Maintenance Management Systems, which are commercial off-the-shelf (COTS) maintenance management systems. The measures of effectiveness presented in this thesis could also be explored for use in evaluating the C-BUMMPS, or at least provide the process necessary to arrive at the appropriate MOEs for this capstone.

The second thesis reviewed was “Machine Learning Techniques for Development of a Condition-Based Maintenance Program for Naval Propulsion Plants” by Eric A. Therrio. Therrio (2018) explores the use of a specific machine learning algorithm as the foundation for a CBM software program. This thesis showed that the effectiveness of the CBM system can hinge on the algorithms used to identify and report faults. As a result, any C-BUMMPS architecture developed will need to account for computing techniques that improve fault detection and prediction.

The third thesis reviewed was “Conditions-Based Maintenance through Autonomous Logistics” by Michael Whitaker. Whitaker (2019) shows that CBM can be employed relatively inexpensively through COTS hardware and software integrated with the system of interest. The use of these materials indicate CBM can be employed after the system has been deployed, but since C-BUMMPS has not been developed yet, various sensors can be worked into the architecture based on stakeholder inputs and preliminary system analysis. Interestingly, Whitaker uses hardware which interfaces with the platform of interest’s native diagnostic capability. This approach by Whitaker demonstrates that using components with the ability to report raw data can reduce the need for extra sensors to monitor key operational parameters.

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III. METHODOLOGY

This section presents the referenced documentation that guides the systems engineering processes employed in the project. The Concept of Operations (CONOPS) context for the C-BUMMPS will be derived from stakeholder engagement as well as research into how other domains handle CBM. The Naval Surface Warfare Center Carderock Division (NSWCCD), Marine, Aviation, and Unmanned Systems Division Team intends to use a model-based systems engineering (MBSE) approach to build a model for the C-BUMMPS concept. This MBSE approach will allow the team to present the C-BUMMPS concept from requirements to a generic physical architecture from the stakeholder's perspective, thus providing a blueprint for more detailed designs and eventually implementation. The Department of Defense Architecture Framework version 2.0 (DODAF v2.0) will be the architecture framework used to model the C-BUMMPS since all DOD components “are expected to conform to the DODAF when developing architectures within the [Department of Defense]” (Chief Information Officer (CIO) n.d.). Conformance to the DODAF “ensures reuse of information and that architecture artifacts, models, and viewpoints can be shared with common understanding (Chief Information Officer (CIO) n.d.). The systems engineering process used for this capstone project was tailored from the Defense Acquisition Guidebook (DAG) version 4, chapter 3 (DAU 2020). Figure 1 is an IDEF0 representation of the tailored system engineering process used for this capstone project.

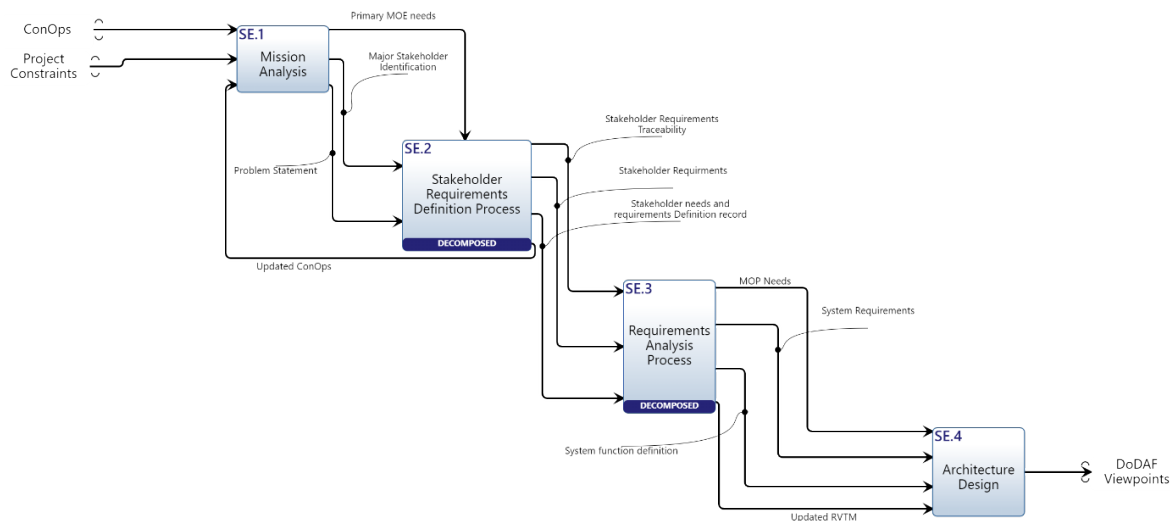


Figure 1. Systems Engineering Approach

A. ACQUISITION LIFE CYCLE PHASES

Department of Defense Instruction (DODI) 5000.02 defines the system acquisition life cycle for DOD systems. Since the C-BUMMPS will be a system integrated on Navy UUVs, it was decided that the DODI 5000.02 would provide the context for the stage of development of the C-BUMMPS in the overall life cycle that this project addresses. DAG Chapter 3 summarizes the DODI 5000.02 life cycle perspective and will be used along with the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook 4th Edition as the primary references for implementing the tailored life cycle perspective for the project.

Per the DAG Chapter 3, the DODI 5000.02 framework details six phases to the acquisition life cycle: Pre-Materiel Development Decision (Pre-MDD) phase, Materiel Solution Analysis (MSA) phase, Technology Maturation and Risk Reduction (TMRR) phase, Engineering and Manufacturing Development (EMD) phase, Production and Deployment phase, and the Operations and Support phase. The intent of this project is to develop an architecture that captures the initial C-BUMMPS concept, therefore, only the Pre-MDD and MSA phases will be considered (DAU 2020).

The primary goals of the Pre-MDD phase is to fully understand user needs, identify materiel solution approaches, and develop a plan for the following acquisition

phase, among other things (DAU 2020). This phase will be important as it will provide the foundation for user-driven requirements as well as an understanding of the potential technical solutions for the C-BUMMPS. Following the Pre-MDD phase, the MSA phase encapsulates several critical systems engineering activities. Some of these activities include a system model and architecture that captures the operational context and concepts, system boundaries and interfaces, and the operational and functional requirements. In addition to the system model and architecture, a preliminary performance specification will be developed that will define the performance of the C-BUMMPS (DAU 2020).

B. SYSTEMS ENGINEERING PROCESSES

There are several systems engineering processes that were used to guide the C-BUMMPS project study. The life cycle phases described for the project have several technical and technical management processes occurring within them. Table 1 shows the processes that will be occurring during the Pre-MDD and MSA phases of the acquisition life cycle as described by DODI 5000.02.

Table 1. C-BUMMPS Technical Processes. Source: DAU (2020).

	Process	Pre-MDD	MSA
Technical Management Processes	Requirements Management		X
	Interface Management		X
Technical Processes	Mission Analysis	X	X
	Stakeholder Requirements Definition	X	X
	Requirements Analysis	X	X
	Architecture Design		X

1. Mission Analysis Process

The purpose of the Mission Analysis Process is to define the operational concept and actions for a C-BUMMPS subsystem within a UUV's operational context. A Design Reference Mission (DRM) will define the C-BUMMPS operating conditions and challenges, identify maintenance metrics of interest, and explore operational scenarios to identify high level activities and operational tasks. The Mission Analysis is performed iteratively with the Stakeholder Needs and Requirements activity to better understand the problem space, define the solution space, and identify mission requirements (IEEE. 1998).

2. Stakeholder Requirements Definition Process

The Stakeholder Requirements Definition Process is a technical process that facilitates the translation of stakeholder capability needs into technical requirements (DAU 2020). This process will be conducted partially in the Pre-MDD phase as well as the MSA phase to ensure thorough coverage of stakeholders' needs and concerns. This will enable the NSWCCD Marine, Aviation, and Unmanned Systems Division Team to develop a concept that meets the needs of the stakeholders.

3. Requirements Analysis Process

The Requirements Analysis Process is a technical process that decomposes the stakeholder requirements, defined in the Stakeholder Requirements Definition Process, to "clear, achievable and verifiable requirements" (DAU 2020). This process will be initiated in the Pre-MDD phase but will continue in the MSA phase as well to allocate and derive requirements down to the various system components of the C-BUMMPS.

4. Architecture Design Process

The Architecture Design Process is a technical process that translates the requirements of the Stakeholder Requirements Definition Process and the Requirements Analysis Process into the architectural design solution. This architectural solution will be a system model that would be a concept for future C-BUMMPS development. Unlike the other processes that would be iterative in both the Pre-MDD and the MSA phases, the

Architecture Design Process would only occur in the MSA phase of the C-BUMMPS life cycle.

5. Requirements Management Process

The Requirements Management Process is a technical management process that deals with the maintenance of requirements throughout the life cycle (DAU 2020). This will be conducted in both the Pre-MDD and the MSA of C-BUMMPS development and will cover stakeholder and system requirements. Digital Modeling tools are employed to aid the Requirements Management Process for C-BUMMPS requirements.

6. Interface Management Process

The Interface Management Process is a technical management process that deals with the C-BUMMPS interfaces. Specifically, this process “provides a framework to identify, define, manage, and ensure compliance with internal and external system interfaces” (DAU 2020). An initial look at interfaces will be conducted in the Pre-MDD phase with a more detailed modeling of the interfaces occurring in the MSA phase. Digital Modeling tools are employed to aid the Interface Management Process for C-BUMMPS interfaces.

C. PROJECT MANAGEMENT

A project management plan (PMP) was developed at the start of this project and is provided as a supplementary document to this report. The PMP has been updated and modified as the project progressed.

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IV. MISSION ANALYSIS

This chapter seeks to provide a context for the C-BUMMPS within the operational mission of a UUV and was conducted at the beginning of the project based on the team member's years of experience designing unmanned undersea systems. An operational concept is presented to describe characteristics and elements of the C-BUMMPS. A design reference mission (DRM) presents the conditions and boundaries that the C-BUMMPS will operate in, challenges to a successful mission, and identifies maintenance metrics of interest. Then operational situations are given to inform high level activities and operational tasks which the C-BUMMPS will have to conduct to successfully complete a mission. The mission analysis was performed iteratively with the stakeholder needs and requirements definition activities to better understand the problem space, define the solution space, and influence the development of the C-BUMMPS system requirements and architecture design.

A. OPERATIONAL CONCEPT

The C-BUMMPS's Operational Concept Diagram is depicted in Figure 2. The C-BUMMPS will monitor and record UUV system, subsystem, and component performance parameters. Initial data collection will form a baseline performance profile for the onboard equipment. The In-Service Engineering Agent (ISEA) will collect, analyze, and use the data to form maintenance and failure prediction algorithms. As the UUV performs missions, and other test and training operations, the C-BUMMPS will continuously monitor and record equipment performance in relation to the environmental conditions and UUV command and control. As anomalies and off nominal performance are sensed, the C-BUMMPS will detect potential issues and failure modes and communicate alert message along with UUV health assessments. These messages will be communicated to the UUV controller and relayed to the Operations Center via Satellite Communications (SATCOM). The Operations Center will make decisions on whether to continue or abort the mission and relay the UUV Health data to the ISEA. The ISEA will then analyze the data and determine appropriate maintenance actions to be performed when the UUV returns. These maintenance actions are communicated to the Maintenance

Activity as Maintenance Instructions. Early information provided by the C-BUMMPS while the UUV is still underway allows the Maintenance Activity additional time to plan and resource the maintenance actions in advance, for immediate execution upon UUV return to port. When maintenance actions are complete, the UUV will be tested to verify repair and the C-BUMMPS will monitor the UUV to append the life cycle performance profile as a result of the repaired or replaced equipment.

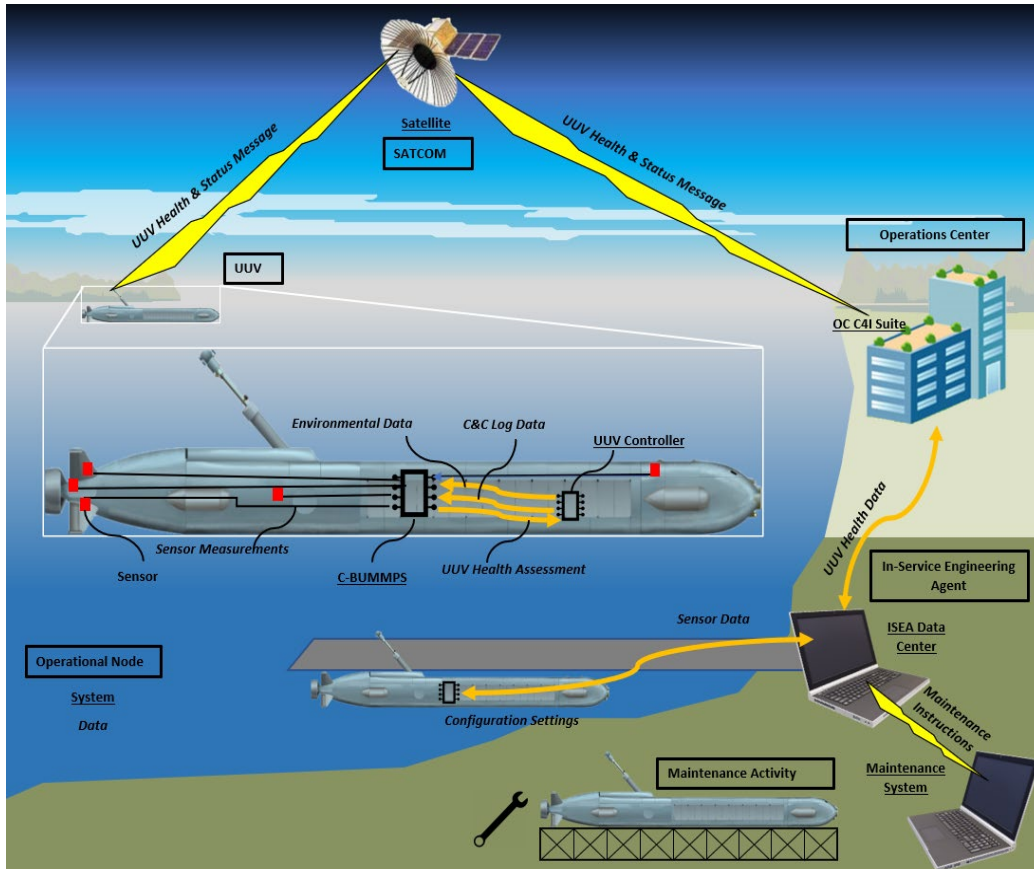


Figure 2. C-BUMMPS Operational Concept Diagram. Adapted from Sutton (2019).

B. DESIGN REFERENCE MISSION

1. Operating Conditions

The C-BUMMPS will be installed on LDUUVs and XLUUVs and subject to the same extreme operational environments these vehicles encounter. Sensors may be

installed in dry, ambient-pressure housings, oil-filled pressure compensated (i.e., at hydrostatic pressure at depth) enclosures, and external mountings exposed to the surrounding ocean environment. Data acquisition and processing equipment will be installed in dry, ambient-pressure housings to protect their electronics. The C-BUMMPS will operate for all times when the vehicle or its individual subsystems are operating, including testing, training, maintenance, and transportation. Therefore, C-BUMMPS should perform within the same operating conditions that a UUV may experience.

2. Threat Details

The threats to the C-BUMMPS are primarily due to the operating environment and conditions. Additionally, information assurance is a major consideration for a system which will rely on data measurement, collection, and analysis system that informs vehicle and operator decisions for mission continuation.

The National Institute of Standards and Technology (NIST) describes information assurance as “the degree of confidence one has that security measures protect and defend information and systems by ensuring their availability, integrity, authentication, confidentiality, and non-repudiation. These measures include providing for restoration of systems by incorporating protection, detection, and reaction capabilities” (NIST 2017).

Thus, threats to information assurance must be considered with this system. Such threats may involve:

- Authentication: Verifying the identity of a user, process, or device, often as a prerequisite to allowing access to resources in a system (NIST 2017)
- Integrity: Guarding against improper information modification or destruction and includes ensuring information non-repudiation and authenticity (NIST 2017)
- Availability: Ensuring timely and reliable access to and use of information (NIST 2017)

Threats to data integrity could be due to human influence as well as data corruption due to software or hardware malfunctions and errors. This would be present

for both onboard UUV recording as well as shore-based data analysis and storage centers. Additionally, electromagnetic interference (EMI) within the UUV system and its external environment can corrupt data. This could affect raw data in transit (active, real-time measurement signals or stored data transfer) and data at rest (stored on the UUV or shore-based repositories).

In the case of C-BUMMPS, information availability is primarily concerned with whether the system, subsystem, and component performance parameters have been monitored and recorded. This is necessary to allow for building a comprehensive baseline history of performance to develop prediction algorithms and to later have prediction algorithms applied to assess the component or system status, and likelihood of failure within a future time. Availability can be threatened by non-operating or failed sensors or data loss, resulting in a gap in the performance history or lack of monitoring and identifying a degraded condition to trigger a maintenance activity response.

3. Mission Definition

The C-BUMMPS will be installed on UUVs to monitor and record system performance parameters that define the operational health of the various subsystems and components of the UUV. The environmental and associated vehicle control data collected will be used to build a nominal performance baseline. As operating hours increase, deviations from the baseline, off-nominal performance, and other anomalies will provide indications of degraded health and performance leading up to failures or preventive maintenance activities. This parametric data will be analyzed and used to develop prediction algorithms, and then they will alert operators to perform recommended maintenance activities including replacement of components and subsystems with predicted impending failures. As C-BUMMPS is an enabling system, activities are associated with those activities in a UUV system's life cycle. The C-BUMMPS design reference mission (DRM) is decomposed into four operational activities:

1. UUV Performance Baseline
2. UUV Pre-Mission Checkout
3. UUV Mission Operations

4. UUV Post-Mission and Maintenance Activities

4. Maintenance Metrics

Implementation of the C-BUMMPS supports Navy Tactical Task (NTA) 4.3: Repair/Maintain Equipment, provided in Table 2, as defined in the Universal Naval Task List (UNTL 3.0). NTA 4.3 provides a set of relevant metrics where the C-BUMMPS can facilitate repair and maintenance of UUVs. These maintenance metrics include:

- Schedule/Coordinate Task Force Repair Assets (UNTL 3.0)
- Repair, Maintain, and Modify Equipment (UNTL 3.0)
- Perform Preventative Maintenance (UNTL 3.0)
- Diagnose and Repair (UNTL 3.0)

Based on the description of the C-BUMMPS and its activities, particularly early identification, and notice of equipment in need of maintenance, the technology will be a significant enabler to UUV reliability, availability, and maintainability. The C-BUMMPS allows the ISEA and Maintenance Activity to plan and be ready to perform maintenance activities as soon as the UUV arrives in port. This early initiation of activities could enable a major reduction in maintenance down-time due to diagnostics, as well as logistics delay times, by enabling early execution and scheduling of resources. Once confidence is gained in the C-BUMMPS, the ISEA may be able to redefine scheduled maintenance frequency to be condition based, rather than in accordance with a somewhat arbitrary periodicity prescribed independent of actual operating conditions and history.

Table 2. Navy Tactical Tasks Supported by C-BUMMPS. Source: UNTL 3.0 (2017).

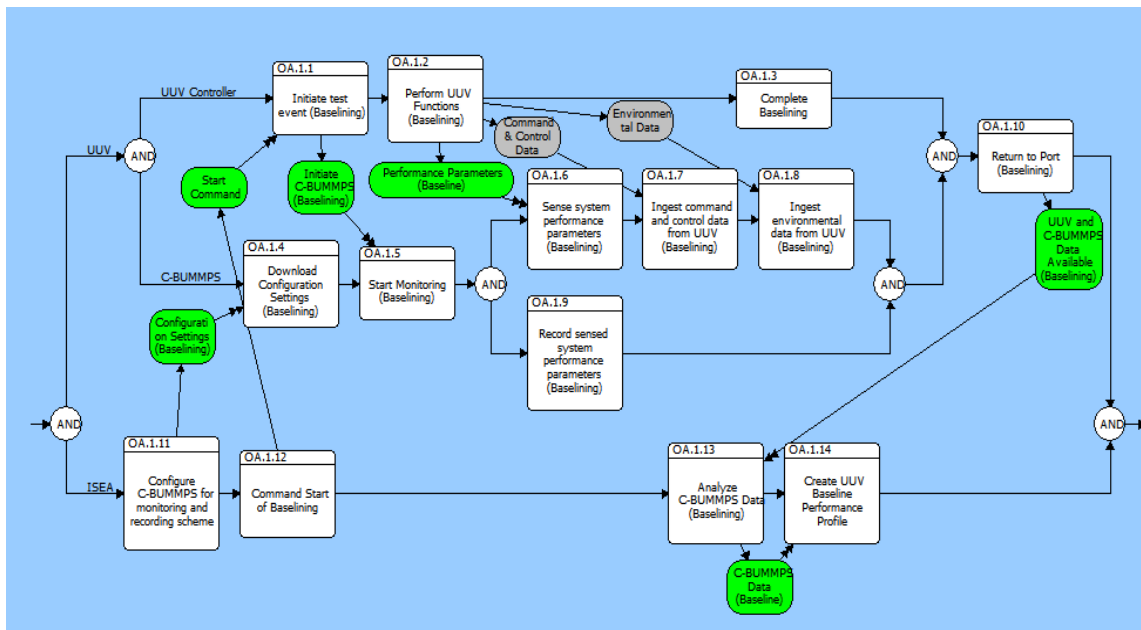
NTA 4.3 Repair/Maintain Equipment		
To preserve, repair, and ensure continued operation and effectiveness of units (ships, aircraft, ground forces, weapons systems, and their equipment). It includes the policy and organization related to the maintenance of equipment (afloat and ashore); development of maintenance strategies; standards of performance for both preventive and corrective maintenance; technical engineering support; provision of repair parts and end items; and battle damage repair. (JP 4-0, NDP-4, NWP 4-07, MCWP 4-1, MCWP 4-11, 3M MANUAL, OPNAVINST 4790.16, 4790.2J, 4790.4D, NSTM 001)		
M1	Hours	After receipt of warning order, command staff has developed concept and policies for equipment repair, maintenance and evacuation, and establishment of rear area facilities.
M2	Percent	Of the support policies and procedures completed using the joint operations planning and execution system (JOPES) planning process.
M3	Days	Average equipment down time.
NTA 4.3.1 Schedule/Coordinate Task Force Repair Assets		
To schedule and coordinate the repair and maintenance assets of naval/amphibious forces. (JP 4-0, NDP 4, NWP 4-07, MCWP 4-1, MCWP 4-11, OPNAVINST 4790.2J, 4790.4D, NSTM 001)		
M1	Percent	Of the support policies and procedures completed using JOPES planning process.
M2	Percent	Of operational ready of equipment.
M3	Percent	Of TPFDD maintenance units deployed and operational.
NTA 4.3.2 Repair, Maintain, and Modify Equipment		
To repair, maintain, and modify naval forces; to ensure continued support to forces operating ashore during the repair process; and to ensure coordination of the internal task force repair, maintenance, and modification assets. This function includes the provision of repair parts and end items at the right place and right time and all the actions taken before, during, and after battle to keep equipment operational. It also includes employment of depot level maintenance, dry-docking, and deployable repair capabilities such as a tender, battle group intermediate maintenance activity (IMA) or amphibious ready group IMA. (JP 4-0, NDP 4, NWP 4-07, MCWP 4-1, MCWP 4-11, OPNAVINST 4790.2J, 4790.4D, NSTM 001)		
M1	Percent	Of the support policies and procedures completed using JOPES planning process.
M2	Percent	Of equipment operational ready.
M3	Percent	Of TPFDD maintenance units deployed and operational.
NTA 4.3.2.1 Perform Preventive Maintenance		
To conduct maintenance checks and services to quickly identify potential problems. Preventive maintenance includes quick turnaround repairs by component replacement, minor repairs, performance of scheduled services, and calibration. (JP 4-0, MCWP 4-1, 4-11, NDP 4, NWP 4-07, 3M MANUAL, OPNAVINST 4790.2J, 4790.4D, NSTM 001)		
M1	Number	Of planned maintenance system (PMS) tasks.
M2	Number	Of PMS tasks completed.
M3	Percent	Of PMS tasks completed.
NTA 4.3.2.2 Diagnose and Repair		
To monitor equipment and material performance through the use of on-board sensors, diagnostic equipment, and visual inspections in order to identify impending and/or actual malfunctions. This task includes trend analysis and efforts taken to restore an item to serviceable condition through correction of a specific failure or unserviceable condition. (JP 4-0, NDP 4, NWP 4-07, MCWP 4-1, MCWP 4-11, 3M MANUAL, OPNAVINST 4790.4D, NSTM 001)		
M1	Percent	Of equipment operational ready.
M2	Percent	Of TPFDD maintenance units deployed and operational.
M3	Percent	Of equipment deadlines for maintenance.

C. OPERATIONAL SITUATIONS

The following operational situations (OPSITs) are considered for the C-BUMMPS and will define the high-level activities for the C-BUMMPS DRM. Note that the action diagrams presented in this section were developed using a digital modeling tool, CORE, which is different from the models developed during this project in Innoslate. The DRM OPSIT action diagrams were produced prior to the start of this project, and helped to guide the ideas and inputs to this project. These OPSITs are revisited in architecture design are presented in Innoslate, and have been updated to reflect the additional information elicited from the stakeholder needs and requirements definition process, and system requirements definition.

1. UUV Performance Baselineing

At the start of UUV acceptance testing, and through training and other pre-operational UUV activities, the C-BUMMPS will begin monitoring and recording system and subsystem performance parameters. The C-BUMMPS will also ingest environmental data from the UUV sensors and vehicle command and control messages. Thus, performance data will be associated with the environmental conditions and the commanded operating performance for the UUV subsystems and components. The data will be collected and stored in a shore-based data center managed by the ISEA. As the performance data record grows, it forms a baseline for nominal performance of subsystems and components. Off-nominal performance and anomalies, combined with harsh operating conditions, and subsequent maintenance activities, or lack thereof, will influence reliability and the MTBF of the subsystems and components. This comprehensive data record will provide input to the development of algorithms for UUV Health Assessments, maintenance recommendations, and failure predictions. The UUV Performance Baselineing Action Diagram is provided in Figure 3.



2. UUV Pre-Mission Checkout

Prior to embarking on a mission, the UUV will perform a pre-mission checkout. Subsystems and components will be exercised by commanding the UUV to execute sortie activities and functions with C-BUMMPS monitoring and recording data. Performance parameters that exceed threshold bounds set from the baseline data will indicate a potential issue. Subsequent maintenance actions can be performed by the Maintenance Activity prior to mission execution, to ensure reliability and avoid failures during the mission. The ISEA will collect and analyze this data to determine operational readiness and inform the Operations Center. The UUV Pre-Mission Checkout Action Diagram is provided in Figure 4.

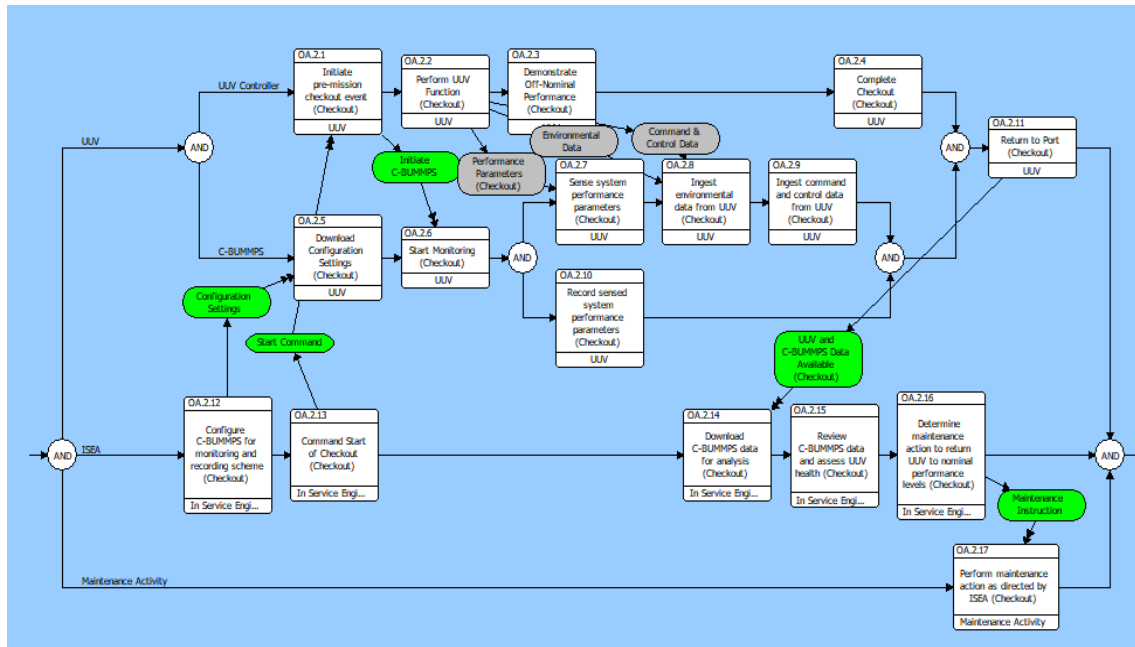


Figure 4. UUV Pre-Mission Checkout Action Diagram

3. UUV Mission Operations

During an operational mission, the C-BUMMPS will continuously monitor and record UUV performance parameters. The C-BUMMPS sensors will collect subsystem and component performance parameter measurements along with ingested environmental data and vehicle command and control logs. Using the baseline performance profile, and the previously developed algorithms, the C-BUMMPS will continuously assess the health of the UUV and its constituent subsystems and components. Performance parameters that exceed threshold bounds set from the baseline data will indicate a potential issue and trigger an alert message to be communicated back to the Operations Center by the UUV SATCOM, or other communication methods. Algorithms will calculate a time to failure and/or degraded performance level within a set of confidence bounds. Various levels of alerts, associated with the criticality of an off-nominal system, and the magnitude of performance deviation from the baseline, can inform operator and potentially autonomy decisions.

During scheduled or event driven (e.g., emergency, condition-based rulesets, etc.) communications activities, the UUV will communicate the C-BUMMPS generated UUV Health Assessment and alert messages via SATCOM to the Operations Center. Operators

will make risk-informed decisions about whether to continue the mission, or abort and command return to port, or initiate recovery activities. Additionally, the Operations Center will communicate the UUV Health Assessment Data to the ISEA. The ISEA can determine the appropriate maintenance actions to perform and then initiate planning and resourcing of the unscheduled maintenance actions by the Maintenance Activity prior to the UUV's return to port. These are communicated by the ISEA to the Maintenance Activity as Maintenance Instructions. Repair and replacement parts can be ordered, personnel can be scheduled, and tools, facilities, and resources can be allocated with days, if not weeks, of advanced notice before the UUV is even accessible at the port. The UUV Mission Operations Action Diagram is provided in Figure 5.

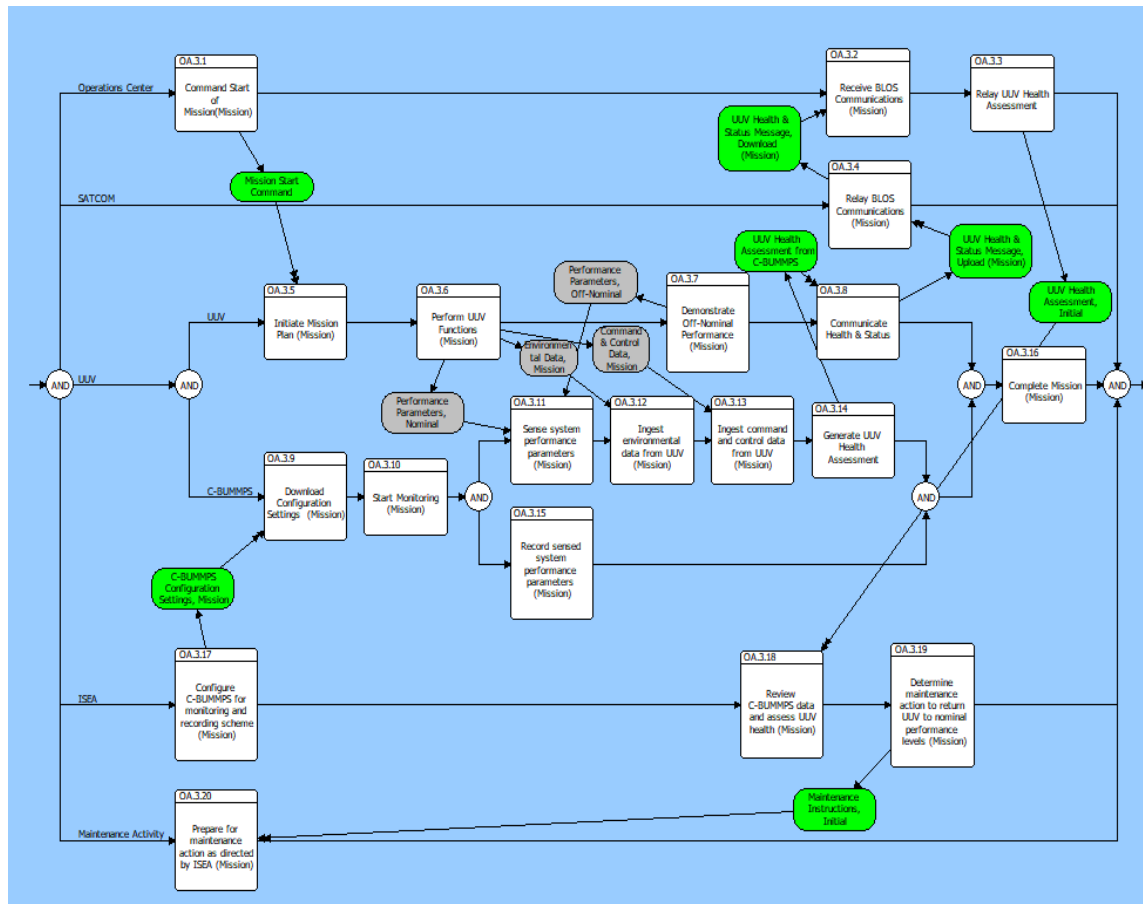


Figure 5. UUV Mission Operations Action Diagram

4. UUV Post-Mission and Maintenance Actions

Upon return of the UUV to port after a mission, the C-BUMMPS raw data and health assessments will be downloaded from the C-BUMMPS by the ISEA. The data is entered into the data center and appended to the life cycle performance profiles for the UUV subsystems and components. Analysis of the data will identify any trending deviations over time that may indicate wear or subtle degradation. Additional maintenance activities may be recommended or planned for future availabilities based on performance data that indicates a growing issue that did not exceed threshold to generate alert messages during the mission.

Following maintenance activities, post-maintenance testing of repaired and replaced components is performed. The C-BUMMPS will monitor and collect performance data in a manner like performance baselining and pre-mission checkout. This data will verify the maintenance activities were successful and did not introduce additional problems. The C-BUMMPS will also use collected subsystem and component data to either re-calibrate the life cycle performance profiles or create a new baseline performance profile for replaced elements. The collected data is analyzed to update the life cycle performance profile. The UUV Post-Mission and Maintenance Action Diagram is provided in Figure 6.

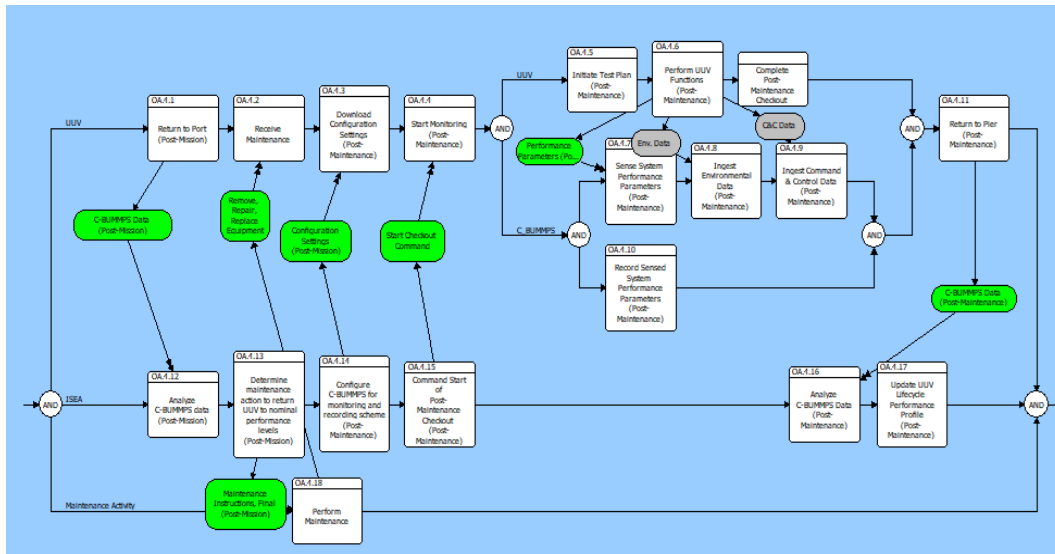


Figure 6. UUV Post-Mission and Maintenance Action Diagram

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V. STAKEHOLDER REQUIREMENTS DEFINITION

A. STAKEHOLDER IDENTIFICATION

The Unmanned Undersea Vehicle Squadron (UUVRON-1) is the Navy's primary fleet operators for UUVs. They have a need for reliable UUV systems to ensure mission success is not compromised by mission-critical failures. System reliability will also be a critical factor in the warfighter gaining trust in unmanned systems to take over mission sets from traditional, manned platforms.

The ISEA is responsible for managing and executing sustainment activities to support UUV systems throughout their operational life cycle. They have an inherent desire to optimize their activities by addressing maintenance needs, when necessary, not simply according to a prescribed periodicity, and maximizing system reliability and availability to ensure it's ready for missions.

Naval Sea Systems Command (NAVSEA) Program Management Offices have a need to reduce total cost of ownership of their systems, ensure mission readiness, and prevent loss of vehicles at sea on missions that result in expensive and risky recovery efforts, loss of an operational asset, and potential loss technological advantage by adversaries capturing a UUV that has suffered failures due to reliability.

National leaders and decision makers need to be able to rely on UUV systems to conduct missions in support of national interests. Operations have costs, schedule and timelines, and risk associated with execution. These stakeholders need to have confidence that the UUV system allocated to complete a mission has a reasonable likelihood of success that is not driven by reliability and the probability of experiencing a system or component failure independent of the risks associated with a particular mission.

The stakeholders for this project, which holds an interest in this project's goals and results, are identified in Table 3.

Table 3. Stakeholders and Subject Matter Experts Roles and Organizations

Stakeholder Group	Role	Organization
Program Office	UUV Principal Assistant Program Manager	Unmanned Maritime Systems Program Office (PMS 406)
	Unmanned Undersea Warfare (UUV) Systems Engineer	Unmanned Maritime Systems Program Office (PMS 406)
Technical Authority	XLUUV/LDUUV Ship Design Manager	Naval Systems Engineering and Logistics, Submarine and Submersible Design & Systems Engineering, Advance Undersea Systems (NAVSEA 05U5)
	UUV Waterfront Chief Engineer	NAVSEA 05U5
	XLUUV Reliability Engineer	Naval Surface Warfare Center Carderock Division
Integrated Product Support	XLUUV IPS Lead	Naval Undersea Warfare Center Keyport Division
	LDUUV IPS Lead	Naval Undersea Warfare Center Keyport Division
	UUV In-Service Engineering Agent Representatives	Naval Undersea Warfare Center Keyport Division
Data Analytics	Marine Aviation Branch F-18 Data Analytics Lead Engineer	Naval Surface Warfare Center Carderock Division
	XLUUV Software SME	Naval Surface Warfare Center Carderock Division
	Cyber C4I Lead, Unmanned Maritime Systems Program Office	Unmanned Maritime Systems Program Office (PMS 406)
Unmanned Maritime Systems	SSTM, Director, USW Unmanned Systems and Autonomous Behavior	Naval Undersea Warfare Center Newport Division
	Director, Integrated Unmanned Maritime Mobility Systems	Naval Surface Warfare Center Carderock Division
Strategic Planning and Direction	Chief Technology Officer, Digital Twin Advocate	Naval Surface Warfare Center Carderock Division
	Naval Architecture & Engineering Department Chief Engineer	Naval Surface Warfare Center Carderock Division
	Head, Unmanned Undersea Systems Branch	Naval Surface Warfare Center Carderock Division
	Head, Maritime, Aviation, and Unmanned Systems Division	Naval Surface Warfare Center Carderock Division
Fleet Operators	Commanding Officer	UUV Squadron One

B. STAKEHOLDER ANALYSIS

Telephone interviews were held with some of the identified stakeholders, as time and availability allowed. Interviews were scheduled via an introductory email that explained the purpose of the project and the C-BUMMPS concept. A presentation providing an overview of the preliminary CONOPs, major system activities, and project development approach was also sent to the attendees and presented by the team during the interview. Additionally, a broad set of questions were included, intended to elicit stakeholder needs, requirements, feedback, and project direction, as well as recommendations for additional resources to pursue. These questions and the presentation can be found in APPENDIX B. Stakeholder Interactions. This stakeholder interaction process was reviewed by the Naval Postgraduate School's Institutional Review Board and determined not to be Human Subjects Research.

C. STAKEHOLDER NEEDS

The stakeholder needs were identified during stakeholder interviews and the team member's years of experience working closely with Navy UUV systems and the stakeholders. The stakeholders needs are summarized and presented in Table 4.

Table 4. Stakeholder Needs

Stakeholder	Number	Name	Description
Program Office	StkNd.1.1	Improved availability	UUVs need improved availability.
Program Office	StkNd.1.2	Cyber security	Systems added to the UUV need to take cyber security requirements into consideration.
Technical Authority	StkNd.2.1	Corrosion Monitoring and Prediction	UUVs need better monitoring of corrosion, environmental conditions promoting corrosion, and prediction of failures due to corrosion.
Technical Authority	StkNd.2.2	Rigorous Maintenance Documentation	UUVs need maintenance systems that rigorously document criteria and results of inspections, deficiencies, and the corrective actions
Technical Authority	StkNd.2.3	Maintenance Resource Efficiency	The Navy needs to be efficient with its maintenance resources (time, funding, manpower) by prioritizing informed maintenance decisions and activities rather than scheduled maintenance at arbitrary, un-validated periodicities.

Stakeholder	Number	Name	Description
Technical Authority	StkNd.2.4	Inherent Sensing	CBM systems need to take advantage of existing and inherent system performance parameter sensing to minimize the addition of redundant sensors and reduce the space, weight, power, and data requirements for the integration of a CBM system.
Technical Authority	StkNd.2.5	Automated Software Algorithms	CBM systems need to have a path to evolve from human-based data analysis to automated software algorithms and eventually artificial intelligence to identify system degradation, impending failures, rate of degradation and time to failure
Technical Authority	StkNd.2.6	Open Data Format	CBM data collected, particularly environmental data, should use open data formats to be available and accessible for other modeling and simulation efforts.
Integrated Product Support and In-Service Engineering Agent	StkNd.3.1	Use Data from All Classes of UUVs	A UUV Condition Based Maintenance system should use data across all UUV classes to take advantage of data for components that are common across size classes as well as attempt to correlate performance, degradation, and failure modes across similar types of components and subsystems
Integrated Product Support and In-Service Engineering Agent	StkNd.3.2	Use Modeling and Simulation	CBM systems, data, and algorithms should support modeling and simulation to predict failures, service life, mean time between failures, etc.
Integrated Product Support and In-Service Engineering Agent	StkNd.3.3	Inform Probability of Mission Success	CBM systems should generate or inform estimates of probability of mission success.
Integrated Product Support and In-Service Engineering Agent	StkNd.3.4	Use Past Performance Data	CBM systems should predict outcome based on past performance data.
Integrated Product Support and In-Service Engineering Agent	StkNd.3.5	Life cycle predictions	CBM systems should project estimated life cycles of components and subsystems to inform future years budgeting for spares and resources for maintenance activities.
Integrated Product Support and In-Service Engineering Agent	StkNd.3.6	Analyze Environmental Parameters across systems	CBM systems should consider whether environmental parameters (e.g., temperature, salinity, solar loading, etc.) have common effects across most systems, regardless of size class or architecture

Stakeholder	Number	Name	Description
Integrated Product Support and In-Service Engineering Agent	StkNd.3.7	Inform Operators of likelihood of failure	C-BUMMPS should be able to estimate probability of sortie completion or expected time until mission critical failure and generate a message to inform the operators.
Integrated Product Support and In-Service Engineering Agent	StkNd.3.8	Allow degraded performance for continued operation	C-BUMMPS should allow for completion of mission with systems and components continuing to operate with degraded performance when calculating probability of sortie completion.
Fleet Operators	StkNd.7.1	Need for ability to Correct System Failures	UUVs need the ability to correct system failures.
Fleet Operators	StkNd.7.2	Need for Resilience	UUVs need increased resilience to re-program their autonomy and control to utilize their available resources (energy, systems, components, performance limitations) within the current performance and environmental limitations.
Fleet Operators	StkNd.7.3	Need for UMAA Compliance	UUV health and performance monitoring systems should be developed to be compliant with the Unmanned Maritime Autonomy Architecture (UMAA)
Fleet Operators	StkNd.7.4	Need for Scalable CBM approach	A condition based maintenance system for UUVs must be scalable and apply different techniques to different UUV classes to maximize the return on investment. Greater mission durations, which scale with size class, warrant greater investment.
Fleet Operators	StkNd.7.5	Right-Sized Maintenance Requirements	UUV Maintenance requirements need to be appropriate for the UUV class size, mission set, and life cycle to achieve the most economical maintenance strategy that still meets mission requirements for the system.

D. STAKEHOLDER REQUIREMENTS

The stakeholder requirements have been derived from the stakeholder needs analysis. The stakeholder requirements are presented in Table 5.

Table 5. Stakeholder Requirements

Number	Name	Description	Traces To Number
StkRq.1.1.1	Increase reliability	The C-BUMMPS shall increase UUV reliability compared to demonstrated performance without CBM strategies applied.	StkNd.1.1
StkRq.1.1.2	Increase availability	The C-BUMMPS shall increase UUV availability compared to demonstrated performance without CBM strategies applied.	StkNd.1.1
StkRq.1.2.1	Comply with latest Cyber security policy	The C-BUMMPS shall comply with the latest cyber security policy and requirements as applicable.	StkNd.1.2
StkRq.1.2.2	Manage data at lowest classification	The C-BUMMPS shall have provisions to collect and maintain data at the lowest classification required for the information that the data reveals.	StkNd.1.2
StkRq.2.1.1	Corrosion Monitoring	The C-BUMMPS shall measure conditions responsible for promoting corrosion.	StkNd.2.1
StkRq.2.2.1	Data Management	The C-BUMMPS shall provide data management capability to maintain measured, calculated, and user entered data.	StkNd.2.2
StkRq.2.2.2	Integrate with Maintenance Database	The C-BUMMPS shall integrate with UUV maintenance databases to allow correlation of measured performance data with maintenance actions and inspection findings.	StkNd.2.2
StkRq.2.3.1	Maintenance Priority Recommendations	The C-BUMMPS shall use algorithms to make maintenance prioritization recommendations based on current and past performance, criticality of component failure, and estimated time to failure.	StkNd.2.3
StkRq.2.4.1	Prioritize Use of Inherent Sensing Capabilities	The C-BUMMPS shall prioritize the use of inherent and existing sensing capabilities within components and subsystems to collect performance data that contributes to assessing component and subsystem health and failure detection capability.	StkNd.2.4
StkRq.2.5.1	Software Analysis and Prediction Algorithms	The C-BUMMPS shall use software algorithms to augment and replace human analysis of data to assess system health and predict time to failure.	StkNd.2.5
StkRq.2.6.1	Use Open Data Formats	The C-BUMMPS shall use open data formats to record measured and generated data and messages.	StkNd.2.6
StkRq.3.1.1	Cross-Platform Data Analysis	The C-BUMMPS shall use data from all UUV platforms and classes, when available, to develop health assessment and failure prediction algorithms.	StkNd.3.1
StkRq.3.2.1	Data for Modeling and Simulation	The C-BUMMPS shall record and generate data in formats readily used by modeling and simulation software.	StkNd.3.2
StkRq.3.3.1	Estimate Probability of Sortie Completion	The C-BUMMPS shall generate estimates of probability of sortie completion based on the health assessments of the systems, performance profiles, and past performance data.	StkNd.3.3
StkRq.3.4.1	Predictions based on Past Performance	The C-BUMMPS shall use past performance data for systems and components when predicting time to failure and degraded performance.	StkNd.3.4

Number	Name	Description	Traces To Number
StkRq.3.5.1	Life cycle predictions	The C-BUMMPS shall predict estimated life cycles of subsystems and components out to the end of the life cycle of the UUV, including multiple replacements.	StkNd.3.5
StkRq.3.6.1	Cross-Platform Environmental Conditions	The C-BUMMPS shall collect, combine, and analyze environmental parameter data across all UUV Platforms (when data is available) to allow correlation of environmental effects on systems.	StkNd.3.6
StkRq.3.7.1	Messages to Inform Operators	The C-BUMMPS shall generate and communicate messages to inform the UUV and operators of system health assessments.	StkNd.3.7
StkRq.3.8.1	Degraded Performance Allowed	The C-BUMMPS shall allow for systems and components continuing to operate with degraded performance when estimating probability of sortie completion.	StkNd.3.8
StkRq.7.1.1	C-BUMMPS shall recommend corrective actions	The C-BUMMPS shall generate messages of recommended corrective actions to the UUV system autonomy.	StkNd.7.1
StkRq.7.2.1	Preserve Degraded Systems	C-BUMMPS shall be able to recommend alternative operating modes to preserve degraded systems and components.	StkNd.7.2
StkRq.7.2.2	Mitigate Effects of Degraded Systems	C-BUMMPS shall be able to recommend alternative operating modes to mitigate the effects of degraded systems and components.	StkNd.7.2
StkRq.7.3.1	UMAA Compliant Messaging	The C-BUMMPS communications with the UUV shall be compliant with the Unmanned Maritime Autonomy Architecture.	StkNd.7.3
StkRq.7.4.1	C-BUMMPS shall be scalable	The Implementation approach for C-BUMMPS shall be scalable based on UUV size/class and mission requirements.	StkNd.7.4
StkRq.7.4.2	Monitoring Approach	The C-BUMMPS shall provide UUV system-level monitoring at a minimum, with increased detail and fidelity of monitoring at the subsystem and component level as UUV size, complexity, and data streams allow, as well as mission needs require.	StkNd.7.4
StkRq.7.4.3	C-BUMMPS Sensing Techniques	The C-BUMMPS shall utilize a variety of sensing and measurement techniques.	StkNd.7.4
StkRq.7.4.4	Onboard and Offboard Techniques	The C-BUMMPS shall utilize sensing and measurement techniques that can be situated both onboard and offboard the UUV system	StkNd.7.4
StkRq.7.5.1	Inform Maintenance	The C-BUMMPS shall inform adjustments and revisions to scheduled/planned maintenance activities.	StkNd.7.5

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VI. REQUIREMENTS ANALYSIS

The requirements analysis process drew from three distinct efforts. First was the stakeholder analysis to elicit the stakeholder needs and then translate them into requirements. These yielded both functional and non-functional requirements for the C-BUMMPS. Next, the system CONOPS was refined through further development of the operational situations, yielding C-BUMMPS functions that must be performed to support the operational activities. Finally, a generic UUV physical architecture was developed and underwent failure mode and detection analysis. This yielded additional functional requirements for how the C-BUMMPS may detect failures. Ultimately, the results of these efforts were consolidated into a set of functional requirements and non-functional requirements. Figure 7 provides a graphical depiction of this process.

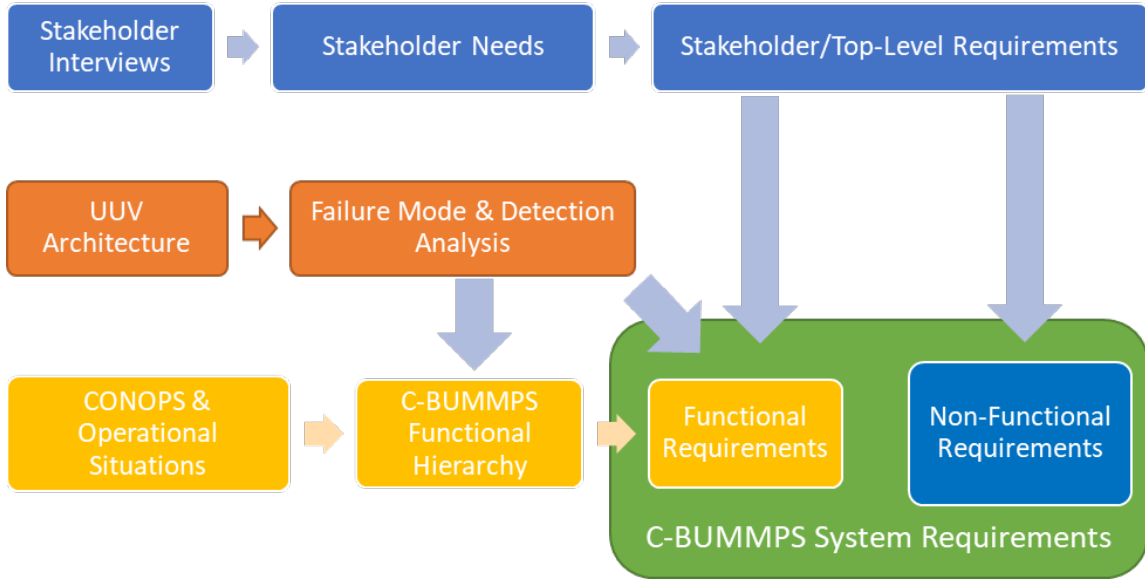


Figure 7. Process Flow for generating C-BUMMPS System Requirements

A. DEFINITION OF UUV PHYSICAL ARCHITECTURE

Analyzing the physical hierarchy of a UUV is the logical starting point for identifying functional parameters which the C-BUMMPS needs to measure. UUVs come in a several different size classes, thus there can be several different UUV physical

hierarchies that could be used. It was decided that developing a generic UUV physical hierarchy that can be adapted according to the specific needs and requirements of a UUV would be a better approach than deriving a hierarchy for a specific UUV class. Using MIL-HBK-881, a generic UUV physical hierarchy was derived from the Unmanned Maritime System (UMS) Work Breakdown Structure (WBS). The derived UUV physical hierarchy is depicted in Figure 8, Figure 9, and Figure 10. The generic UUV Physical Architecture was developed using the digital modeling tool Innoslate.

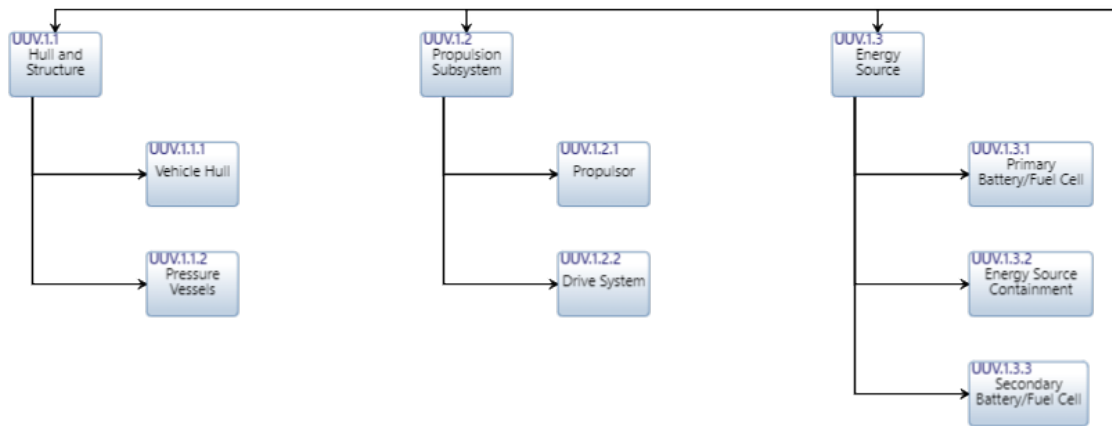


Figure 8. Derived UUV Physical Hierarchy, Pt. 1

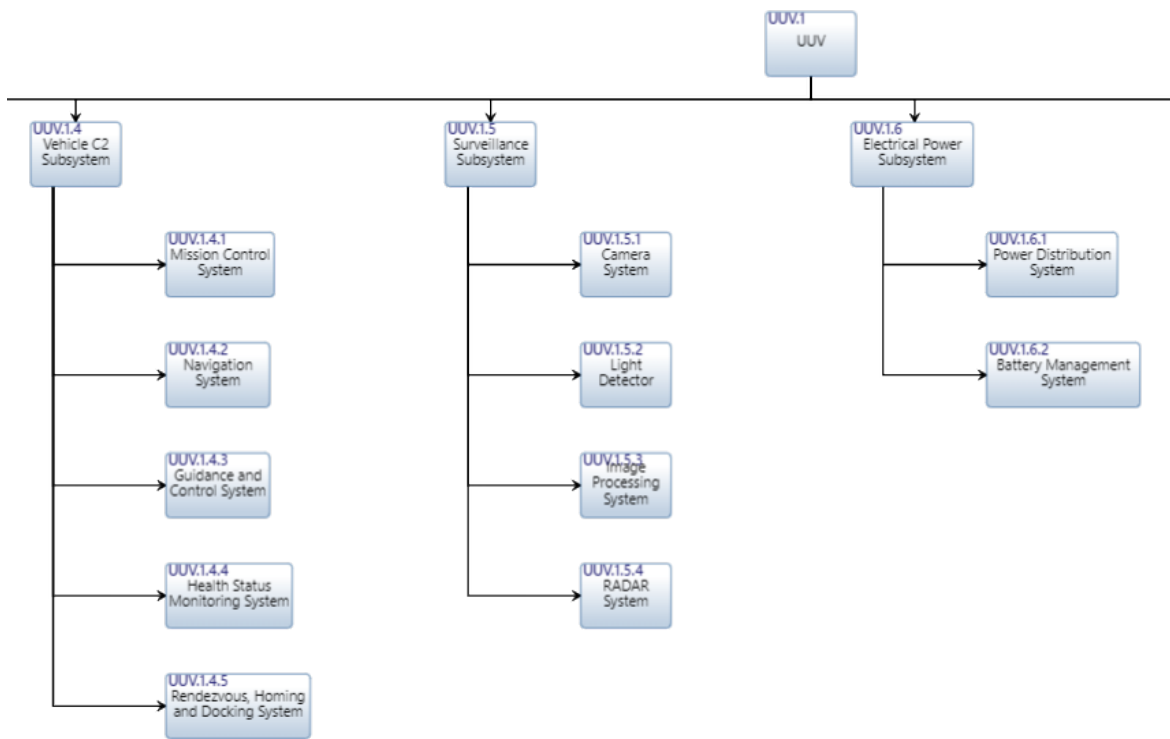


Figure 9. Derived UUV Physical Hierarchy, Pt. 2

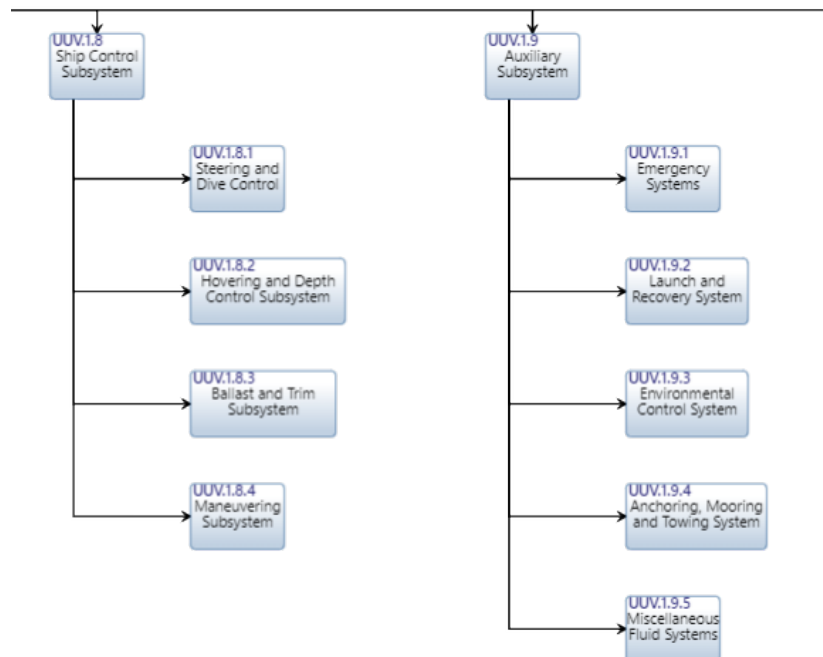


Figure 10. Derived UUV Physical Hierarchy, Pt. 3

B. UUV SUBSYSTEM FAILURE MODE AND DETECTION ANALYSIS

An analysis of potential UUV failure modes, causes, and means of detection, was performed using the generic UUV physical hierarchy to better understand the signals and measurements the C-BUMMPS will need to collect. The foundation of this analysis is derived from a failure mode and detection analysis (FMDA). According to Blanchard and Fabrycky, the FMDA “is a design technique that can be applied to identify and investigate potential system (product or process) weaknesses” (Blanchard and Fabrycky 2011). A traditional FMDA is usually conducted using a spreadsheet, but this approach was found to be inadequate since it did not allow for easy traceability between the generic UUV physical entity and its failure mode. It was decided that the FMDA would ultimately be captured in Innoslate, but the Innoslate schema needed to be expanded. Extending the database schema in Innoslate to accommodate a FMDA was accomplished by creating three new classes: Failure Mode, Failure Cause, and Failure Detection. The Failure Mode class was created to relate a failure mode to the appropriate physical entity, with respect to the UUV, a physical entity would be a system or subsystem within the UUV. A Failure Mode entity is caused by Failure Cause class entities. Last, the Failure Cause class entities are detected by Failure Detection class entities. The Failure Mode class has severity and frequency ratings as part of its attributes, while the Failure Cause class was an attribute for probability of detection, which can be set according to the associated Failure Detection class entity. Figure 11 depicts this FMDA modeling approach.

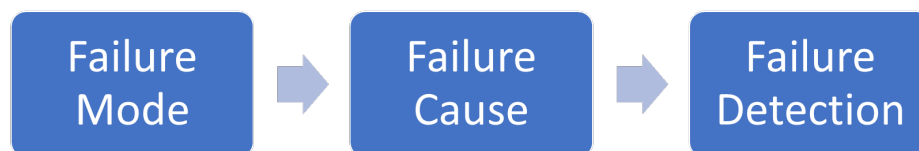


Figure 11. Innoslate FMDA Approach

Failure Modes were identified for every level of the derived generic UUV hierarchy, but only the failure modes that correspond to the lowest levels of the hierarchy were further analyzed for Failure Causes. The result of this approach were 56 failure modes of concern, 28 causes of failure, and 12 methods of detecting the causes of failure. Table 6 details the Failure Modes, Table 7 details the Failure Causes, and Table 8 details the Failure Detections.

Table 6. Generic UUV Failure Modes

Failure Mode #	Failure Mode Description
FM.1.1	Hull/Structure fails to provide form and structure
FM.1.2.1.1	Degraded thrust production
FM.1.2.1.2	Physical Damage
FM.1.2.2.1.1	Failure to move drivetrain
FM.1.2.2.1.2	Failure to control motor
FM.1.2.2.2	Damaged or impaired linkages and gears
FM.1.3.1	Degraded energy sourcing capability of primary source
FM.1.3.2	Energy source containment structural damage
FM.1.3.3	Degraded energy sourcing capability of secondary source
FM.1.4.1.1	Autonomy Controller fails to communicate with Vehicle Controller and Payload Controller
FM.1.4.2.1.1	Accelerometers fail to measure accelerations
FM.1.4.2.1.2	Gyroscopes fail to measure angular rate
FM.1.4.2.1.3	GNSS receiver fails to receive satellite signals
FM.1.4.2.1.4	GNSS Receiver provides questionable position calculations
FM.1.4.2.1.5	Data Processing Unit generates incorrect navigational calculations
FM.1.4.2.3	Navigation Sonar System unable to determine position
FM.1.4.2.5	Correlation Velocity Log unable to determine UUV velocity
FM.1.4.2.6	Geophysical Mapping System unable to determine ocean floor topography
FM.1.4.3.1	Vehicle Controller unable to communicate with vehicle elements
FM.1.4.5.1	SONAR fails to correctly provide range to an object
FM.1.4.5.4	Controller failed to coordinate docking actions docking
FM.1.5.1.1	Visible Light Camera system fails to capture visible light imagery
FM.1.5.1.2	Infrared Camera System Fails to capture IR imagery
FM.1.5.2	Light detector fails to respond to light stimulus
FM.1.5.3	Image processing system draws incorrect conclusions from imagery
FM.1.5.4	RADAR system misses objects
FM.1.6.1.1	No power at the output of the converters
FM.1.6.1.2	Relays and switches fail to open or close when commanded
FM.1.6.2	Battery management system fails to manage charge/discharge of energy source

Failure Mode #	Failure Mode Description
FM.1.7.1.1	UUV SATCOM cannot link to SATCOM Satellites
FM.1.7.2.1	ACOMMS system unable to receive acoustic messages
FM.1.7.2.2	UUV RF system unable to receive RF messages
FM.1.8.1.1	Control surfaces are damaged
FM.1.8.1.2	Control surface actuators fail to move
FM.1.8.1.3	Controller unable to communicate with actuators
FM.1.8.2.1	Unable to measure pressure
FM.1.8.2.2	Incorrectly reports depth
FM.1.8.3.1	Unable to adjust ballast
FM.1.8.4.1	Fails to provide thrust
FM.1.8.4.2	Fails to communicate with thruster
FM.1.8.4.3	Damage to control surfaces
FM.1.8.4.4	Actuators fail to move
FM.1.8.4.5	Maneuvering Actuator controller fails to communicate with actuators
FM.1.9.1.1	Leak detector system fails to alert of leaks
FM.1.9.1.2	Emergency Surfacing System fails to activate
FM.1.9.2.1	Fails to accomplish launch operations
FM.1.9.2.2	Fails to accomplish recovery operations
FM.1.9.3.1	Temperature Sensor provides incorrect temperature measurements
FM.1.9.3.3	Climate control unit unable to connect to climate sensors
FM.1.9.3.4	Climate control unit fails to control environment
FM.1.9.4.1	Anchor never deploys
FM.1.9.4.2	Unable to tow or be towed
FM.1.9.5.1	Water cooling system fails to control water flow
FM.1.9.5.2	Hydraulic fluid system fails to manage hydraulic fluid

Table 7. Generic UUV Failure Causes

Failure Cause #	Failure Cause Description
FC.1	Cracks go undetected
FC.2	Seals not verified
FC.3	Collision with external object
FC.4	Biofouling
FC.5	Too much resistance or friction in drivetrain
FC.6	Motor is damaged electrically
FC.7	Interface between motor and drivetrain has failed
FC.8	Damage to transmission line
FC.9	Fault in feedback sensors
FC.10	Unable to receive commands from VC
FC.11	Normal wear and tear

Failure Cause #	Failure Cause Description
FC.12	Corrosion
FC.13	Battery End of Life
FC.14	Recharge required
FC.15	Energy source is damaged or faulty
FC.16	Undetected software bugs
FC.17	Incorrect configuration settings
FC.18	Sensor is uncalibrated
FC.19	Sensor is damaged
FC.20	GNSS Receiver is damaged
FC.21	Requires software update
FC.22	Damaged CPU
FC.23	Electrical component failure
FC.24	Damaged lens
FC.25	Mechanical component failure
FC.26	Transponder Failure
FC.27	Actuator is damaged electrically
FC.28	Communication failure

Table 8. Generic UUV Failure Detection

Failure Detection #	Failure Detection Description
FD.1	Visual Inspection
FD.2	Leak Sensor
FD.3	Vibration Measurement
FD.4	Noise Measurement
FD.5	Thrust Measurements
FD.6	Torque Measurement
FD.7	Electrical Measurements
FD.8	Data Integrity Checks
FD.9	Output Values
FD.10	Data Messages
FD.11	Pre-Mission Checkout
FD.12	Output Image

See Appendix A for additional results. Table 15 shows what Failure Causes contribute to particular Failure Modes, and Table 16 shows which particular Failure Detections mitigate each of the Failure Causes.

The FMDA revealed that the C-BUMMPS should be capable of measuring basic electrical parameters (voltage, current, total power, RF loads, etc.), and should also be capable of measuring non-electrical parameters such as vibration, noise levels, and various forces experienced by the various subsystems. Beyond the low level sensor monitoring, the C-BUMMPS will need to be capable of monitoring the message traffic between the various controllers and digital systems throughout the UUV. The data contained within the messages combined with the low level sensor data will help C-BUMMPS determine if a system is performing within the baseline parameters.

C. FUNCTIONAL ANALYSIS

The requirements derived from the stakeholder requirements analysis, failure analysis, and the operational activities identified in the operational situations developed in the mission analysis were leveraged to identify the functions the C-BUMMPS would need to perform. Section VII.C.1 - System Functionality Definition contains the functional hierarchy and detailed descriptions of the functional decomposition of the C-BUMMPS architecture.

D. FUNCTIONAL REQUIREMENTS

The functional requirements for the C-BUMMPS were derived from multiple sources, namely the Stakeholder requirements, the operational situations developed in the mission analysis, described in, and the subsequent functional decomposition performed in the functional analysis. Functional requirements account for the majority of the C-BUMMPS system requirements and are list in Table 9.

Table 9. Functional Requirements

Requirement Number	Requirement Name	Requirement Description	Decomposes
FR.1	Perform Data Acquisition Requirement	The C-BUMMPS shall be able to perform Data Acquisition.	StkRq.3.2.1
FR.1.1	Ingest Vehicle C&C Data Requirement	The C-BUMMPS shall be able to receive data from the vehicle autonomy controller.	FR.1
FR.1.2	Ingest Environmental Data Requirement	The C-BUMMPS shall be able to receive data from the vehicle environmental sensors.	FR.1
FR.1.3	Record Data Requirement	The C-BUMMPS shall record data received from its sensors, UUV autonomy controller messages, and UUV sensors	FR.1
FR.1.4	Monitor Data Inputs Requirement	The C-BUMMPS shall provide for continuous and periodic monitoring of data input channels.	FR.1
FR.2	Communicate Data Requirement	The C-BUMMPS shall be able to communicate with the UUV, Operators, and Maintenance Systems.	StkRq.3.7.1
FR.2.1	Receive Monitoring Configuration Settings Requirement	The C-BUMMPS shall be able to receive configuration settings that define the Onboard C-BUMMPS monitoring, recording, assessment, and communication schemes.	FR.2
FR.2.2	Transfer Sensor Data Requirement	The C-BUMMPS shall be able to transfer sensor data from the Onboard C-BUMMPS to the Offboard C-BUMMPS.	FR.2
FR.2.3	Communicate UUV Health Assessment Requirement	The C-BUMMPS shall be able to communicate messages reporting health assessments of the UUV, its subsystems, and components.	FR.2
FR.2.3.1	Communicate Health from Offboard to Onboard Requirement	The C-BUMMPS shall upload the current performance profile to the Onboard C-BUMMPS for future comparison against collected sensor data .	FR.2
FR.2.3.2	Communicate Health from Onboard to Offboard Requirement	The Onboard C-BUMMPS shall be able to communicate it's health assessments of the UUV, its subsystems, and components to the Offboard C-BUMMPS	FR.2
FR.3	Assess UUV Health Requirement	The C-BUMMPS shall be able to assess the health of the UUV and its subsystems and components	StkRq.7.5.1
FR.3.1	Predict Anticipated Performance Loss Based on Sortie Parameters Requirement	The C-BUMMPS shall be able to predict performance loss and degradation of the UUV, its subsystems, and components based on measured and past performance and the operational parameters of the sortie plan.	FR.3

Requirement Number	Requirement Name	Requirement Description	Decomposes
FR.3.1.1	Perform Onboard Performance Loss Predictions Requirement	The Onboard C-BUMMPS shall be able to predict performance loss and degradation of the UUV, its subsystems, and components based on measured and past performance and the operational parameters of the sortie plan.	FR.3
FR.3.1.2	Perform Offboard Performance Loss Predictions Requirement	The Offboard C-BUMMPS shall be able to predict performance loss and degradation of the UUV, its subsystems, and components based on measured and past performance and the operational parameters of the sortie plan.	FR.3
FR.3.2	Receive Sensor Data Requirement	The C-BUMMPS shall be able to acquire data from onboard sensors.	FR.3
FR.3.2.1	Receive Sensor data Onboard Requirement	The C-BUMMPS shall be able to receive data from onboard sensors.	FR.3
FR.3.2.2	Receive Sensor data Offboard Requirement	The Offboard C-BUMMPS shall be able to download sensor data from the Onboard C-BUMMPS.	FR.3
FR.3.3	Compare Sensor Data to Known Reference Requirement	The C-BUMMPS shall be able to compare sensor data to past performance data.	FR.3
FR.3.3.1	Compare Sensor Data Onboard Requirement	The Onboard C-BUMMPS shall be able to compare sensor data to the current performance profile of the UUV, its subsystems, and components.	FR.3
FR.3.3.2	Compare Sensor Data Offboard Requirement	The Offboard C-BUMMPS shall be able to compare sensor data to the stored performance profiles of the UUV, its subsystems, and components and past performance data.	FR.3
FR.3.4	Generate Health Assessment Requirement	The C-BUMMPS shall be able to generate health assessments of the UUV, its subsystems, and components.	FR.3
FR.3.4.1	Onboard Health Assessment Requirement	The Onboard C-BUMMPS shall be able to generate health assessments of the UUV, its subsystems, and components.	FR.3
FR.3.4.2	Offboard Health Assessment Requirement	The Offboard C-BUMMPS shall be able to generate health assessments of the UUV, its subsystems, and components.	FR.3
FR.4	Sense Performance Parameters Requirement	The C-BUMMPS shall be able to sense operating parameters of the UUV, subsystems, and components that indicate performance.	StkRq.7.4.3
FR.4.1	Measure Temperature Requirement	The C-BUMMPS shall be able to Measure Temperature of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.2	Measure Deflections Requirement	The C-BUMMPS shall be able to Measure Strain of the UUV, its subsystems, and their components	FR.4

Requirement Number	Requirement Name	Requirement Description	Decomposes
FR.4.3	Measure Voltage Requirement	The C-BUMMPS shall be able to Measure Voltage of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.4	Measure Current Requirement	The C-BUMMPS shall be able to Measure Current of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.5	Measure Accelerations Requirement	The C-BUMMPS shall be able to Measure Acceleration of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.6	Measure Load Requirement	The C-BUMMPS shall be able to Measure Load of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.7	Measure Sound Requirement	The C-BUMMPS shall be able to Measure Sound of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.8	Measure Pressure Requirement	The C-BUMMPS shall be able to Measure Pressure of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.9	Measure Angular Velocity Requirement	The C-BUMMPS shall be able to Measure Angular velocity of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.10	Measure Linear Velocity Requirement	The C-BUMMPS shall be able to Measure Linear velocity of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.11	Measure Angular Position Requirement	The C-BUMMPS shall be able to Measure Angular position of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.12	Measure Linear Position Requirement	The C-BUMMPS shall be able to Measure Linear position of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.13	Measure Impedance Requirement	The C-BUMMPS shall be able to Measure Impedance of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.14	Measure Data Rate Requirement	The C-BUMMPS shall be able to Measure Data Rate of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4
FR.4.15	Measure Error Growth Requirement	The C-BUMMPS shall be able to Measure Error Growth and Rate of the UUV, its subsystems, and their components, as applicable to their modes of operation and indication of performance.	FR.4

Requirement Number	Requirement Name	Requirement Description	Decomposes
FR.4.16	Measure Corrosion Requirement	The C-BUMMPS shall be able to Measure parameters that indicate the potential and rate of corrosion of the UUV, its subsystems, and their components.	FR.4
FR.5	Perform Data Analysis Requirement	The C-BUMMPS shall be capable of analyzing data from sensors onboard the UUV, its subsystems and components, and received through communications from the UUV controller or external data sources such as mission planning and command control software applications.	StkRq.2.5.1
FR.5.1	Store Data Requirement	The C-BUMMPS shall be able to store data collected, generated, and imported into C-BUMMPS.	FR.5
FR.5.1.1	Store Data Onboard Requirement	The Onboard C-BUMMPS shall be able to store collected data from sensors, vehicle command and control messages, configuration settings, and performance profile generated and downloaded from the Offboard C-BUMMPS.	FR.5
FR.5.1.2	Store Data Offboard Requirement	The Offboard C-BUMMPS shall be able to store collected data from sensors, vehicle command and control messages, configuration settings, generated performance profiles, past performance data from other systems, and imported maintenance data.	FR.5
FR.5.2	Process Data Requirement	The C-BUMMPS shall be able to process data received from sensors, vehicle command and control messages, configuration settings, generated performance profiles, past performance data from other systems, and imported maintenance data.	FR.5
FR.5.2.1	Process Data Onboard Requirement	The Onboard C-BUMMPS shall be able to process data received from sensors, vehicle command and control messages, configuration settings, and generated performance profiles.	FR.5
FR.5.2.2	Process Data Offboard Requirement	The Offboard C-BUMMPS shall be able to process data received from sensors, vehicle command and control messages, configuration settings, generated performance profiles, past performance data from other systems, and imported maintenance data.	FR.5
FR.5.3	Perform Health Assessment Requirement	The C-BUMMPS shall be able to generate health assessments of the UUV, its subsystems, and components.	FR.5
FR.5.3.1	Perform Onboard Assessment Requirement	The Onboard C-BUMMPS shall be able to generate health assessments based on ingested sensor and UUV data and performance profiles.	FR.5
FR.5.3.2	Perform Offboard Assessment Requirement	The Onboard C-BUMMPS shall be able to generate health assessments based on ingested sensor and UUV data, performance profiles, and historical data from other unmanned systems and testing.	FR.5
FR.5.4	Recommend Corrective Action Requirement	The C-BUMMPS shall generate recommended corrective actions to be performed by the UUV, operators, and maintainers.	FR.5

Requirement Number	Requirement Name	Requirement Description	Decomposes
FR.5.4.1	Generate Onboard Corrective Action Recommendation Requirement	The Onboard C-BUMMPS shall generate recommended corrective actions to be performed by the UUV, operators, and maintainers.	FR.5
FR.5.4.2	Generate Offboard Corrective Action Recommendation Requirement	The Offboard C-BUMMPS shall generate recommended corrective actions to be performed by the UUV, operators, and maintainers.	FR.5
FR.6	Update UUV Performance Profile Requirement	The C-BUMMPS shall be able to generate updated performance profiles of the UUV, subsystems, and components based on analyzed data collected by the Onboard C-BUMMPS.	StkRq.3.5.1
FR.6.1	Update Estimated failure rate Requirement	The C-BUMMPS shall update the predicted failure rate of the UUV, its subsystems, and components, based on collected system data.	FR.6
FR.6.2	Update health assessment Requirement	The C-BUMMPS shall update the health assessments of the UUV, its subsystems, and components, based on collected system data.	FR.6
FR.6.3	Update Sortie Completion Probability Requirement	The C-BUMMPS shall update the calculated sortie completion probability of the UUV, based on collected system data.	FR.6

E. NON-FUNCTIONAL REQUIREMENTS

A smaller set of non-functional requirements for the C-BUMMPS were also identified during requirements analysis. These include adaptability, interface, and operational requirements that don't identify a specific function or action to be performed, but define how the system should operate, interface, or adapt with the UUV and external systems. These non-functional requirements are listed in Table 10. It is important to note that at this high level of development of the C-BUMMPS architecture for a generic UUV, this list of requirements is small. However, as C-BUMMPS is applied to specific UUV systems, with specific missions and objectives, it is expected that this list would grow with requirements more specific to the UUV system it supports.

Table 10. Non-Functional Requirements

Number	Name	Description	Requirement Type	Traces To Number
StkRq.7.3.1	UMAA Compliant Messaging	The C-BUMMPS communications with the UUV shall be compliant with the Unmanned Maritime Autonomy Architecture.	Interface Requirement	StkNd.7.3
StkRq.7.4.1	C-BUMMPS scalability	The Implementation approach for C-BUMMPS shall be scalable based on UUV size/class and mission requirements.	Adaptability Requirement	StkNd.7.4
StkRq.1.1.1	Increase reliability	The C-BUMMPS shall increase UUV reliability compared to demonstrated performance without CBM strategies applied.	Operational Requirement	StkNd.1.1
StkRq.1.1.2	Increase availability	The C-BUMMPS shall increase UUV availability compared to demonstrated performance without CBM strategies applied.	Operational Requirement	StkNd.1.1
StkRq.1.2.1	Comply with latest Cyber security policy	The C-BUMMPS shall comply with the latest cyber security policy and requirements as applicable.	Operational Requirement	StkNd.1.2
StkRq.1.2.2	Manage data at lowest classification	The C-BUMMPS shall have provisions to collect and maintain data at the lowest classification required for the information that the data reveals.	Operational Requirement	StkNd.1.2
StkRq.2.2.2	Integrate with Maintenance Database	The C-BUMMPS shall integrate with UUV maintenance databases to allow correlation of measured performance data with maintenance actions and inspection findings.	Interface Requirement	StkNd.2.2
StkRq.2.4.1	Prioritize Use of Inherent Sensing Capabilities	The C-BUMMPS shall prioritize the use of inherent and existing sensing capabilities within components and subsystems to collect performance data that contributes to assessing component and subsystem health and failure detection capability.	Non-Functional Requirement	StkNd.2.4
StkRq.2.6.1	Use Open Data Formats	The C-BUMMPS shall use open data formats to record measured and generated data and messages.	Interface Requirement	StkNd.2.6
StkRq.3.8.1	Allow Degraded Performance	The C-BUMMPS shall allow for systems and components continuing to operate with degraded performance when estimating probability of sortie completion.	Operational Requirement	StkNd.3.8

VII. ARCHITECTURE DESIGN

Architecture design is a step in the system engineering process that translates the stakeholder requirements into potential solutions in a system model. The functional architecture provides a functional decomposition that defines the functions and subfunctions to achieve the mission and stakeholder objectives. Once the functional architecture has been established a physical architecture allocates physical elements to the functional requirements. The architecture design process is iterative and usually consists of several functional and physical alternative solutions that can be analyzed and ultimately chosen to proceed into the implementation process.

A. C-BUMMPS ARCHITECTURE

The C-BUMMPS architecture was modeled in DODAF v2.02 viewpoints since it is a system envisioned to operate on U.S. Navy UUVs. The scope of this project did not necessitate the use of every model in the DODAF, therefore certain models were chosen that properly conveyed the C-BUMMPS architecture at this early stage in its development. The key viewpoints chosen were within the Operational Viewpoints, the Data and Information Viewpoints, and the System Viewpoints. Table 11 details the specific models selected for the C-BUMMPS.

Table 11. Models Describing C-BUMMPS Architecture

View	Definition	C-BUMMPS Architecture Definition
DIV-1	Conceptual Data Model	X
DIV-2	Logical Data Model	
DIV-3	Physical Data Model	X
OV-1	High-Level Operation Concept Graphic	X
OV-2	Operation Resource Flow Description	X
OV-3	Operation Resource Flow Matrix	
OV-4	Organizational Relationships Chart	
OV-5a	Operational Activity Decomposition Tree	
OV-5b	Operational Activity Model	X
OV-6c	Event-Trace Description	X
SV-1	Systems Interface Description	

View	Definition	C-BUMMPS Architecture Definition
SV-2	Systems Resource Flow Description	
SV-3	Systems-Systems Matrix	
SV-4	Systems Functionality Description	X
SV-5a	Operational Activity to Systems Functions Traceability Matrix	
SV-5b	Operational Activity to Systems Traceability Matrix	
SV-6	Systems Resources Flow Matrix	
SV-7	Systems Measures Matrix	
SV-8	Systems Evolution Description	
SV-9	Systems Technology and Skills Forecast	
SV-10c	System's Event-Trace Description	

B. OPERATIONAL VIEWPOINTS

The operational viewpoint models of the C-BUMMPS architecture help describe the activities, operational elements, and flow and exchange of resources with respect to the C-BUMMPS. The following sections explain and detail the C-BUMMPS architecture from an operational perspective.

1. C-BUMMPS Operational Concept (OV-1) and Resource Flow (OV-2)

The operational concept model of the C-BUMMPS is comprised of an On-Board element and Off-Board element. The C-BUMMPS On-Board element resides in the UUV, and the Off-Board element consists of a computing and data processing center, referred to as the data center. While in port, the On-Board element communicates with the Off-Board element's data center and ISEA to receive performance baseline parameters and configuration updates. While deployed on a mission, the C-BUMMPS On-Board element monitors UUV performance, provides health assessments, and provides corrective action recommendations to the Vehicle Controller and autonomy software. The UUV Vehicle Controller ingests information from the C-BUMMPS, and forwards it to the Off-Board element's data center, Operations Center, and the ISEA. The ISEA may act on corrective actions in real time during the mission. Prior to the UUV returning to port, the Off-Board element data center will process the in-mission data from

the On-Board element and generate maintenance recommendations for the ISEA. When the UUV arrives back in port, the On-Board element will transfer all in-mission data to the Off-Board element for algorithm adjustments and detailed mission data processing. The C-BUMMPS high-level operational concept graphic (OV-1) is depicted in Figure 12.

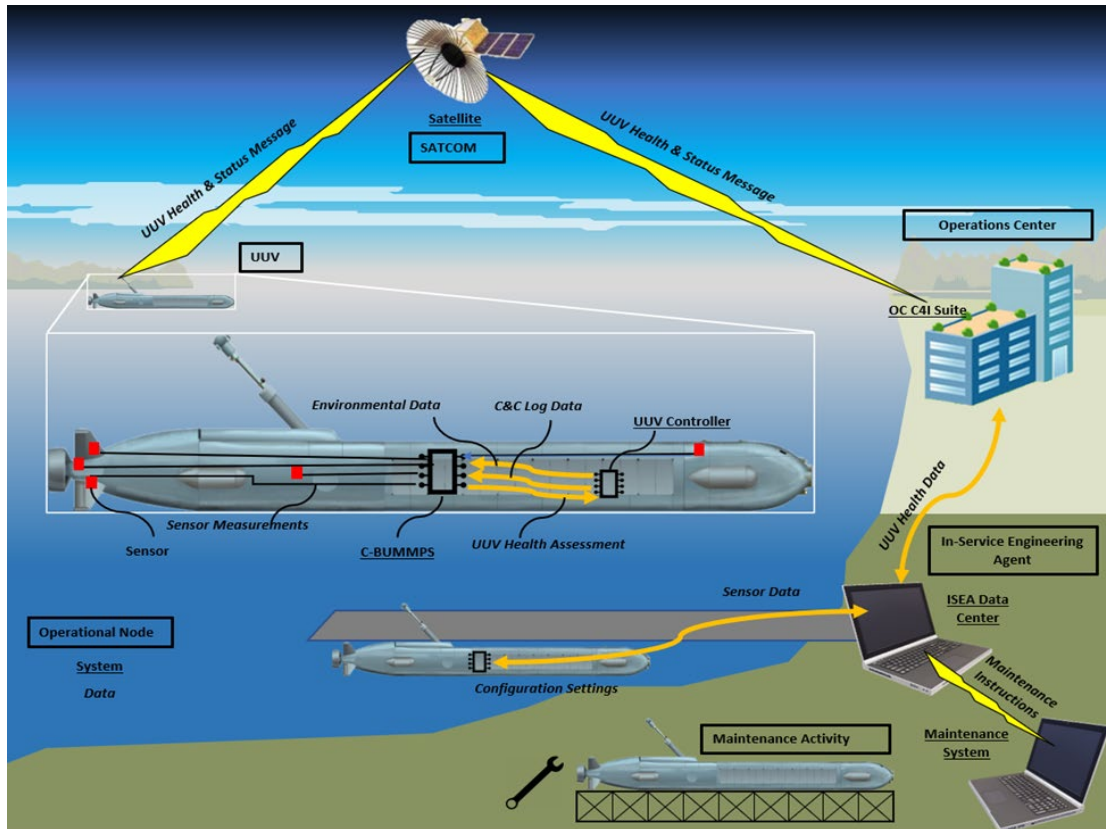


Figure 12. C-BUMMPS High-Level Operational Concept Graphic (OV-1).
Adapted from Sutton (2019).

The C-BUMMPS operational resource flow model (OV-2) is depicted in Figure 13, and identifies which resources are passed between the C-BUMMPS and key external entities. Prior to a mission, the ISEA will forward configuration settings and updated algorithms to the On-Board element. The configuration settings help the C-BUMMPS understand the baseline operational parameters of the UUV, while the updated algorithms allow the C-BUMMPS to more accurately analyze data collected from the UUV. During a mission, the On-Board element captures sensor data and communication traffic from key subsystems in the UUV, and it uses this information to generate health assessments

and corrective action recommendations. The On-Board element forwards health assessments and corrective actions to the UUV Vehicle Controller and is then transmitted to the Off-Board element, Operations Center, and ISEA. The UUV will attempt to act on these corrective actions if able to do so. Once the UUV is in port, the On-Board element sends the full mission performance data to the ISEA, who in turn sends the data to the Off-Board element. The Off-Board C-BUMMPS uses this information along with component data to further recommend maintenance actions and improve the algorithm parameters.

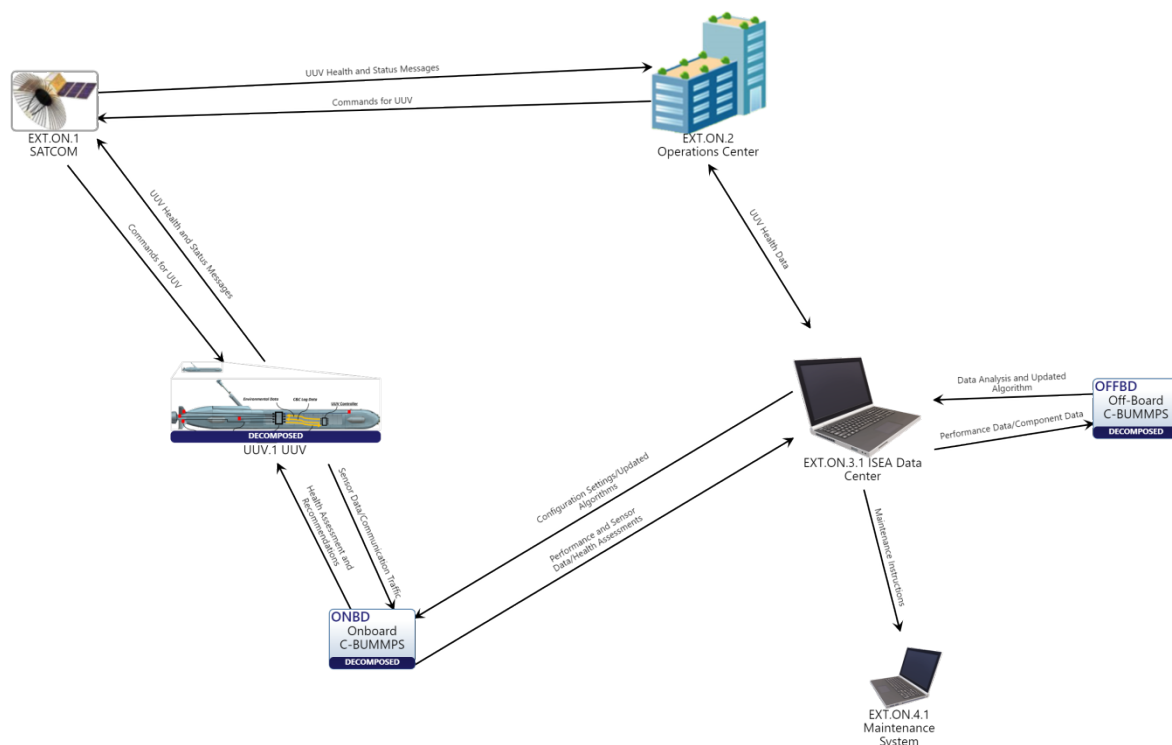


Figure 13. C-BUMMPS Operational Resource Flow Model (OV-2)

2. C-BUMMPS Operational Activities

The operational activities for the C-BUMMPS, previously presented in the Mission Analysis, have been updated to depict the functions derived from the System Requirements Definition Process. The following sections show the high-level functions as part of the key operational activities.

a. Performance Baselineing

The Performance Baselineing operational activity, depicted in Figure 14, has the On-Board C-BUMMPS “Receiving Monitoring Configuration Settings” (FUNC.2.1) at the start of the baselining process. After monitoring is Initiated by the “Mission Control System,” the On-Board C-BUMMPS then performs three threads in parallel: Data Acquisition, Parameter Sensing, and Data Processing. In the Data Acquisition thread, the On-Board C-BUMMPS performs the “Perform Data Acquisition” function (FUNC.1). This function is triggered by Command and Control Data, Environmental Data, and Sensor Data which is generated as the UUV performs its own functions. As outputs, the “Perform Data Acquisition” function generates Ingested Command and Control Data, Ingested Environmental Data, and Ingested Data to the Data Processing thread, specifically the “Perform Data Analysis” function (FUNC.5). In the Parameter Sensing Thread, the On-Board C-BUMMPS performs the “Sense Performance Parameters” function (FUNC.4), which is triggered by vehicle Performance Parameters. The “Sense Performance Parameters” function generates Ingested Performance Parameters for the “Perform Data Analysis” function. Last, the Data Processing thread, the “Perform Data Analysis” function analyzes the ingested data and sends the analyzed data to the “Assess UUV Health” function (FUNC.3). Once the UUV returns to port, the On-Board C-BUMMPS sends the sensor data and health assessments to the ISEA and the Off-Board C-BUMMPS. The Off-Board C-BUMMPS then processes the data, performs its own health assessment, and then performs the “Update Assessment Parameters” function (FUNC.6). The “Update Assessment Parameters” function generates Updated Failure Predictions and Updated Mission Success Parameters.

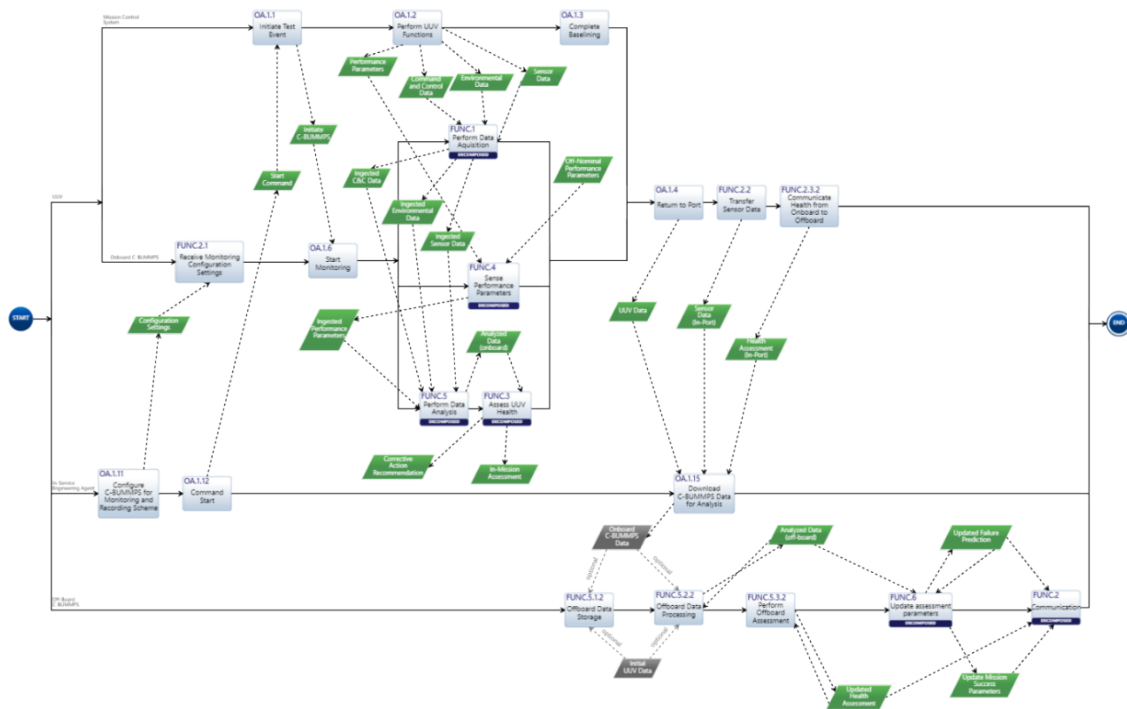


Figure 14. Updated Performance Baseline Action Diagram (OV-5b/6c)

b. *Pre-Mission Checkout*

The Pre-Mission Checkout operational activity, depicted in Figure 15, focused on the ISEA and Maintenance Activity preparing the UUV its mission. From the C-BUMMPS perspective, the configurations and parameters for processing and analyzing UUV performance are sent from the ISEA to the On-Board C-BUMMPS. These configurations and parameters ultimately originate from the Off-Board C-BUMMPS, which processed and analyzed the data collected during the baselining operational activity. The UUV will then perform certain functions while in port and the C-BUMMPS will perform its parallel threads of Data Acquisition, Parameter Sensing, and Data Processing as described in Section B.2.a of Chapter 7. Unlike the Performance Baselining operational activity, the C-BUMMPS is actively sensing Off-Nominal Performance Parameters in the Pre-Mission Checkout activity. The Off-Nominal Performance Parameters are sensed by the “Sense Performance Parameters” function of the C-BUMMPS, which provides Ingested Performance Parameters to the “Perform Data Analysis” function. Another interaction that is different from the C-BUMMPS parallel thread in the Performance Baselining activity are the outputs from the “Assess UUV

Health” function. This function provides the UUV with an in-mission health assessment and corrective action recommendations, which the UUV will not act on during the Pre-Mission Checkout activity. Instead, the On-Board C-BUMMPS will communicate the assessments and recommendations to the ISEA along with the data collected during the checkout. The ISEA will feed these outputs from the On-Board C-BUMMPS to the OFF-Board C-BUMMPS for further processing and analysis. Outputs from the Off-Board C-BUMMPS will drive pre-mission maintenance activities as well as updates to the On-Board C-BUMMPS configurations and parameters.

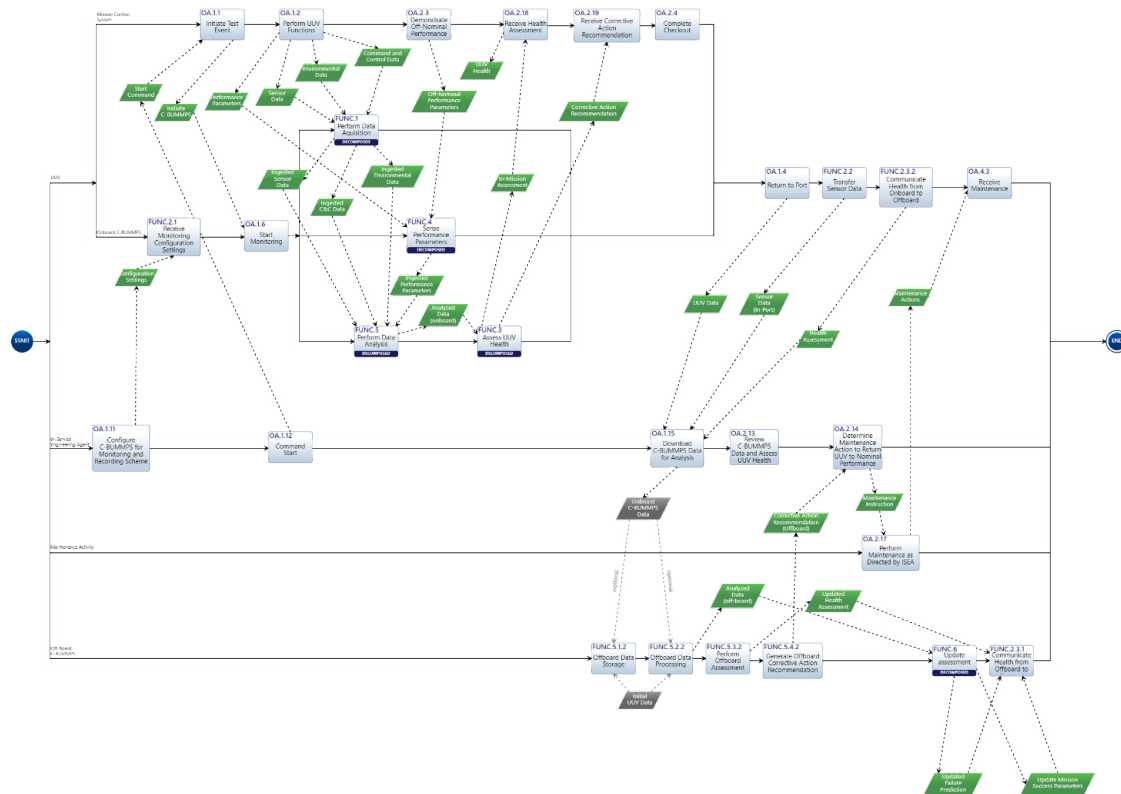


Figure 15. Updated Pre-Mission Checkout Action Diagram (OV-5b/6c)

c. Mission Operations

The next operational activity in the UUV sequence is the Mission Operations. This operational activity is similar to the Pre-Mission Checkout activity, but the In-

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d. Post-Mission and Maintenance Actions

The last operational activity in the UUV sequence is the Post-Mission and Maintenance Actions activity, which is depicted in Figure 17. Once the UUV returns to port, the process to offload, analyze and process the data from the mission operations are the same as that of the Pre-Mission Checkout activity. Once the Off-Board C-BUMMPS completes its analysis, the ISEA forwards maintenance actions to the Maintenance Activity to be acted on during the in-port period. Additionally, the Maintenance Activity will act on the recommendations generated while the UUV was performing its mission. Once the maintenance activities have been completed, the UUV will go through another checkout to verify the maintenance actions were effective. As with the Pre-Mission Checkout, the On-Board C-BUMMPS will monitor system performance and collect data on system operations. This data will be analyzed by the ISEA and the Off-Board C-BUMMPS to determine if further maintenance actions are required.

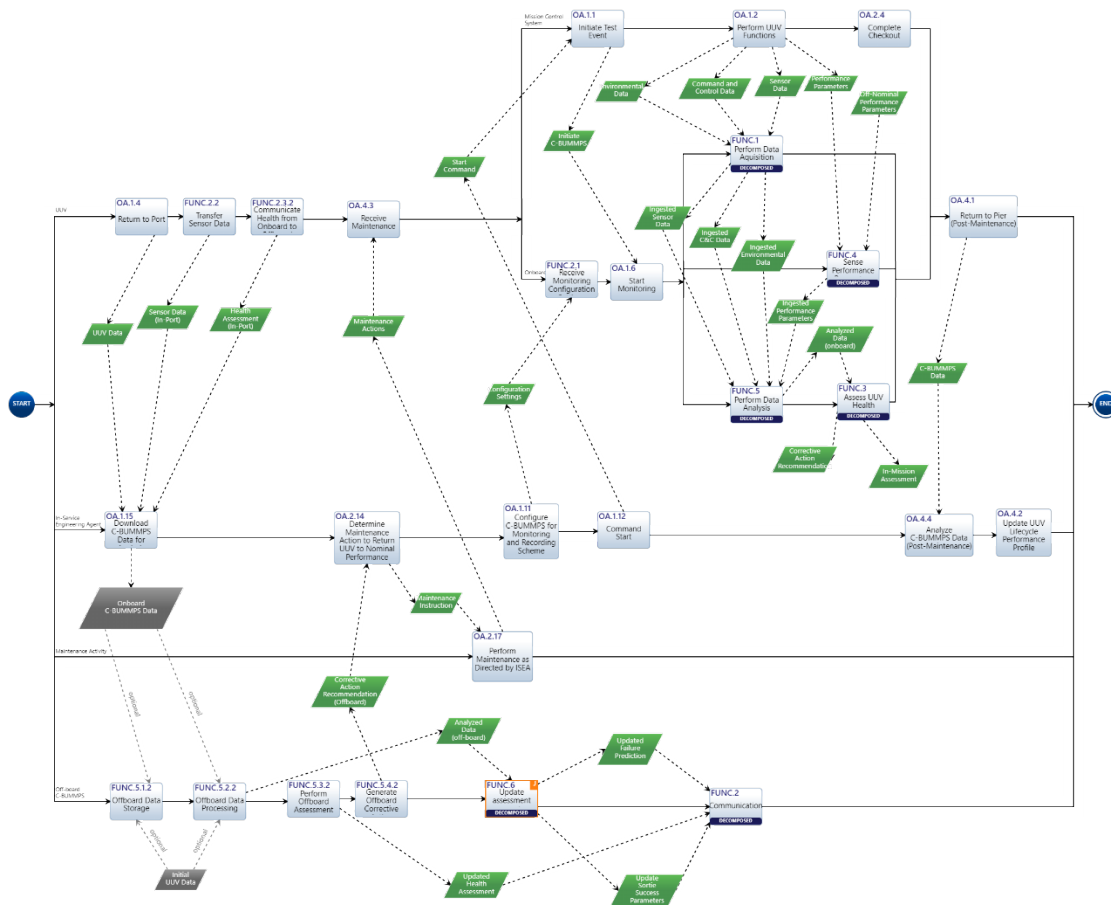


Figure 17. Updated Post-Mission and Maintenance Action Diagram (OV-5b/6c)

C. SYSTEM VIEWPOINTS

The systems viewpoint models of the C-BUMMPS architecture help describe the systems performing and enabling certain functions of the C-BUMMPS. The following sections explain and detail the C-BUMMPS architecture from a systems perspective.

1. System Functionality Definition

The systems functionality definition of the C-BUMMPS describes the functions that are performed by the system. Decomposing the main C-BUMMPS function results in six key functions: Perform Data Acquisition (FUNC.1), Communication (FUNC.2), Assess UUV Health (FUNC.3), Sense Performance Parameters (FUNC.4), Perform Data

Analysis, (FUNC.5), Update UUV Performance Profile (FUNC.6). Each of the six key functions of the C-BUMMPS are decomposed by three or more subfunctions, all of which are necessary for the C-BUMMPS to accomplish its mission. Figure 18 depicts the complete functional decomposition of the C-BUMMPS. The individual functions of the decomposition will be further explained in the following sections.

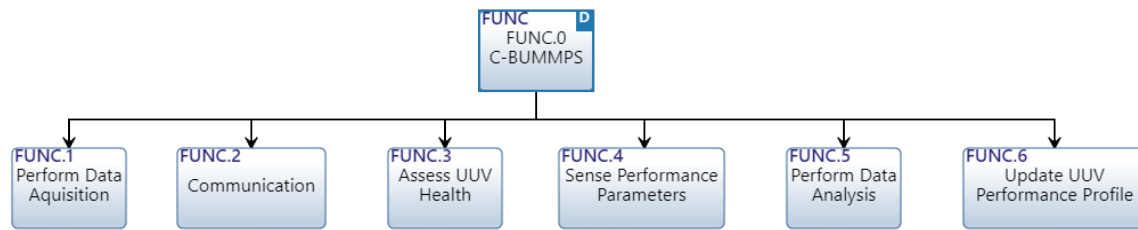


Figure 18. C-BUMMPS Functionality Definition (SV-4)

a. *FUNC.1: Perform Data Acquisition*

FUNC.1, Perform Data Acquisition, is the high-level function that encompasses the ability to collect UUV and environmental data. The Perform Data Acquisition function is decomposed by four subfunctions: Ingest Vehicle Command and Control Data, Ingest Environmental Data, Record Data, and Monitor Data Inputs. These functions enable the C-BUMMPS to acquire, monitor, and record data that will help the system analyze the health of the UUV. Figure 19 depicts the functional decomposition of the Perform Data Acquisition function.

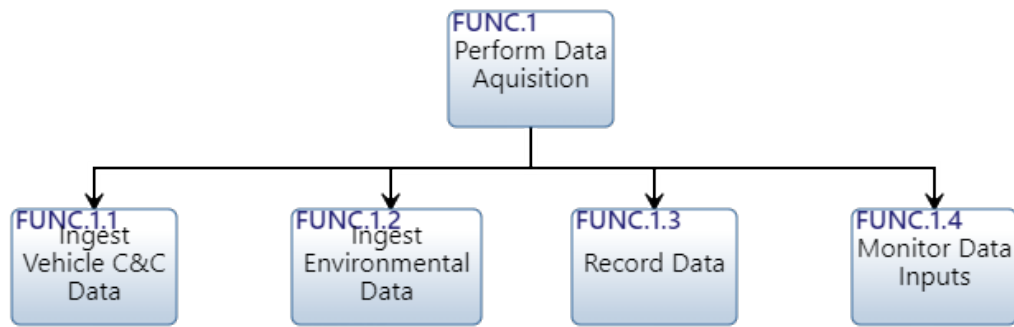


Figure 19. FUNC.1: Perform Data Acquisition Decomposition

b. FUNC.2: Communication

FUNC.2, Communicate Data is the high-level function that encompasses the ability to communicate with the ISEA, On-Board C-BUMMPS, and OFF-Board C-BUMMPS. This function is decomposed by three subfunctions: Receive Monitoring Configuration Settings, Transfer Sensor Data, and Communicate UUV Health Assessment. The Communicate UUV Health Assessment is also decomposed by subfunctions, specifically Communicate Health from Off-Board to On-Board C-BUMMPS and Communicate Health from On-Board to Off-Board C-BUMMPS. Figure 20 depicts the functional decomposition of the Communication function.

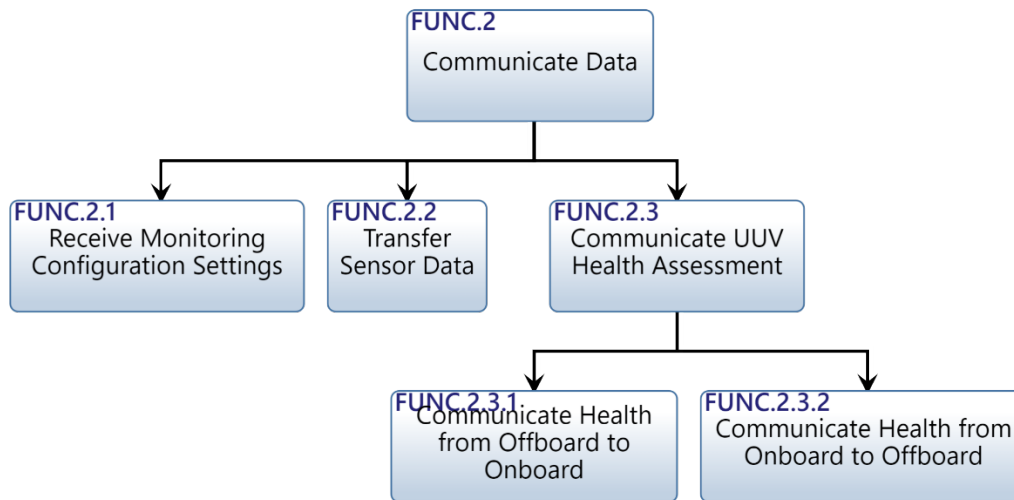


Figure 20. FUNC.2: Communicate Data Decomposition

c. FUNC.3: Assess UUV Health

FUNC.3, Assess UUV Health, is the high-level function that encompasses the ability to determine performance capability and health status based on the data collected by the Perform Data Acquisition function. This function is decomposed by four subfunctions: Predict Anticipated Performance Loss Based on Sortie Parameters, Receive Sensor Data, Compare Sensor Data to Known Reference, and Generate Health Assessment. All these subfunctions of Assess UUV Health are themselves decomposed by subfunctions. The Predict Anticipated Performance Loss Based on Sortie Parameters is decomposed by the Perform Onboard Performance Loss Predictions and the Perform Offboard Performance Loss Predictions subfunctions. Next, the Receive Sensor Data function is decomposed by Receive Sensor Data Offboard and Receive Sensor Data Onboard. The third subfunction of Assess UUV Health, Compare Sensor Data to Known Reference, is decomposed by Compare Sensor Data Onboard and Compare Sensor Data Offboard. Last, the Generate Health Assessment function is decomposed by the Onboard Health Assessment and the Offboard Health Assessment functions. This decomposition of the Assess UUV Health function is depicted in Figure 21.

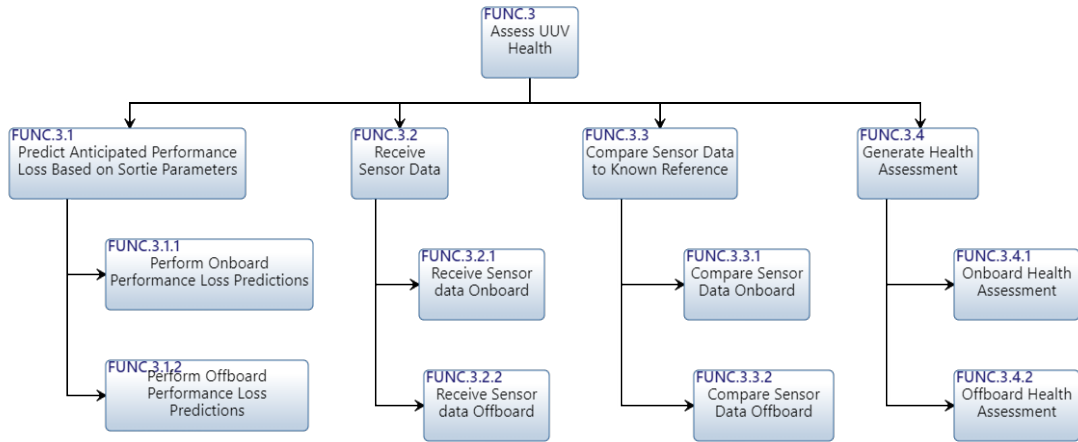


Figure 21. FUNC.3: Assess UUV Health Decomposition

d. FUNC.4: Sense Performance Parameters

FUNC.4, Sense Performance Parameters, is the high-level function that enables the C-BUMMPS to sense vehicle and environmental parameters. This function is decomposed by sixteen subfunctions: Measure Temperature, Measure Deflections, Measure Voltage, Measure Current, Measure Accelerations, Measure Load, Measure Sound, Measure Pressure, Measure Angular Velocity, Measure Linear Velocity, Measure Angular Position, Measure Linear Position, Measure Impedance, Measure Data Rate, Measure Error Growth, and Measure Corrosion. Figure 22 depicts the decomposition of the Sense Performance Parameters function.

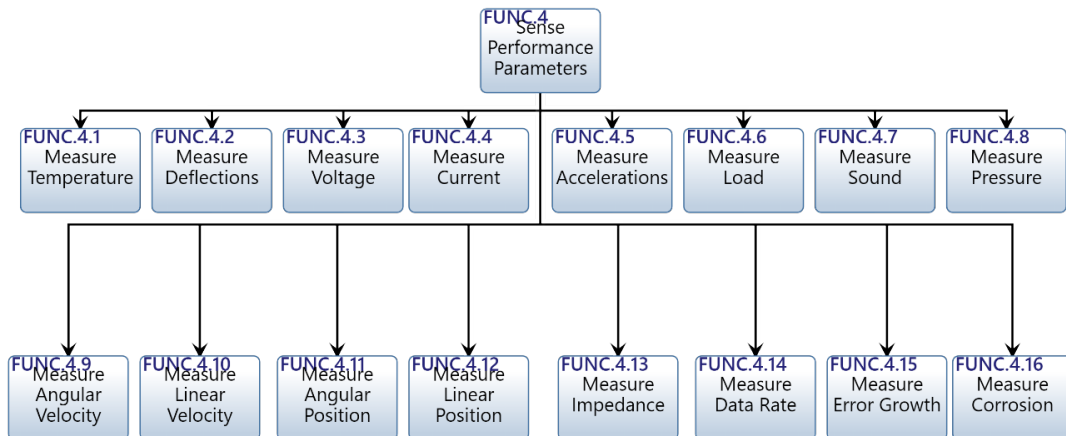


Figure 22. FUNC.4: Sense Performance Parameters Decomposition

e. FUNC.5: Perform Data Analysis

FUNC.5, Perform Data Analysis, is the high-level function that enables the C-BUMMPS to generate health assessments and corrective action recommendations by analyzing UUV data, communications, and performance parameters. This function is decomposed by four subfunctions: Store Data, Process Data, Perform Health Assessment, and Recommend Corrective Action, and each of these subfunctions are decomposed themselves by two subfunctions. The Store Data subfunction is decomposed by the Onboard Data Storage and Offboard Data Storage functions, both of which capture the need for C-BUMMPS to store the data that was collected while the UUV was operating. Next, the Process Data function is decomposed by the Onboard Data Processing and Offboard Data Processing. These subfunctions capture the need to process data while the UUV is on mission and in port, with the Onboard Data Processing function requiring just enough processing power to perform in-mission analysis while the Offboard Data Processing would be accomplished by a system with significantly more processing capability to accomplish a more in-depth analysis of UUV health and performance. The third subfunction of the Perform Data Analysis function is the Perform Health Assessment, which is decomposed by the Perform Onboard Assessment and Perform Offboard Assessment functions. Just as processing is performed both Offboard and Onboard, the health assessments are generated both Onboard and Offboard. Last, the Recommend Corrective Action subfunction is decomposed by the Generate Onboard Corrective Action Recommendation and the Generate Offboard Corrective Action Recommendation functions enable the C-BUMMPS to provide corrective action recommendations to the UUV controller and to the ISEA if offboard. Figure 23 depicts the decomposition of the Perform Data Analysis function.

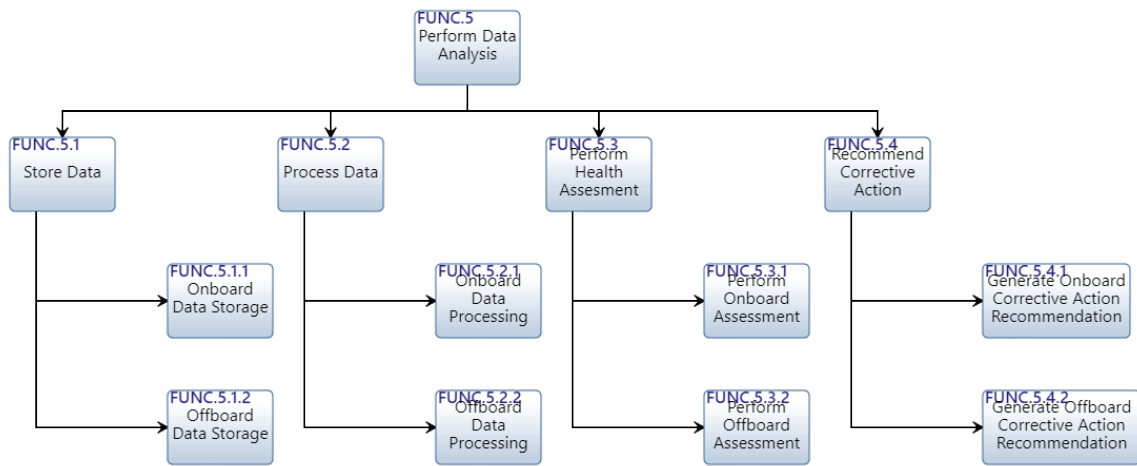


Figure 23. FUNC.5: Perform Data Analysis

f. FUNC.6: Update UUV Performance Baseline

FUNC.6, Update UUV Performance Baseline, is high-level function that enables the C-BUMMPS to adjust algorithms, thresholds, and parameters to facilitate more accurate predictions of UUV health and performance. This function is decomposed by three subfunctions: Update Estimated Failure Rate, Update Health Assessment, and Update Sortie Completion Probability. All these subfunctions would be performed by the C-BUMMPS both onboard and offboard the UUV during the Pre-Mission Checkout, Mission Operations, and Post-Mission and Maintenance operational activities. Figure 24 depicts the decomposition of the Update UUV Performance Baseline function.

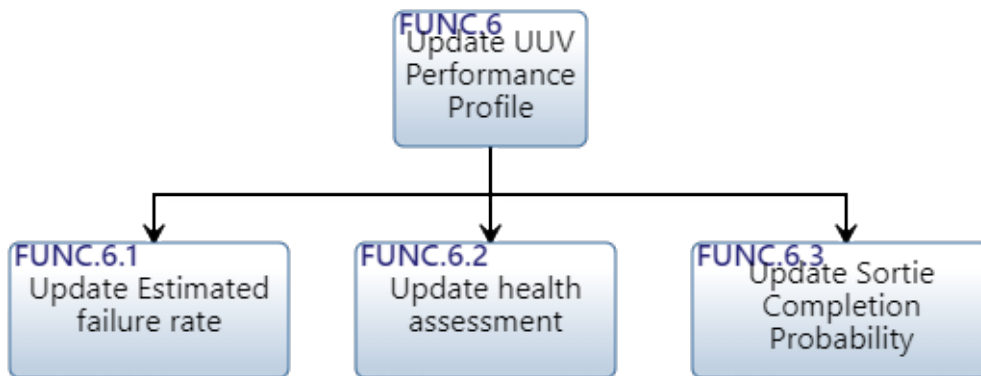


Figure 24. FUNC.6: Update UUV Performance Baseline Decomposition

2. Physical Hierarchy

The physical hierarchy of the C-BUMMPS describes the physical attributes that are performing the functions as described above in the functional decomposition. Decomposing the C-BUMMPS physical hierarchy resulted in defining the C-BUMMPS physical components onboard the UUV and offboard at the ISEA location. There are six key physical groups onboard the UUV as shown in Figure 25 below: CPU (ONBD.1), Sense (ONBD.2), Data Acquisition System (ONBD.3), Software (ONBD.4), Power, (ONBD.5), Structure (ONBD.6). The offboard physical hierarchy shown in Figure 32 is decomposed into two physical groups which are Communication (OFFBD.1) and Data Processing (OFFBD.2). Each of the key physical hierarchy blocks onboard and offboard the UUV of the C-BUMMPS are decomposed by three or more subfunctions, all of which are necessary for the C-BUMMPS to accomplish its mission. Future efforts beyond the scope of this capstone project would further decompose these main physical blocks to identify the make and model of the item that is eventually selected.

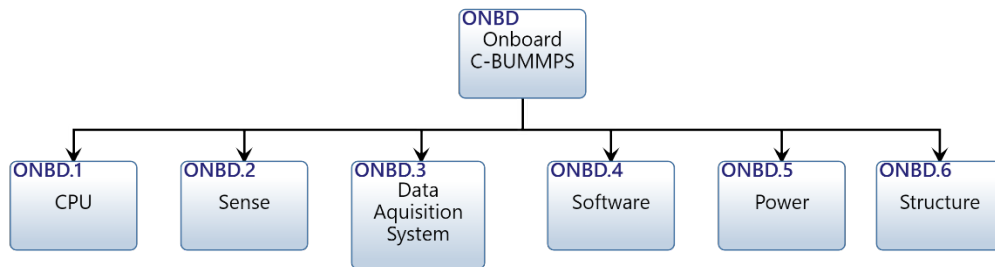


Figure 25. On-Board C-BUMMPS Top Level Physical Hierarchy

a. *ONBD.1: Central Processing Unit (CPU)*

ONBD.1, CPU, is the high-level physical block that encompasses the ability to process and store data. The CPU is decomposed by four sublevels: Memory, Volatile, Non-volatile, and Storage. These physical blocks enable the C-BUMMPS to make decisions based on the information that is being collected real time and historical knowledge of baseline system performance. Figure 26 depicts the physical hierarchy decomposition of the CPU.

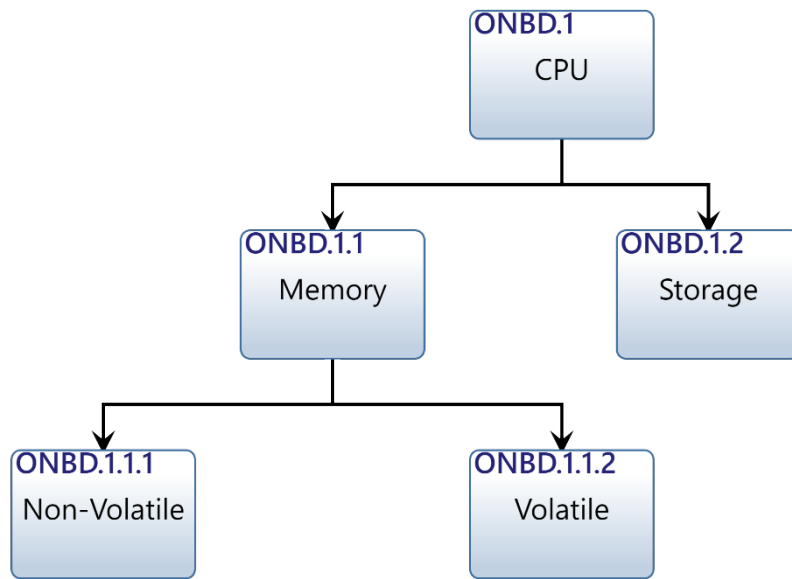


Figure 26. CPU Function Decomposition

b. ONBD.2 Sense

ONBD.2, Sense, is the high-level physical block hierarchy that encompasses the ability to connect the sensors to the data collection system and identifies the engineering parameters being collected by the C-BUMMPS system. The Sense physical system is decomposed into signal cabling and sensor sub elements as well as decomposed into the required engineering parameters. Figure 27 depicts the physical hierarchy decomposition of the sense physical elements.

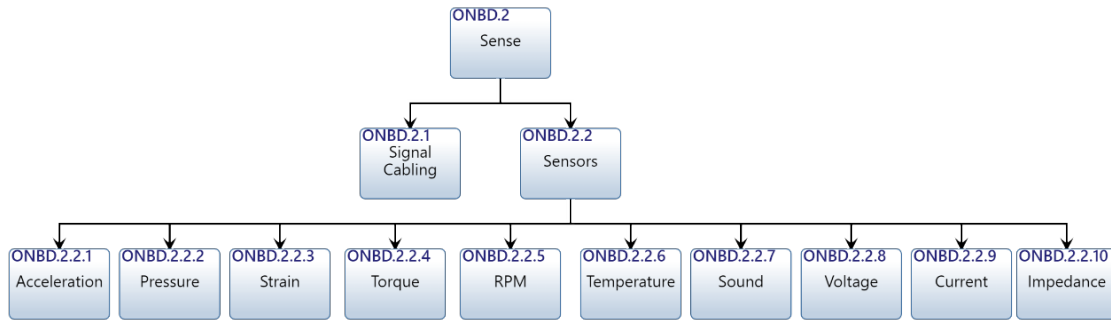


Figure 27. Sense Physical Decomposition

c. ONBD.3: Data Acquisition System

ONBD.3, Data Acquisition System, is the high-level physical block hierarchy that encompasses the ability to condition, process and store the sensor data collected in ONBD.2. The Data Acquisition System physical hierarchy is decomposed further into Data Storage, Processor, and Signal Conditioning sub elements. The elements in this hierarchy map to FUNC.5 Perform Data Analysis and its subfunctions. Figure 28 depicts the physical hierarchy decomposition of the Data Acquisition System physical elements.

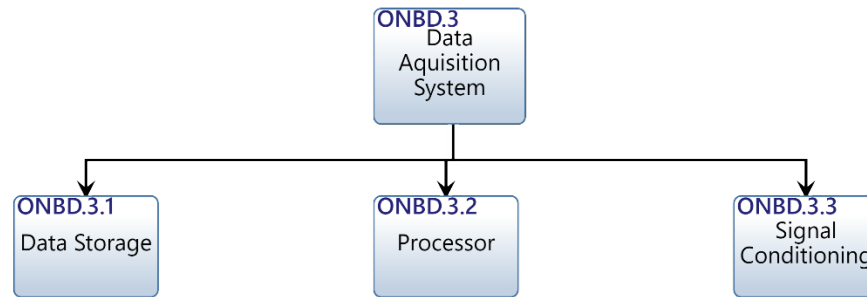


Figure 28. Data Acquisition System Physical Decomposition

d. ONBD.4 Software

ONBD.4, Software, is the high-level physical block hierarchy that encompasses the software that is necessary onboard the UUV to do data analysis, sensing, monitoring, and data storage. The physical software hierarchy is decomposed further into Processing,

Analysis, Alert, and Messaging sub elements. The Software elements in this hierarchy map to multiple functions and subfunction listed above. Figure 29 depicts the physical hierarchy decomposition of the Software physical elements.

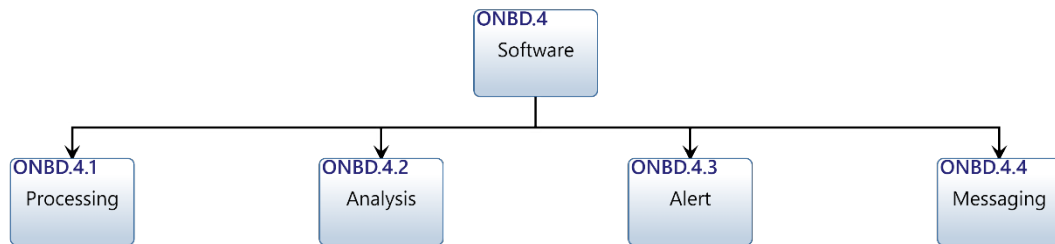


Figure 29. Software Physical Decomposition

e. ONBD.5 Power

ONBD.5, Power, is the high-level physical block hierarchy that depicts the physical elements needed to provide the necessary power onboard the UUV to do data analysis, sensing, monitoring, and data storage. The physical power hierarchy is decomposed further into Power Control, Energy Source, Protection, and Underwater Cabling sub elements. The Power elements in this hierarchy map to multiple functions and subfunction listed above. Figure 30 depicts the physical hierarchy decomposition of the Software physical elements.

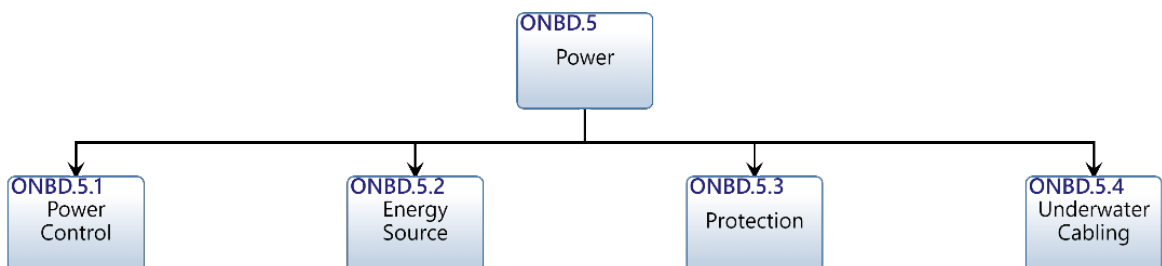


Figure 30. Power Physical Decomposition

f. ONBD.6 Structure

ONBD.6, Structure, is the high-level physical block hierarchy that depicts the physical elements needed to provide the necessary structure onboard the UUV to provide adequate mounting, housings, pressure vessels, and associated cable management. The physical structure hierarchy is decomposed further into Sensor Mounting, Cable Management, Processor Housing, Penetrations, and Pressure Housing sub elements. The Structure elements in this hierarchy map to multiple functions and subfunction listed above. Figure 31 depicts the physical hierarchy decomposition of the Software physical elements.

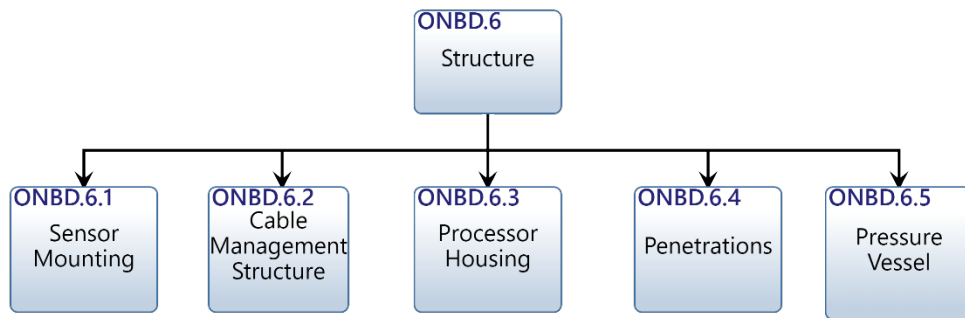


Figure 31. Structure Physical Decomposition

The previous physical hierarchy diagrams focused on the onboard C-BUMMPS physical elements. In Figure 32 the off-board elements are decomposed in Communication and Data Processing sub elements. These physical elements trace back to the ISEA action diagram in Figure 6 which allows the ISEA to communicate and conduct the necessary data analysis to inform current and future mission success. StkNd.3.3 was translated into the functional and physical element to accomplish this requirement.

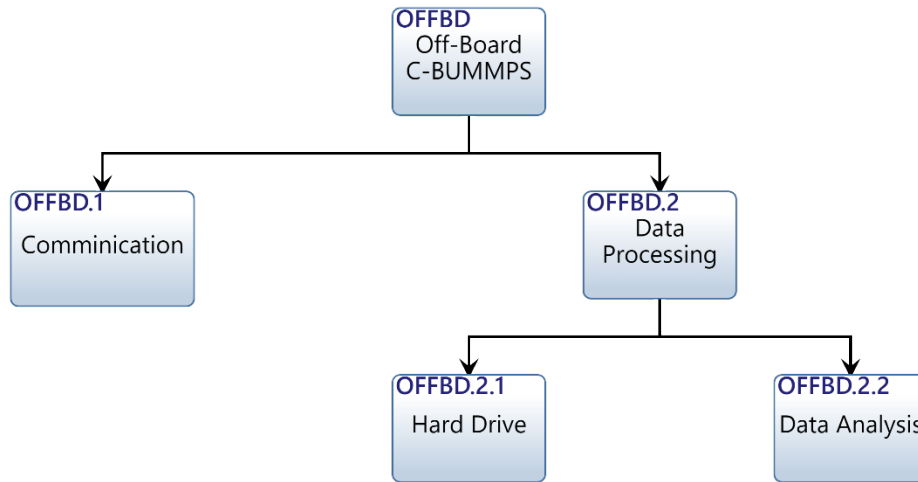


Figure 32. Off-Board C-BUMMPS Physical Decomposition

D. DATA AND INFORMATION VIEWPOINTS

The data and information viewpoint models provide a way to depict the information requirements for the C-BUMMPS. Generally for the data and information viewpoints detailed herein, open data formats are expected to be utilized, therefore the specific communication protocols are not called out in the models. This enables the use of the models without forcing the implementation of a specific message scheme, which allows for more flexibility in implementing the C-BUMMPS architecture. Additionally, the details within these viewpoints with respect to the attributes of information representations were identified based on the experience of the authors but are not prescribed for the implementation of the C-BUMMPS.

The conceptual data model for the C-BUMMPS can be observed in Figure 33. Depicted in the center of this model is the Performance Assessment (DI.10) information representation. The Performance Assessment requires Environmental Data (DI.8), Subsystem Messages (DI.2), Sensor Data (DI.1), UUV Command and Control Data (DI.9), Baseline Performance Profile (DI.3), Mission Profile (DI.7), and Configuration (DI.6). All these information representations are generated by the C-BUMMPS except for the Mission Profile which would be provided by the ISEA by way of the Operations Center asset. The Performance Assessment information segment is required by the Health Assessment and Correction Action Recommendation information representations, both of

which are necessary for providing the UUV and ISEA important information regarding UUV health and performance. Another prominent information representation is the Baseline Performance Profile. The Baseline Performance Profile requires Environmental Data, Subsystem Messages, Sensor Data, and UUV Command and Control Data, and it in turn is required information for the Performance Assessment. The specific attributes for each information representation is depicted in Figure 34.

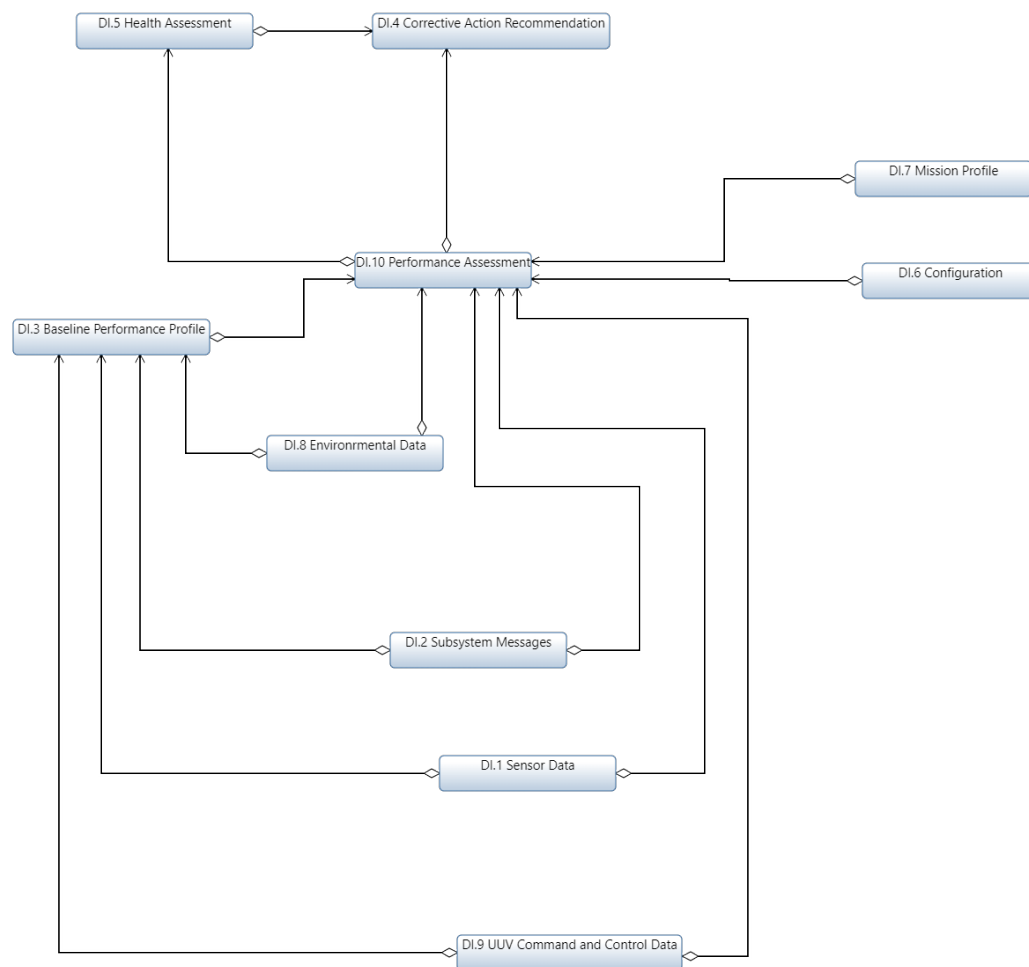


Figure 33. Conceptual Data Model (DIV-1)

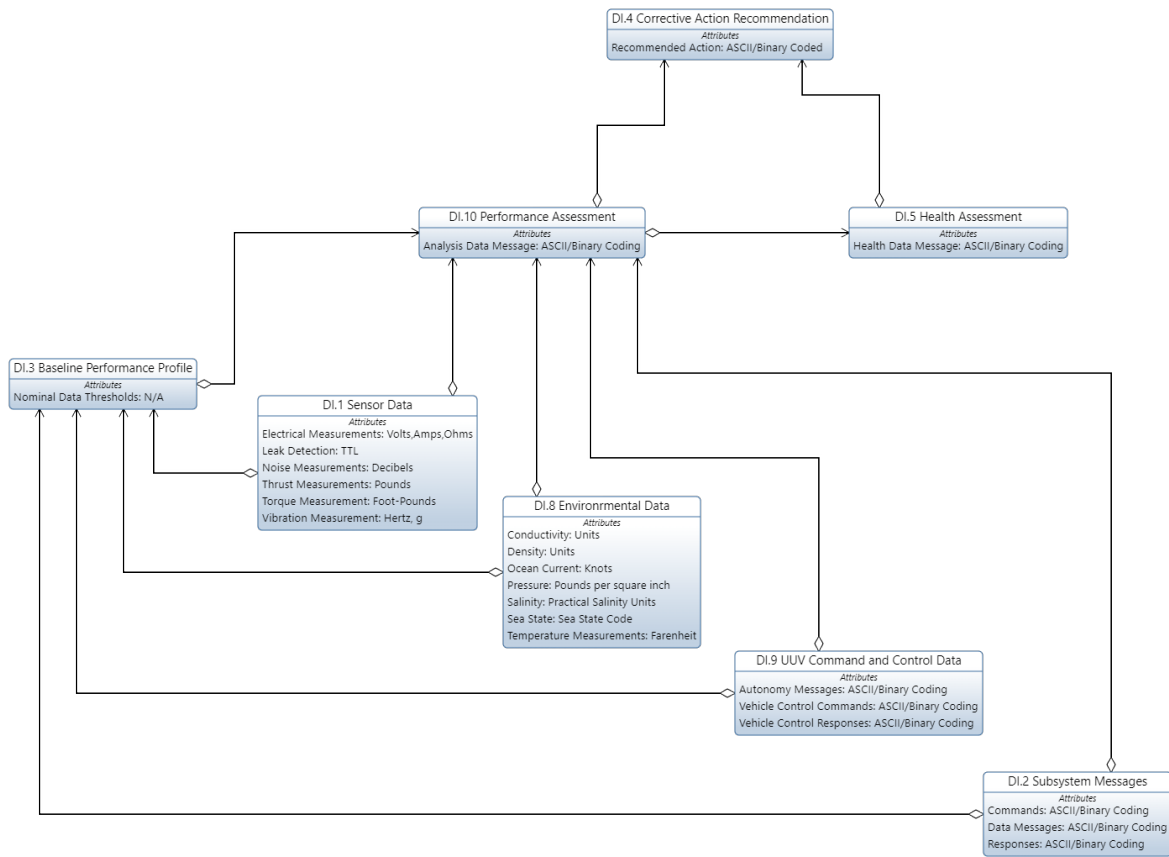


Figure 34. Physical Data Model (DIV-3)

VIII. ALTERNATIVE ARCHITECTURE ANALYSIS

This alternative architecture analysis seeks to explore alternative UUV maintenance concepts to the C-BUMMPS. It is important to remember the mission of the C-BUMMPS as an enabling technology to extend reliability of the UUV and facilitate a condition-based maintenance strategy. The proposed C-BUMMPS measures basic operating parameters, such as voltage or vibration, so there isn't a lot of opportunity at this stage of development to explore trades within the details of the C-BUMMPS. However, we can explore alternative approaches to improve the maintenance strategy by measuring equipment operating parameters to detect off-nominal performance.

The Guide to the Systems Engineering Body of Knowledge (SEBoK) lists the following as some considerations for "System Maintenance":

- Maximizing system availability to meet the operational requirements. This must consider the designed-in reliability and maintainability of the system and resources available.
- Preserving system operating potential through proper planning of system scheduled maintenance. This requires a reliability-centered maintenance strategy that incorporates preventive maintenance to preempt failures, thereby extending the mean time between corrective maintenance, as well as enhancing the availability of the system.
- Segmenting maintenance activities for potential outsourcing of non-critical activities to approved maintenance subcontractors as to optimize scarce technical manpower resources and maintenance/repair turn-around times.
- Harnessing IT technology for maintenance management. This involves rigorous and systematic capturing and tracking of operating and maintenance activities to facilitate analysis and planning. (Jackson, Gallagher, and Dorgan. 2021)

The second bullet point really speaks to the status quo, which relies on properly identified and planned "scheduled" and "preventive" maintenance to pre-empt failures. The SEBoK also recommends several activities including "scheduled servicing, such as daily inspection/checks, servicing, and cleaning." At a high level, this makes sense. However, for UUVs, particularly of a free-flooded design (many individual pressure housings and pressure tolerant components enveloped by a frame and panel hull),

inspections, servicing, and cleaning may require significant resources to access and partially disassemble the system, so these more thorough, but invasive and resource intensive activities are likely to be deferred for longer periods of time and mounting issues may go unidentified until a failure occurs.

A. BASELINE CONCEPT (STATUS QUO)

To begin a comparison of alternative concepts to the C-BUMMPS architecture, it is necessary to set the baseline of the status quo when it comes to UUV maintenance for reliability. Reliability Centered Maintenance is the current strategy employed by the Navy for XLUUVs. While seemingly good practice, for these nascent technologies, the prescribed schedules at the outset of development are primarily educated guesses, heavily influenced by assumed operating tempos and thus system availability for maintenance activities, rather than backed by decades' worth of parametric data from legacy systems. Reliability data is extremely hard to acquire and thus mean times between failures are often based on theoretical calculations that vary in relevancy to the actual system.

Thus, the Navy won't truly know whether these prescribed maintenance schedules are effective and efficient until years' worth of operating, and maintenance experience is acquired. Costs and resource planning for inspections and preventive maintenance will be well defined, derived from the prescribed schedules, but effectiveness and efficiency will be uncertain as the activities are somewhat arbitrarily prescribed and some may be technically unnecessary while other necessary activities go unknown and unaddressed until failures occur, and unplanned corrective maintenance is required.

B. C-BUMMPS CONCEPT

The C-BUMMPS fulfills its mission by measuring system performance parameters throughout its life cycle and then identifying changes to or off-nominal performance, typically degradation, that may be early indicators of impending failures. Early life cycle data forms the baseline performance profile against which future performance measurements are compared. The C-BUMMPS collects data throughout the entire life cycle of the system and its components, thus trading decades and centuries worth of maintenance data for countless sample systems and components for continuous

operational performance data over months to years on a relatively small sample size of systems and components, that sample set being the UUV itself and sister ships within the fleet, assuming common configuration. Monitoring and eventual onboard assessment during a mission can give operators early indications of components and systems that may require inspection and maintenance. This can allow for early planning and execution of logistics activities prior to return of the UUV, giving the opportunity to minimize system downtime due to logistics and administrative delays. It also ties the performance data directly to real-time conditions, duty-cycles, and performance demands of the UUV.

Some drawbacks are the potentially enormous data archive and analysis efforts. Reliability, or failures, of the C-BUMMPS system may also result in gaps in data collection during random periods in the UUV's life cycle, creating challenges and uncertainty in the life cycle performance profiles and potential absence of knowledge of the environmental and operational conditions the components were exposed to. Also, the C-BUMMPS will require energy from the UUV that will decrease its overall endurance potential. However, the energy consumption of the data collection and processing is likely only a few percentage points compared to the overall UUV energy requirements.

Initial fielding of the C-BUMMPS would likely still require the Navy to continue the traditional reliability centered maintenance strategy as there will be an inadequate performance history built from collected data to create prediction algorithms or a robust baseline performance profile to establish thresholds that separate nominal vs. off-nominal performance. However, eventually, the scheduled, preventive maintenance efforts could likely be reduced, or at least be sustained, by focused and more accurately diagnose and address real issues and allow for a reduction of corrective maintenance efforts and reduce the likelihood of mission critical failures that may result in the need for recovery operations to find, retrieve, and return a UUV to port for corrective maintenance.

C. IN-PORT PERFORMANCE MONITORING

An alternative to C-BUMMPS, which would be onboard the UUV and continuously monitor the system during all operating hours would be a temporarily installed system for use during vehicle checkouts. The burdens of physical integration of a temporary system are likely to reduce the scope of performance parameters monitored

and the frequency with which measurements are performed. That is, it would likely be infeasible to repeatedly install and remove voltage, current, vibration, temperature, and other sensors on all major components. The time required would decrease UUV availability and increase labor costs. There would also be a lack of life cycle operational data. Thus, there may be drastic changes in measured performance data between monthly checkouts exacerbated by the lack of operational data to correlate events and conditions to performance changes. This hinders identifying root causes or the characteristics of degradation. However, data collection and storage concerns would be greatly reduced and there would be no impact to operational energy consumption and overall endurance.

D. ACOUSTIC MEASUREMENT

Another alternative means of assessing conditions of the UUV is acoustic measurement. This method can use hydrophones to measure noise produced by equipment vibrations. This method may require both static and dynamic testing, with static meaning the UUV remains in one location and systems are operated individually. Acoustic measurement has its limitations though as it only picks up vibrations and not electrical performance such as voltage and current, nor temperature or load. Additionally, ambient noise from commercial and recreational activities will limit the range and accuracy of measurement of the UUV.

E. EVALUATION METRICS

The following requirements were identified in Project Deliverable 2, the Design Reference Mission, as essential for the C-BUMMPS to fulfill its objective and contribute to mission success for UUVs.

- The C-BUMMPS shall increase UUV reliability
- The C-BUMMPS shall reduce UUV Maintenance Down Time
- The C-BUMMPS shall reduce UUV Mean Time to Repair
- The C-BUMMPS shall not increase mean UUV Turnaround Time

- The C-BUMMPS shall reduce the frequency of UUV Mission Critical Failures
- The C-BUMMPS shall integrate with the UUV Failure Reporting, Analysis, and Corrective Action System
- The C-BUMMPS shall integrate with the UUV environmental sensors to monitor ambient operating conditions.

Additional metrics were considered as the concepts were generated, which include:

- Development Cost
- Operating Cost
- Data Management Costs
- Inventory Management Costs
- Diagnostics Time

F. ANALYSIS

The swing weight method was used to evaluate the concepts, giving greater weight to metrics based on their importance and variation in range. At this stage of development, quantitative measures of performance for the metrics are not available, so engineering judgement and assumptions were used for a qualitative ranking. Table 12 provides the final selected metrics and their ranking.

Table 12. Swing Weight Ranking of Evaluation Metrics

	Importance of Value Measure		
Variation in Range	High	Medium	Low
High	Time to Detect Issues (Sooner is Better)	Operating Cost (Less is Better)	
	Not Increase Turnaround Time	Failure Prediction Capability	
	Reduce Maintenance Downtime	Data Management Costs	
	20	15	10
Medium	Development Cost (Less is Better)	Inventory Management Costs	Correlate Ambient Operating Conditions to Equipment Condition
	Diagnostics Time		
	15	10	5
Low			
	10	5	1

With the weighting of metrics determined, the concepts were scored by how well they performed for the metric. The following scoring rules were applied:

- 3 = Improvement for metric
- 2 = Metric is satisfactory, meets the baseline
- 1 = Performs worse than baseline
- 0 = Capability non-existent

Table 13 provides the evaluations of the concepts' assumed performance for each of the metrics. Here the swing weights are transformed into percentages as the measure weights. The scoring rules were applied to each of the concepts and multiplied by the measure weight to produce the weighted score. The metric weighted scores for each

concept were summed to determine the relative ranking for each concept. Since the scoring process is qualitative and subjective, the justification for the evaluation scores is provided in Table 14.

Table 13. Concept Evaluation

			Baseline (RCM)		C-BUMMPS		In-port Measurement		Acoustic Measurement	
Metric	Swing Weight	Measure Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Development Cost (Less is Better)	15	10.0%	2	0.200	1	0.100	1	0.100	2	0.200
Operating Cost (Less is Better)	15	10.0%	2	0.200	3	0.300	1	0.100	2	0.200
Failure Prediction Capability	15	10.0%	0	0.000	3	0.300	2	0.200	1	0.100
Time to Detect Issues (Sooner is Better)	20	13.3%	1	0.133	3	0.400	2	0.267	1	0.133
Reduce Maintenance Downtime	20	13.3%	2	0.267	3	0.400	1	0.133	2	0.267
Not Increase Turnaround Time	20	13.3%	2	0.267	3	0.400	1	0.133	2	0.267
Correlate Ambient Operating Conditions to Equipment Condition	5	3.3%	1	0.033	3	0.100	1	0.033	1	0.033
Data Management Costs	15	10.0%	3	0.300	1	0.100	2	0.200	2	0.200
Inventory Management Costs	10	6.7%	2	0.133	3	0.200	2	0.133	2	0.133
Diagnostics Time	15	10.0%	2	0.200	3	0.300	3	0.300	2	0.200
Total	150			1.867		2.600		1.600		1.733

Table 14. Evaluation Metric Considerations and Justifications

Metric	Considerations and Justification
Development Cost (Less is Better)	The C-BUMMPS will have the highest development costs of the concepts as it requires design and integration of the sensor system onboard the UUV. The In-Port measurement system will have a similar level of design required, with the difference being that instead of integrated sensing, there must be alternative interfaces designed into the UUV to accommodate periodic installation and removal of the sensors. The acoustic measurement system would be less intense as external hydrophones can be placed in the water around the UUV, and not be physically integrated.
Operating Cost (Less is Better)	Once installed, the C-BUMMPS should have minimal operating costs and can save traditional diagnostics efforts, whereas the in-port measurement system will require extensive labor efforts to install. The acoustic measurement system is less extensive to implement than the in-port system.
Failure Prediction Capability	The C-BUMMPS has the greatest potential for failure prediction capability due to its continuous monitoring. The in-port system will only have the opportunity periodically, before and after a mission. The acoustic system has less capability due to the limited measurement and the Baseline Reliability Centered Maintenance has no prediction capability
Time to Detect Issues (Sooner is Better)	Due to continuous monitoring, C-BUMMPS has the capability to detect issues immediately, whereas the other options require the UUV to be physically present with the operators/maintainers
Reduce Maintenance Downtime	C-BUMMPS can reduce maintenance downtime by replacing post-mission diagnostics with real-time condition measurement. It can also alert operators to what systems need inspection or maintenance before they return to port, allowing for early planning and acquisition of resources. The in-port measurement system may increase maintenance down time due to its extensive setup.
Not Increase Turnaround Time	C-BUMMPS should reduce turnaround time by reducing diagnostic activities and providing early indication of maintenance activities required during the mission, allowing days to weeks of advance notice to begin logistics processes and administrative delay times. In-port measurement is likely to increase down time as it requires extensive setup. Acoustic measurement will likely require methodical operation of individual systems one at a time to isolate noise to specific components.
Correlate Ambient Operating Conditions to Equipment Condition	All concepts can review UUV log files to identify the operating and environmental conditions the UUV was exposed to. But only the C-BUMMPS can have real-time correlation between conditions and subsequent degradation or failure.
Data Management Costs	Data management costs will be relatively high for the C-BUMMPS due to its continuous data collection. The Baseline only has UUV log files to manage. The other options will generate more data that needs to be analyzed and stored.
Inventory Management Costs	C-BUMMPS has the potential to reduce inventory management costs by not requiring as many spares to be shipped and warehoused with the UUV for minimized logistics delay time. C-BUMMPS should give early warning of performance degradation or failure and allow time for shipping of spares.
Diagnostic Time	C-BUMMPS and In-Port measurement have the potential to reduce traditional diagnostics time by directly measuring equipment performance and identifying off-nominal performance.

G. ANALYSIS RESULTS

Based on analysis of alternatives results and associated assumptions and metrics, the C-BUMMPS appears to be a superior solution for increasing UUV reliability and availability. However, it is important to keep in mind that the metrics used, and their relative importance, may vary between stakeholders. Additionally, further, detailed, quantitative analysis of costs to design, implement, and operate the solutions, as well as their impact on maintenance activities, could change the range in variation. And, whenever cost is involved, sometimes there is a limit to what a sponsor is willing to spend for a yet-to-be-proven capability when there are likely to be many other competing priorities requiring funding.

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IX. CONCLUSIONS, FUTURE WORK, AND RECOMMENDATIONS

A. CONCLUSIONS

The primary objectives for this project were met. Functional and physical architectures were developed for the C-BUMMPS. A set of system requirements were developed for the C-BUMMPS concept to guide future development of condition-based maintenance monitoring systems on UUVs. A methodology was developed of analyzing the UUV physical architecture and performing failure mode analysis. Stakeholder analysis helped to affirm and refine the system CONOPS and operational activities while also eliciting additional needs and extensions of the initial concepts to create a more comprehensive architecture in terms of definition and functional capabilities along with how the C-BUMMPS will better serve the operator through interfaces with external maintenance systems and modeling and simulation for life cycle predictions from the C-BUMMPS data.

It's important to emphasize again that the C-BUMMPS requirements developed from this project are high level and UUV-system agnostic. The C-BUMMPS system requirements are provided with the intent to form a basis for further expansion when applied to specific UUV systems. Due to broad range of capability and size that the Navy's four UUV classes span, there will be limitations, both physical and programmatic, upon how much of the C-BUMMPS proposed capabilities can be applied to any one system. It is expected that small and medium size UUVs will have greater restrictions resulting in a less comprehensive C-BUMMPS architecture being implemented. Therefore, many of the requirements state that the C-BUMMPS "shall be able to" as an attempt to reflect the capability may and should be possible, it just ultimately may not be implemented for a particular system. This is due to the authors recognizing the constant need to balance capability and performance with the applicable need and resultant value or return on investment that the C-BUMMPS can bring to a particular system and its mission set.

B. FUTURE WORK AND RECOMMENDATIONS

While this capstone project succeeded in developing an architecture and set of requirements for the C-BUMMPS, there are several areas that can and should be explored further to provide greater detail and definition of the C-BUMMPS. It will also be necessary and beneficial to take a deeper look into supporting activities and the offboard, shore based data management, analysis, and modeling and simulation to support the C-BUMMPS operations and mission.

The authors' vision for future C-BUMMPS development is to see it advance as an enabling technology for acquisition and integration onboard current UUVs, and incorporation into the system requirements of future UUV systems. However, a substantial amount of concept development, particularly in the areas of achieving commonality across UUV classes and systems and establishing test programs and requirements to characterize failure modes and degraded performance leading to failure. This development work will be important to accomplish prior to embarking on any significant acquisition to ensure the initial products are developed with a fully informed vision and set of requirements to maximize commonality across UUVs and ensure that the land-based support activities are well defined for development to realize the full potential of the C-BUMMPS and maximize its effectiveness.

It is also acknowledged that this capstone project was intentionally kept to be Distribution A, approved for public release. Future work may need to be Distribution D and restricted to DOD Employees and Contractors to allow greater relevancy to be able to reach a lower level of detail and be relevant to current and future Navy systems.

1. Performance Parameter Criticality Analysis

A high level failure mode analysis was performed on a generic UUV architecture to help elicit requirements for failure detection. System, subsystem, and component control and performance parameters are also prime candidates for monitoring since they are either already present and monitored (in the case of control) or are key performance parameters that truly define component or subsystem performance. Further analysis should be performed to identify typical or most likely control and performance

parameters for UUV subsystems and components. This could help identify and prioritize minimum requirements for C-BUMMPS sensing and data acquisition and ensure that important parameters aren't mistakenly overlooked and eliminated during design tradeoff analysis in a particular system.

2. Test Program for Early Failure Characterization

One of the challenges for successful and effective implementation of the C-BUMMPS, and particularly development and application of failure prediction algorithms, is the lack of failure data and performance data capturing system and component degradation over time, leading to a failure. This is understandable since a newly produced system delivered to the Navy should hopefully not be experiencing frequent failures due to component wear and degradation. However, without such data, prediction capability will be extremely limited at first and only grow over time with accumulation of system operating hours. However, a robust reliability growth program would incorporate reliability critical item testing, including accelerated life testing. This could be an important early data source for failure and performance data that otherwise may not be encountered until later in the UUV system life cycle, and likely too late for C-BUMMPS to make a significant impact with failure prediction.

The authors recommend that further research and development efforts be applied toward defining early component and subsystem testing that may be performed during system development and throughout the system life cycle and contribute to building the performance profiles and degradation to failure performance data. This would provide some early failure characterization data that could be applied to the C-BUMMPS prediction capabilities. Of course, one of the larger questions to be answered is the relevancy or validity of laboratory and bench testing data to performance during real world operation. This could drive the definition of the environmental conditions and operating parameters that may need to be incorporated into the test environment to yield relevant and accurate results.

3. Extended Failure Mode Analysis

This project included a high level failure mode analysis on a generic UUV architecture to help elicit requirements for failure mode detection. This analysis was limited in scope due to the constraints of the project timeline and overall scope. Further failure mode analysis may be warranted to identify additional failure modes and causes and validate the detection methods identified and their ability to be monitored effectively to contribute to failure prediction.

4. Performance Requirements

The objectives of this project were to develop a set of system requirements for the C-BUMMPS. While that goal has been achieved, the authors acknowledge that most requirements are high-level functional requirements that do not specify quantitative measures of performance or effectiveness. The authors recommend further research and investigation, to include engagement with other subject matter experts that deal with condition-based maintenance, sensing, and monitoring for various measures of system health and performance, and other related areas. The goal is to define performance attributes like measurement frequency, accuracy, and resolution to maximize the effectiveness without exceeding what is necessary.

While each specific system, subsystem, and component may have unique characteristics and performance parameters (e.g., RPM, electrical switching frequency, radiated noise, etc.) it is likely the Navy can identify minimum performance requirements to ensure that enough data is collected of sufficient quality that it yields performance data that can be effectively used to monitor and predict performance. Likewise, it would be wise to identify upper limits for data collection to manage and control the costs and impacts of supporting the system in the context of data management and analysis and hardware requirements. As an example, measuring the RPM of a motor once every minute may be insufficient to use RPM as a monitored performance parameter. However, measuring or sampling rotational speed at 100kHz for a motor that operates in the range of 10^3 RPM may be an excessive amount of data for that performance parameter, driving the sensors and data acquisition, storage, and analysis far what is useful, let alone necessary.

5. Digital Engineering

The Department of Defense has a thrust area for digital engineering. With the advent of new systems like Model Based Product Support, and broad concepts like Digital Twin, the Navy should investigate where the trends in digital engineering are heading and ensure that C-BUMMPS is compatible with future maintenance and logistics tools while also ensuring those systems and tools have provisions for condition-based maintenance if deemed appropriate and within their current or future scope. There may be additional applications for the capabilities and data collected by the C-BUMMPS. Serving multiple needs and capability gaps could strengthen the argument for undertaking the development and implementation of the C-BUMMPS. These other needs should be identified and evaluated early on in C-BUMMPS development so that the developers can weigh these other considerations and make informed decisions about the system architecture and design, expanding, or limiting, its capabilities based on other needs and the costs or impacts of attempting to meet those needs.

6. C-BUMMPS Corrective Actions

Further research should be applied towards identifying a standard set of potential corrective actions that a C-BUMMPS could recommend to a UUV autonomy controller. Simple things like cycling power or restarting a subsystem could be valuable or could do little to solve a problem. However, having a C-BUMMPS or other system capable of making those recommendations is only half of a solution. The other half is imposing appropriate requirements on the UUV design architecture to have the capability to respond to such recommendations and perform those corrective actions.

7. Scalability of C-BUMMPS to UUV Class Size

As previously discussed, the C-BUMMPS concept can be scalable to UUV class size. However, different monitoring approaches and techniques will be necessary. Medium and Small-class UUVs in particular, typically do not have the onboard space, weight, and power capacity to host the full capability C-BUMMPS onboard. Sensors and data acquisition and processing hardware likely can't be scaled down in the same proportion. However, small and medium class UUVs have significantly different mission

profiles, and specifically endurance, than large and extra-large class UUVs. Thus, the need for long endurance and reliability is absent. And the cost and physical impact of comprehensive onboard sensing, monitoring, and data acquisition may be of minimal benefit to the UUV for the value and importance of the system and its mission.

APPENDIX A. FMDA TABLES

Table 15. Relationship of Failure Cause (FC) and Failure Detection (FD)

	FD. 1	FD. 2	FD. 3	FD. 4	FD. 5	FD. 6	FD. 7	FD. 8	FD. 9	FD. 10	FD. 11	FD. 12
FC.1	X											
FC.2		X										
FC.3			X	X								
FC.4	X				X							
FC.5						X						
FC.6							X					
FC.7	X					X						
FC.8	X						X	X				
FC.9							X		X			
FC.10										X		
FC.11	X		X	X								
FC.12	X											
FC.13							X					
FC.14							X					
FC.15	X						X					
FC.16											X	
FC.17								X		X		
FC.18								X	X			
FC.19								X	X			
FC.20								X		X		
FC.21								X		X		
FC.22									X	X	X	
FC.23							X					
FC.24	X											X
FC.25	X											X
FC.26							X		X			
FC.27							X					
FC.28										X		

Table 16. Relationship of Failure Cause (FC) and Failure Mode (FM)

	FC.1	FC.2	FC.3	FC.4	FC.5	FC.6	FC.7	FC.8	FC.9	FC.10	FC.11	FC.12	FC.13	FC.14	FC.15	FC.16	FC.17	FC.18	FC.19	FC.20	FC.21	FC.22	FC.23	FC.24	FC.25	FC.26	FC.27	FC.28
FM.1.1	X	X																										
FM.1.2.1.1				X																								
FM.1.2.1.2			X																									
FM.1.2.2.1.1					X	X	X																					
FM.1.2.2.1.2								X	X	X																		
FM.1.2.2.2				X							X	X																
FM.1.3.1													X	X	X													
FM.1.3.2			X									X																
FM.1.3.3													X	X	X													
FM.1.4.1.1								X								X	X											
FM.1.4.2.1.1																		X	X									
FM.1.4.2.1.2																		X	X									
FM.1.4.2.1.3																					X							
FM.1.4.2.1.4																					X	X						
FM.1.4.2.1.5																X	X					X	X					
FM.1.4.2.3																X	X		X				X					
FM.1.4.2.5																X	X		X			X	X					
FM.1.4.2.6																X	X		X			X	X					
FM.1.4.3.1								X								X	X						X					
FM.1.4.5.1																	X	X	X			X						
FM.1.4.5.4																X	X						X					
FM.1.5.1.1																	X		X					X	X			

	FC.1	FC.2	FC.3	FC.4	FC.5	FC.6	FC.7	FC.8	FC.9	FC.10	FC.11	FC.12	FC.13	FC.14	FC.15	FC.16	FC.17	FC.18	FC.19	FC.20	FC.21	FC.22	FC.23	FC.24	FC.25	FC.26	FC.27	FC.28
FM.1.5.1.2																			X				X	X				
FM.1.5.2																		X	X				X					
FM.1.5.3																X	X				X	X						
FM.1.5.4																X	X	X			X	X	X					
FM.1.6.1.1								X															X					
FM.1.6.1.2																							X		X			
FM.1.6.2								X									X					X	X					
FM.1.7.1.1																	X						X			X		
FM.1.7.2.1								X									X				X		X			X		
FM.1.7.2.2								X									X						X					
FM.1.8.1.1			X	X																								
FM.1.8.1.2					X																		X				X	
FM.1.8.1.3								X								X	X				X		X					
FM.1.8.2.1																		X	X				X					
FM.1.8.2.2																	X					X						
FM.1.8.3.1										X														X		X		
FM.1.8.4.1			X	X																					X			
FM.1.8.4.2								X								X	X				X	X	X					
FM.1.8.4.3			X	X						X																		
FM.1.8.4.4					X																				X		X	
FM.1.8.4.5								X								X	X				X		X				X	
FM.1.9.1.1																X							X					
FM.1.9.1.2																						X	X					X
FM.1.9.2.1																X						X	X		X			
FM.1.9.2.2																X						X	X		X			

	FC.1	FC.2	FC.3	FC.4	FC.5	FC.6	FC.7	FC.8	FC.9	FC.10	FC.11	FC.12	FC.13	FC.14	FC.15	FC.16	FC.17	FC.18	FC.19	FC.20	FC.21	FC.22	FC.23	FC.24	FC.25	FC.26	FC.27	FC.28
FM.1.9.3.1																		X	X				X					
FM.1.9.3.3								X																				X
FM.1.9.3.4																X						X	X					
FM.1.9.4.1																							X		X			X
FM.1.9.4.2																							X		X			X
FM.1.9.5.1																							X		X			X
FM.1.9.5.2																							X		X			X

APPENDIX B. STAKEHOLDER INTERACTIONS

The following email, questions, and presentation were sent to the stakeholders prior to meeting with the groups identified in Section V.A - Stakeholder Identification.

Stakeholders,

We're writing to you to request a meeting (hopefully within the next two weeks) to discuss the development of a Condition-Based UUV Maintenance Monitoring and Prediction System (C-BUMMPS). This is the topic for our Capstone project for our Master of Science in Systems Engineering degree at the Naval Postgraduate School. We will be executing this project and system development for our last 3 quarters at NPS, with a projected completion date of March 2022.

As we envision it, the Condition-Based UUV Maintenance Monitoring and Prediction System (CBUMMPS) is a sensor and data acquisition system installed on UUVs to support a condition-based maintenance strategy. C-BUMMPS will monitor system conditions and performance in real time, and eventually correlate that data with equipment operating performance profiles to generate a predicted health and performance status assessment for the UUV. The goal of the C-BUMMPS is to give operators and maintainers real-time or near-real time information to inform maintenance planning prior to availability and/or to minimize risk of component or system failures during high priority missions. Attached is a brief overview presentation that illustrates the C-BUMMPS concept in further detail.

Below is a sample of questions we're hoping to address during our meetings with our identified stakeholders and SMEs, but we will tailor our focus to the ones you feel most relevant to your knowledge, interest, and area of cognizance. We consider this to be an opportunity for open discussion and are eager to receive your thoughts, feedback, recommendations, and other needs and priorities that you as a stakeholder and subject matter expert believe we should consider for this project and system development.

Please let us know when you might be available for a discussion by teleconference. A few 1-hour timeslot options would be helpful, but we will certainly

adjust to your availability. We're also open to your inviting or recommending we engage with any other stakeholders or SMEs you believe would be interested or informative to our work. Of course, if you prefer to respond in writing, that would also work.

V/r,

Dana Colegrove
Snakehead LDUUV NSWCCD Technical PM
Maritime Systems Hydromechanics Branch

Jason Delisser
Electrical Engineering Lead
Maritime Systems Hydromechanics Branch

Corey Johnson
Unmanned Systems Engineer
Maritime Systems Hydromechanics Branch

John Stebe
Orca XLUUV Lead Systems Engineer
Unmanned Undersea Systems Branch

Note: We intend to keep our project Distribution A and Approved for Public Release. But as DOD employees, we can hold our discussions at a Distribution D level. We'd appreciate your support in identifying what can and cannot be included in a Dist. A report, as well as pointing us towards any publicly released documents and guidance from DOD that you think might be relevant to our topic of Condition Based Maintenance for UUVs and other autonomous systems.

Questions

1. Do you see reliability as a high-risk capability gap for UUV systems?
2. What is the current maintenance philosophy for UUVs?
3. Has the Navy made any budgetary plans or commitments specifically aimed at advancing/improving UUV reliability, availability, and maintainability?
4. Do you see a need for Navy UUV systems, particularly Large and Extra Large class UUVs, to have a predictive maintenance capability?
5. Do you think a condition-based maintenance is scalable with UUV class-size?
6. What approach would you consider most appropriate for prioritizing subsystem, components, and performance parameters to monitor in a

Condition Based Monitoring system? Are there some parameters and subsystems that you can identify now that should be a priority, regardless of the results of future analysis?

7. What sort of CBM Monitoring do you think should be on the different UUV size classes: Small, Medium, Large, and Extra Large UUVs?
8. Would you consider a CBM Monitoring and Prediction System as contributing to operator confidence in UUVs?
9. Is a C-BUMMPS system development, integration, operation, and sustainment cost worthwhile for increased reliability and availability?
10. How does Condition Based Maintenance fit into the broader DOD vision for Digital Twin and Digital Engineering efforts?
11. Who should we contact to learn more about Digital Twin and Digital Engineering efforts focused on Reliability, Availability, Maintainability and Condition-Based Maintenance?
12. Can you recommend any policy, guidance, references, or other projects to investigate related to CBM and concepts similar to C-BUMMPS?
13. Do you have any recommendations for our development approach?
14. Do you have any recommendations for future work beyond the scope we identified thus far?

C-BUMMPS

(“See – Bumps”)

Condition-Based UUV Maintenance Monitoring and Prediction System

NSWC Carderock Division

Maritime, Aviation, and Unmanned Systems
Division Team

MSSE Capstone Project

October 2021

Dana Colegrove

Jason DeLisser

Corey Johnson

John Stebe



Introduction

- All team members work within NSWC Carderock Division, Maritime, Aviation, and Unmanned Systems Division (Code 88)
- Pursuing a Master of Science Degree in Systems Engineering
(Anticipated Graduation March 2022)
- Capstone Project Goal: Develop Enabling system/technology for UUVs
- Team Members' Professional Work: Design, development, and acquisition engineering support of various Unmanned Undersea Systems for NAVSEA

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Problem Statement

- LDUUVs and XLUUVs need increased endurance, on the order of weeks to months, to begin to take on some of the mission areas of nuclear submarines.
- UUV endurance is dependent on system reliability and the ability to tolerate or avoid system failures.
- The Condition-Based UUV Maintenance Monitoring and Prediction System (C-BUMMPS) is envisioned as an enabling technology to improve reliability and availability by:
 - monitoring UUV health and status to support a condition-based maintenance strategy
 - Informing maintenance planning prior to system availability
 - Minimizing risk of component or system failures during high priority missions

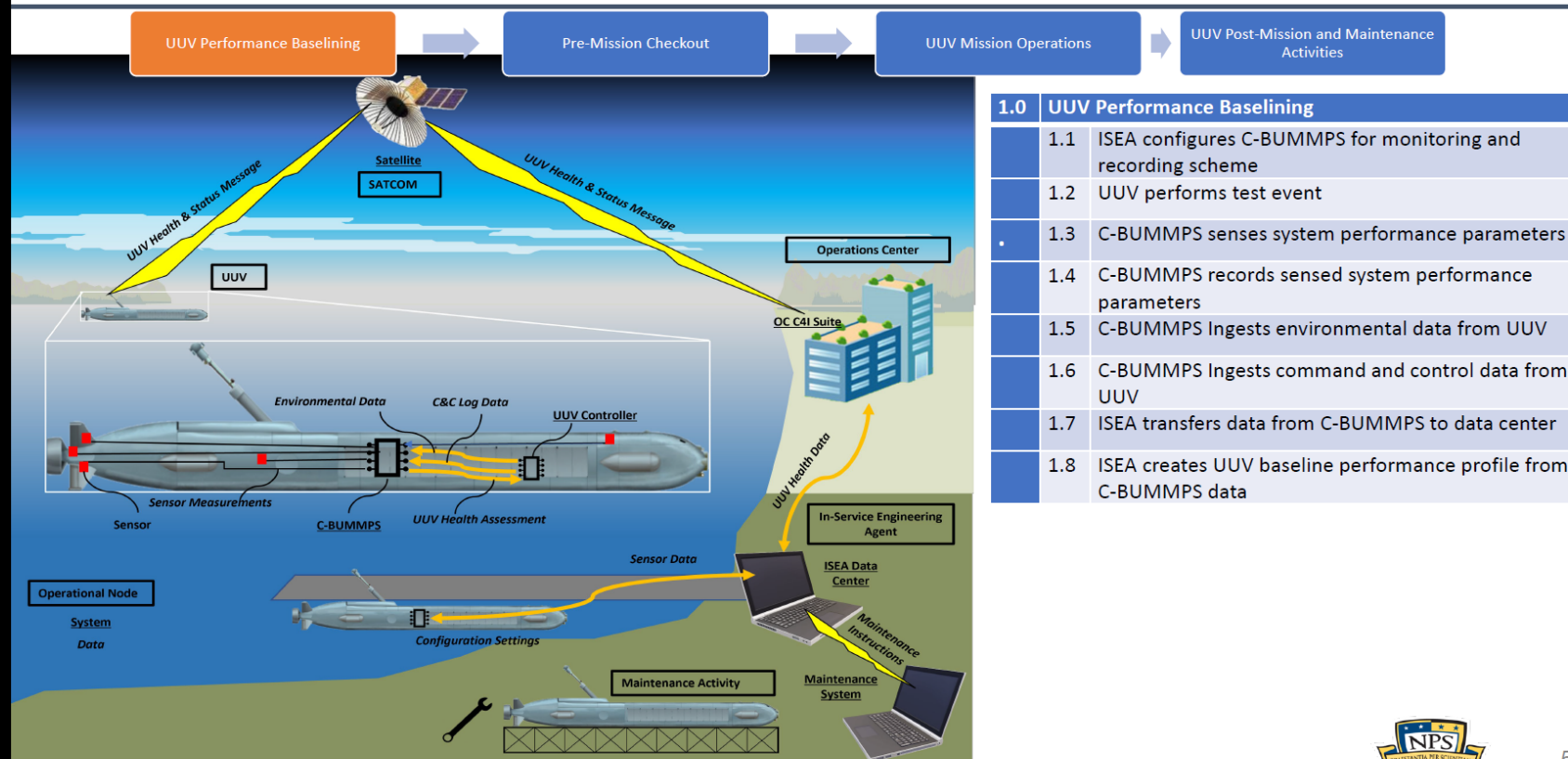


Stakeholders and Subject Matter Experts

Focus Group	Role	Organization
Focus Group 1	UUV Principal Assistant Program Manager	Unmanned Maritime Systems Program Office (PMS 406)
	Unmanned Undersea Warfare (UUW) Systems Engineer	Unmanned Maritime Systems Program Office (PMS 406)
Focus Group 2	XLUUV/LDUUV Ship Design Manager	Naval Systems Engineering and Logistics, Submarine and Submersible Design & Systems Engineering, Advance Undersea Systems (NAVSEA 05U5)
	UUV Waterfront Chief Engineer	
	XLUUV Reliability Engineer	Naval Surface Warfare Center Carderock Division
Focus Group 3	XLUUV IPS Lead	Naval Undersea Warfare Center Keyport Division
	LDUUV IPS Lead	Naval Undersea Warfare Center Keyport Division
	UUV In-Service Engineering Agent Representatives	Naval Undersea Warfare Center Keyport Division
Focus Group 4	Marine Aviation Branch F-18 Data Analytics Lead Engineer	Naval Surface Warfare Center Carderock Division
	XLUUV Software SME	Naval Surface Warfare Center Carderock Division
	Cyber C4I Lead, Unmanned Maritime Systems Program Office	Unmanned Maritime Systems Program Office (PMS 406)
Focus Group 5	SSTM, Director, USW Unmanned Systems and Autonomous Behavior	Naval Undersea Warfare Center Newport Division
	Director, Integrated Unmanned Maritime Mobility Systems	Naval Surface Warfare Center Carderock Division
Focus Group 6	Chief Technology Officer, Digital Twin Advocate	Naval Surface Warfare Center Carderock Division
	Naval Architecture & Engineering Department Chief Engineer	Naval Surface Warfare Center Carderock Division
	Head, Unmanned Undersea Systems Branch	Naval Surface Warfare Center Carderock Division
	Head, Maritime, Aviation, and Unmanned Systems Division	Naval Surface Warfare Center Carderock Division
Focus Group 7	Commanding Officer	UUV Squadron One



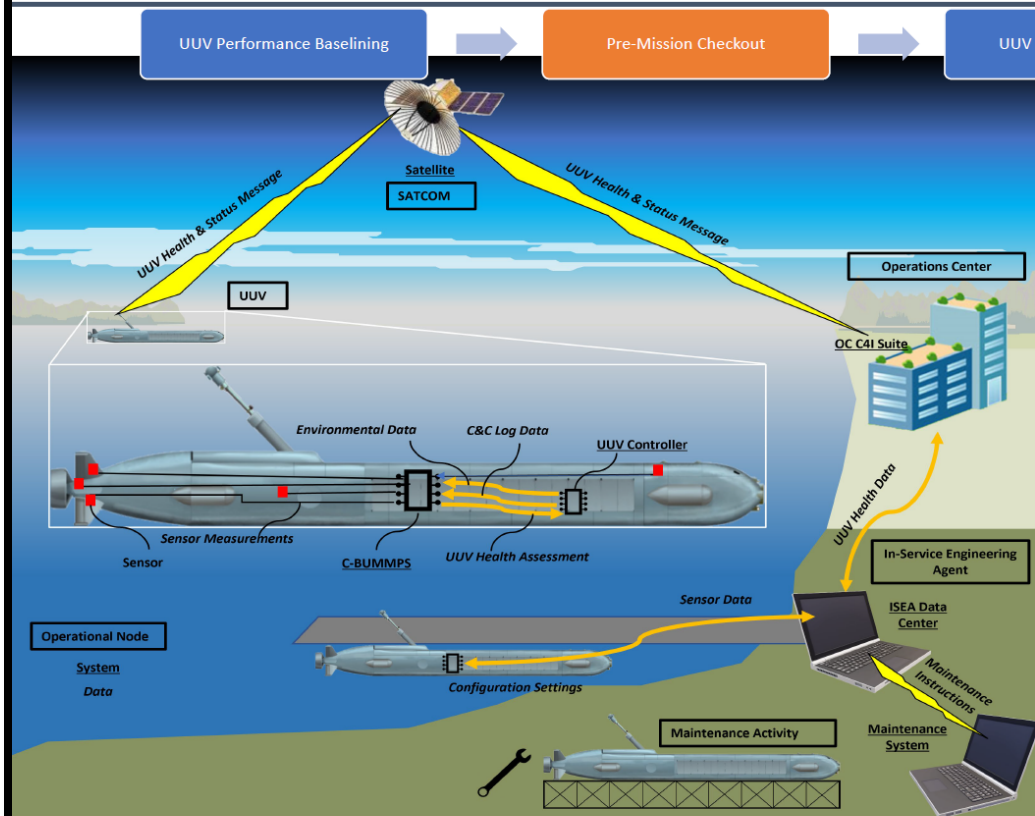
System Description and CONOPS



OV-1: C-BUMMPS Preliminary Operational Concept



System Description and CONOPS

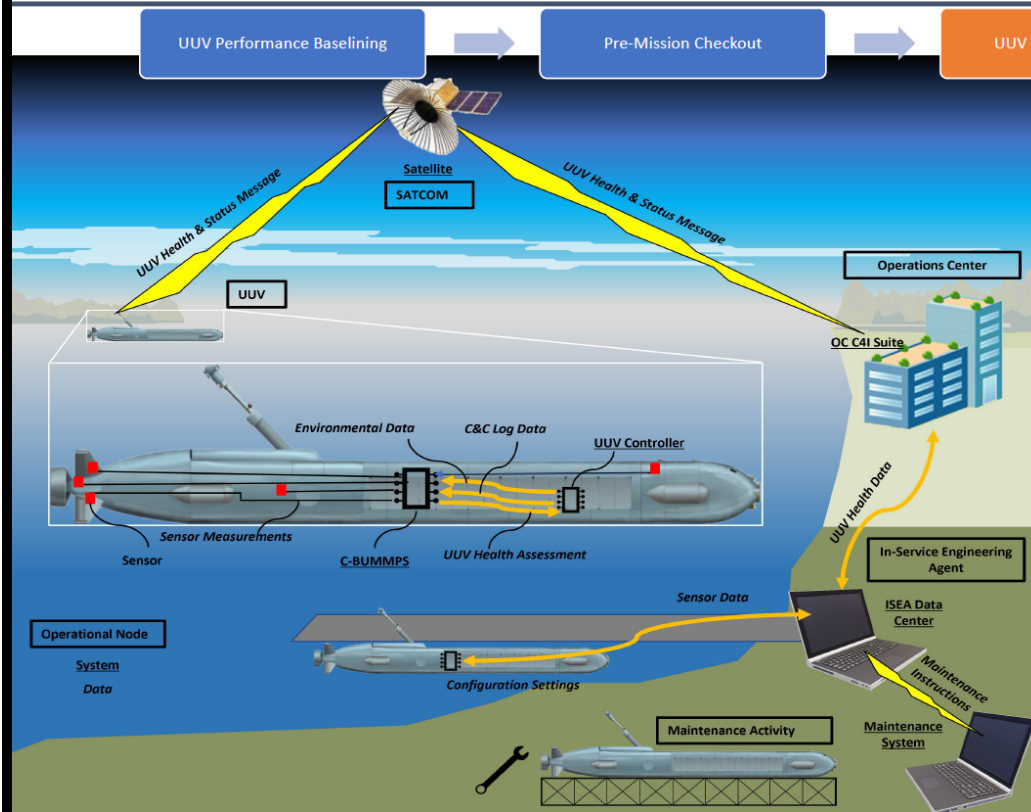


OV-1: C-BUMMPS Preliminary Operational Concept

2.0	UUV Pre-Mission Checkout
2.1	ISEA configures C-BUMMPS for monitoring and recording scheme
2.2	UUV performs pre-mission checkout event
2.3	C-BUMMPS senses system performance parameters
2.4	C-BUMMPS records sensed system performance parameters
2.5	C-BUMMPS Ingests environmental data from UUV
2.6	C-BUMMPS Ingests command and control data from UUV
2.7	UUV demonstrates off-nominal performance
2.8	ISEA downloads C-BUMMPS data for analysis
2.9	ISEA reviews C-BUMMPS data and assesses UUV health
2.10	ISEA determines maintenance action to return UUV to nominal performance levels
2.11	Maintenance Activity performs maintenance action as directed by ISEA
2.12	ISEA determines operational readiness of UUV and Informs Operations Center



System Description and CONOPS

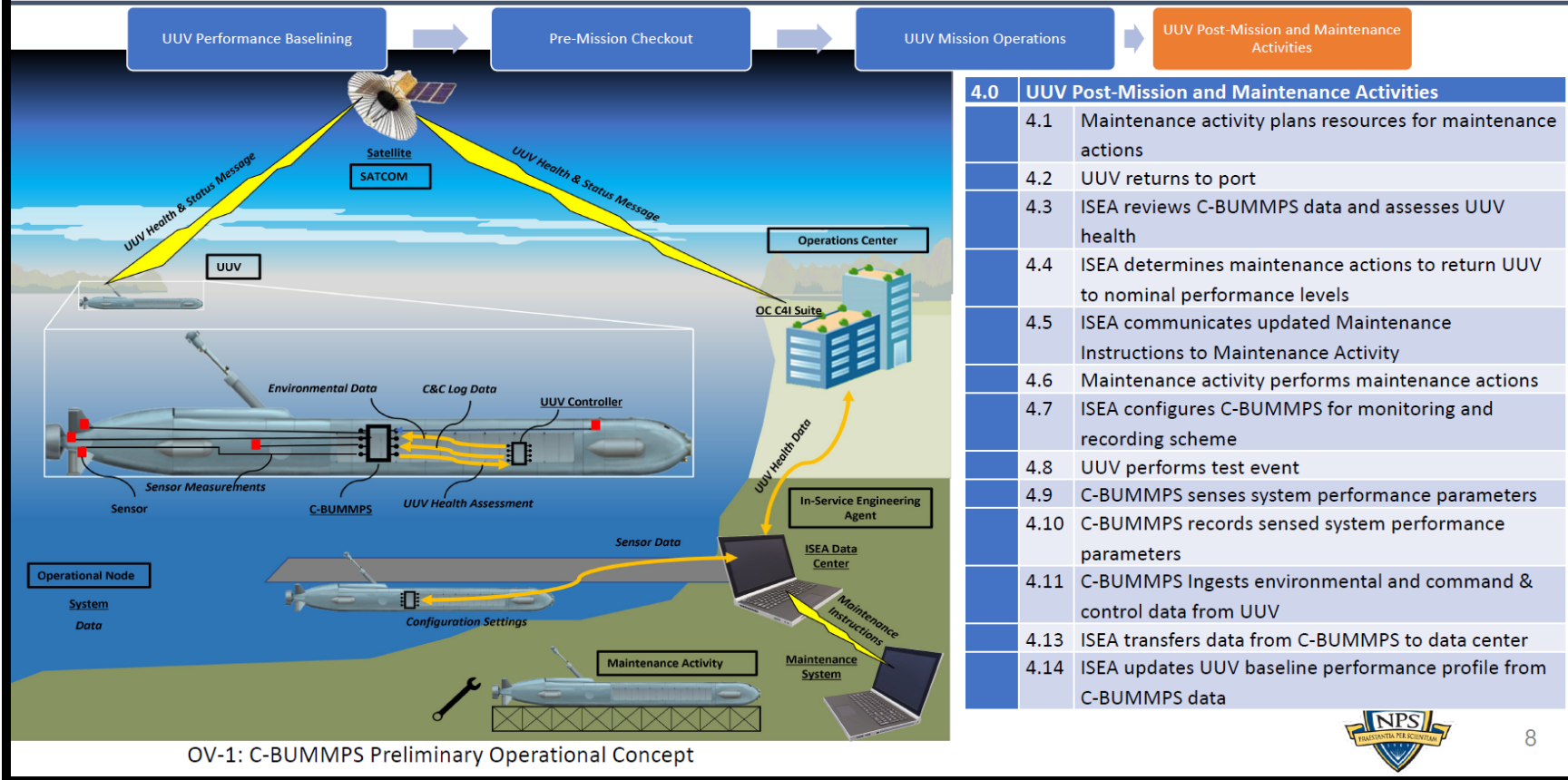


OV-1: C-BUMMPS Preliminary Operational Concept

3.0	UUV Mission Operations
3.1	ISEA configures C-BUMMPS for monitoring and recording scheme
3.2	UUV performs mission
3.3	C-BUMMPS senses system performance parameters
3.4	C-BUMMPS records sensed system performance parameters
3.5	C-BUMMPS Ingests environmental and command & control data from UUV
3.7	UUV demonstrates off-nominal performance
3.8	C-BUMMPS Assesses UUV Health and sends message to UUV
3.9	UUV sends health and status message
3.10	SATCOM relays health and status message to Operations Center
3.11	Operations Center decides to continue mission
3.12	Operations center informs ISEA of UUV Health Assessment
3.13	ISEA plans maintenance actions to address off-nominal performance
3.14	ISEA communicates Maintenance Instructions to Maintenance Activity



System Description and CONOPS



Project Objectives

1. Architect the C-BUMMPS

- Develop a C-BUMMPS architecture that meets stakeholders' needs
- Describe architecture using DoDAF version 2.02 viewpoints

2. Identify and address stakeholder concerns from system developer, operational, and capability viewpoints

- Capture stakeholder needs for improving UUV reliability, maintainability, and availability

3. Develop requirements to inform future C-BUMMPS development and integration to current and future UUVs

- Transform stakeholder needs into operational and functional requirements
- Develop system requirements that meet stakeholder needs
- Also develop requirements for elements not within the UUV (ashore testing, data analytics/AI, and maintenance activities)

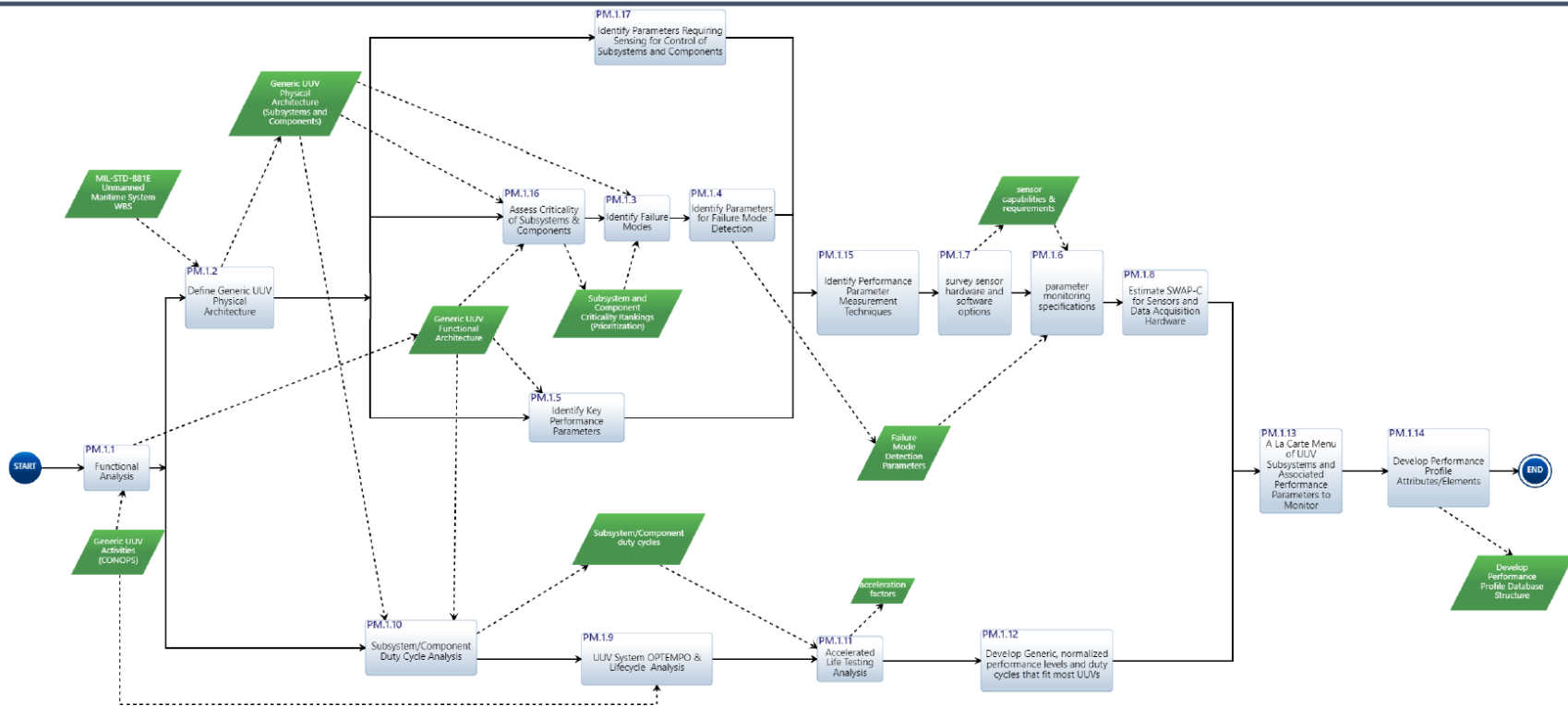


System Development Approach

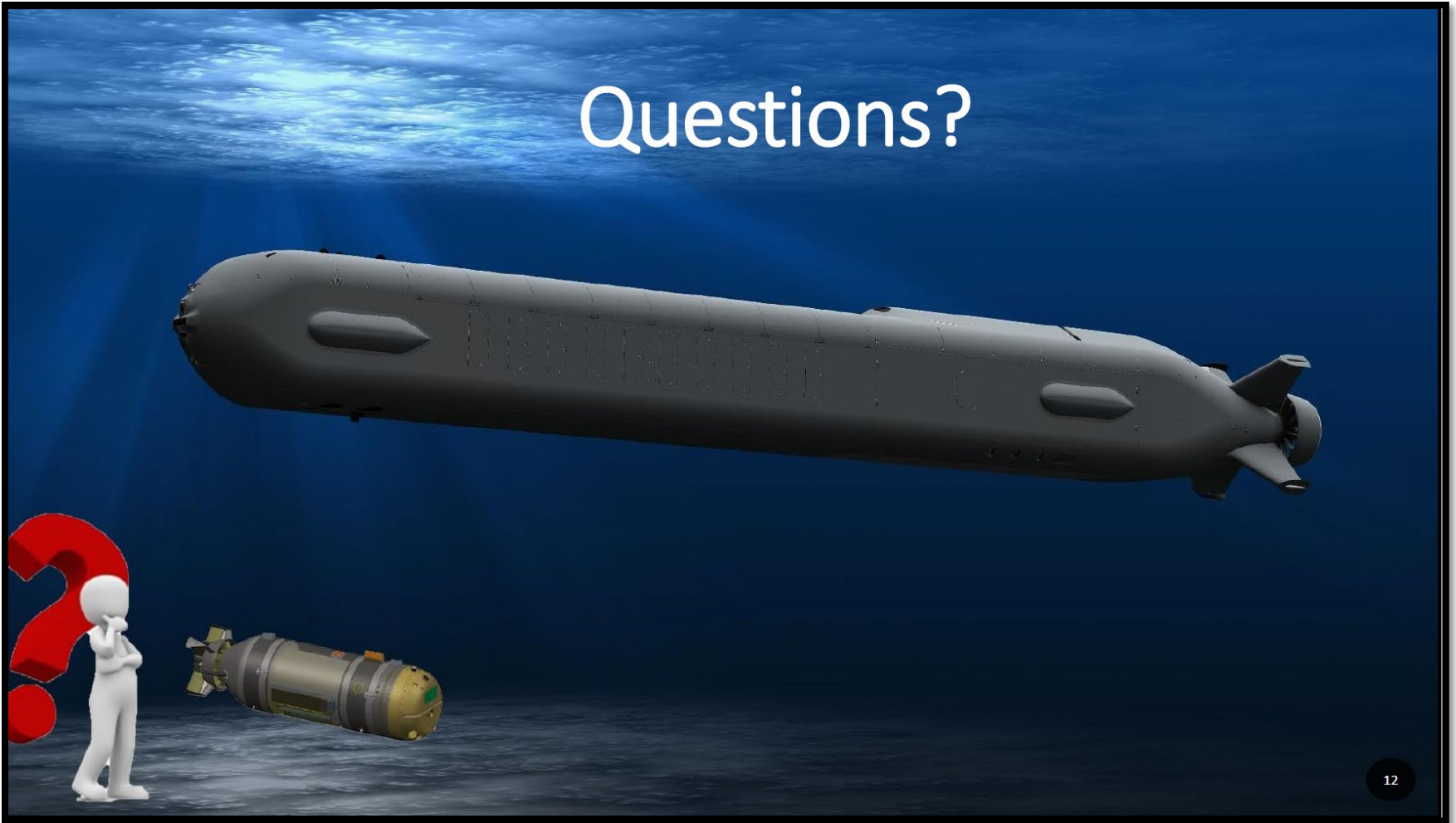
- Develop Generic UUV Architecture (based on MIL-STD-881)
- Identify subsystem & component performance parameters to monitor, through:
 - Criticality, Failure modes & detection parameters (similar to FMECA)
 - Key performance parameters
 - Inherent Sensing Requirements for Control
- Determine high level sensing and data acquisition requirements
- Determine Subsystem and component nominal duty cycles for proposed accelerated life testing to generate performance profiles leading through degradation to failure
- Develop an “A La Carte Menu” Database of recommended parameters for monitoring for a CBM strategy



System Development Approach



Questions?



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APPENDIX C. OPERATIONAL ACTIVITY DIAGRAMS

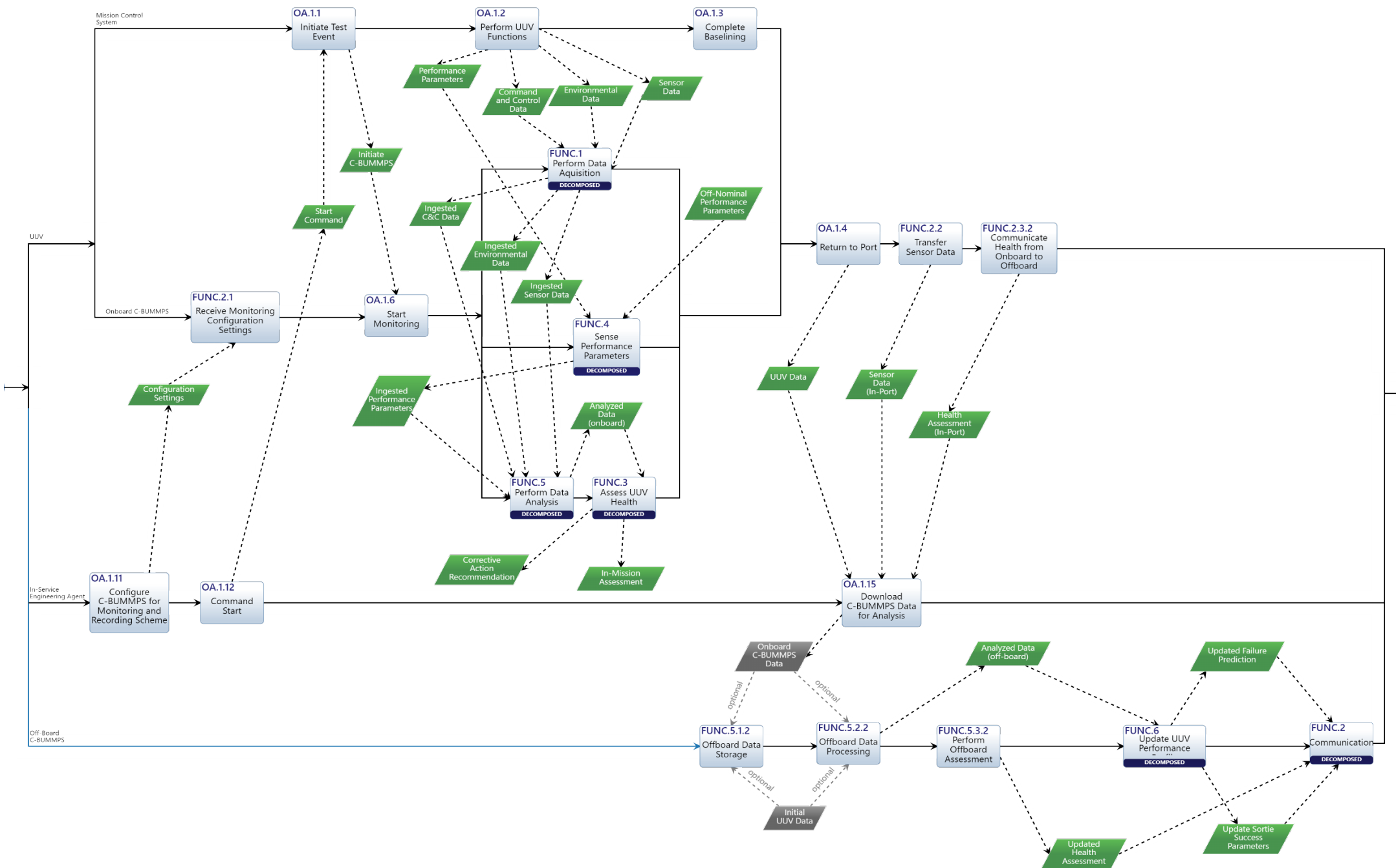


Figure 35. Performance Baseline Operational Activity (OA.1)

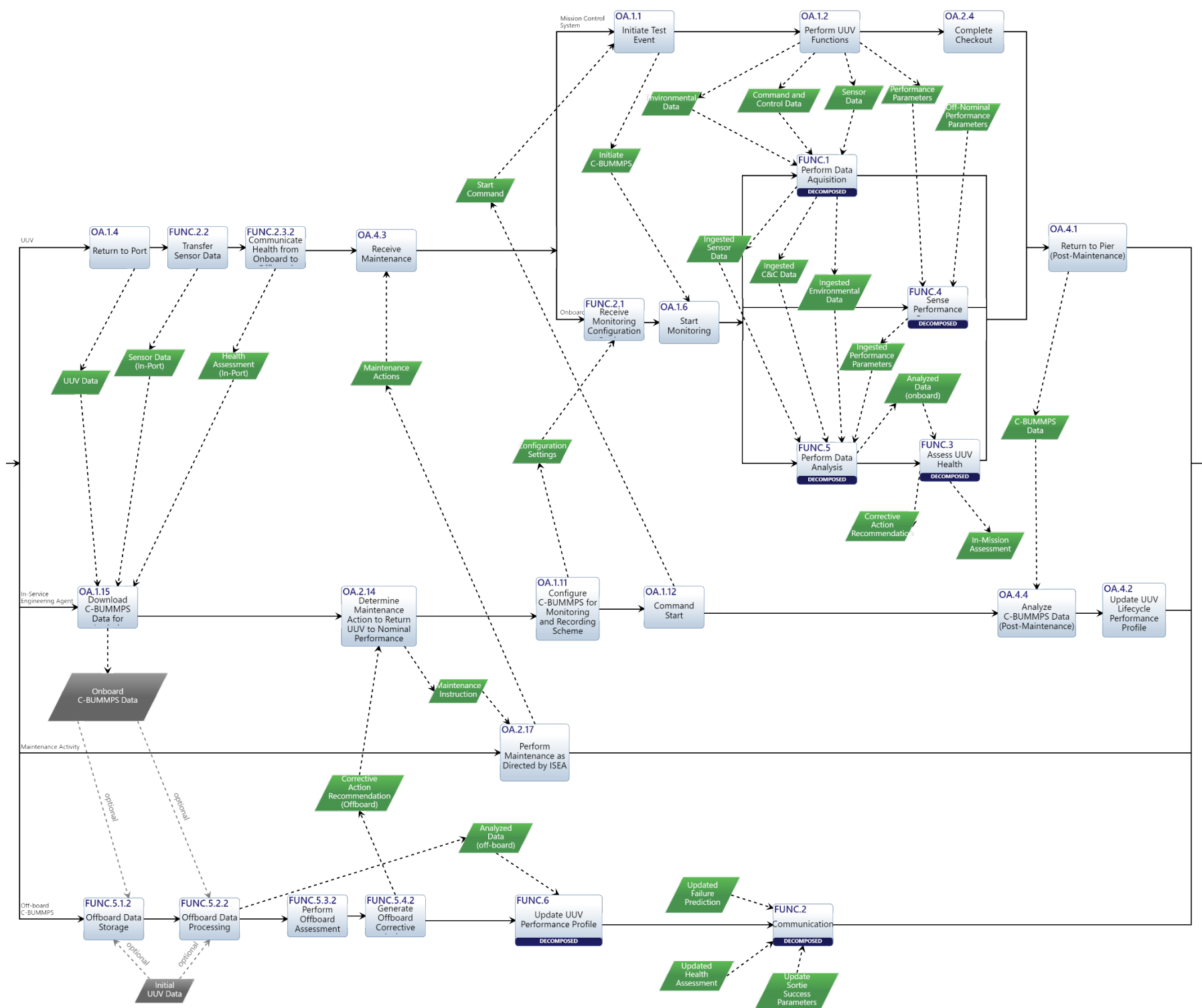


Figure 38. Post-Mission and Maintenance Activities Operational Activity (OA.4)

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