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AUTONOMOUS UNDERWATER VEHICLE ARCHITECTURE SYNTHESIS FOR SHIPWRECK INTERIOR EXPLORATION

by

Ross A. Eldred

December 2015

Thesis Advisor: Fotis A. Papoulias
Co-Advisor: Noel E. Du Toit

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AUTONOMOUS UNDERWATER VEHICLE ARCHITECTURE SYNTHESIS FOR SHIPWRECK INTERIOR EXPLORATION

Ross A. Eldred
Lieutenant, United States Navy
B.S., Embry-Riddle Aeronautical University, 2008

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Approved by: Fotis A. Papoulias
Thesis Advisor

Noel E. Du Toit
Co-Advisor

Ronald E. Giachetti
Chair, Department of Systems Engineering

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The objective of this thesis is to develop, using a systems engineering approach, the functional analysis, general requirements, key performance parameters, and high-level architectural tradeoff considerations that lead to an architecture synthesis for an autonomous underwater vehicle (AUV) capable of shipwreck interior exploration. A design reference mission is used as the basis for the development of a high-level analysis of alternatives, mission planning, high-level essential tasks and constraints analysis. An examination of the problem space leads to the development of effective stakeholder needs and scope, including context, definitions, the identification of key concerns and system objectives. A literature review of the most mission-pertinent AUVs, including DEPTHX, HAUV, ARROWS and ACQUAS, reveals five key capability gaps. A functional analysis, requirements generation, and architectural design tradeoff analysis lead to the development of a potential architectural solution—the wreck interior exploration vehicle (WIEVLE)—and eight recommendations for future architecture development.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACQUAS	Agile Close-Quarters Underwater Autonomous System
ARROWS	Archaeological Robot Systems for the World's Seas
ASW	anti-submarine warfare
AUV	autonomous underwater vehicle
BC	buoyancy compensator
CAVR	Center for Autonomous Vehicle Research
CCRC	combat rubber raiding craft
CIA	Central Intelligence Agency
CQO	close-quarters operations
CTD	conductivity, temperature, depth
DEPTHX	Deep Phreatic Thermal Explorer
DIA	Defense Intelligence Agency
DIDSON	dual frequency identification sonar
DOD	Department of Defense
DOE	Department of Energy
DOF	degrees of freedom
DOTMLPF	doctrine, organization, training, materials, leadership, education, personnel and facilities
DR	dead reckoning
DRM	design reference mission
DV	delivery vehicle
DVL	Doppler velocity log
EKF	extended Kalman filter
EOD	Explosive Ordinance Disposal
EOD HULS	Explosive Ordinance Disposal Hull Unmanned Underwater Vehicle Localization System
FAE	functional architecture element
FOG	fiber optic gyro
FOM	freedom of movement
FR	functional requirement
GPS	Global Positioning System
HAUV	Hovering Autonomous Underwater Vehicle
HAZMAT	hazardous materials
HD	high definition
HLET	high-level essential task

HS	host submarine
IED	improvised explosive device
IMU	inertial measurement unit
IMU	inertial measurement unit
ISR	intelligence, surveillance and reconnaissance
KPP	key performance parameter
LBL	long baseline
LED	light emitting diode
LIDAR	Light Detection and Ranging
MARTA	Marine Tool for Archaeology
MIT-SG	Massachusetts Institute of Technology Sea Grant
MSL	mean sea level
MTBF	mean time between failures
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
ND	Navy Diver
NOAA	National Oceanic and Atmospheric Association
NR	non-functional requirement
ONI	Office of Naval Intelligence
ONR	Office of Naval Research
PAE	physical architecture element
RDSM	removable data storage module
REMUS	Remote Environmental Monitoring Units
RHIB	rigid hull inflatable boat
ROV	remotely operated vehicle
SA	situational awareness
SAS	synthetic aperture sonar
SCUBA	self-contained underwater breathing apparatus
SLAM	simultaneous localization and mapping
SMART	specific, measurable, attainable, realistic, time-bound/traceable
TASTE	Target Submarine Test Environment
TS	target submarine
TTPs	tactics, techniques and procedures
UAV	unmanned aerial vehicle

USV	unmanned surface vehicle
UUV	unmanned undersea vehicle
UUVMP	Unmanned Undersea Vehicle Master Plan
VERTREP	vertical replenishment
WHOI	Woods Hole Oceanographic Institute
WIEVLE	Wreck Interior Exploration Vehicle

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EXECUTIVE SUMMARY

The objective of this thesis is to develop, using a systems engineering approach, the functional analysis, general requirements, key performance parameters, and high-level architectural tradeoff considerations that lead to an architecture synthesis for an autonomous underwater vehicle (AUV) capable of shipwreck interior exploration. A design reference mission, featuring the interior exploration of the *Komsomolets*, a Soviet nuclear submarine wreck, for the purpose of intelligence reconnaissance, is offered early in the work, establishing the framework for a challenging and interesting mission.

Today, shipwreck interior exploration is important for many reasons other than the simple thrill of traveling to an extreme environment. The capability to explore shipwreck interiors is potentially beneficial to a number of organizations including the Department of Defense, the archaeological community, the commercial salvage industry, and agencies concerned with the exploration of marine environments, such as Woods Hole Oceanographic Institute. The following list provides specific examples of the benefit of wreck interior exploration for each of these types of organizations:

- The Department of Defense may be interested in the collection of intelligence from foreign wrecks, the location and salvage of certain objects within wrecks, conducting rescue operations for survivors within new wrecks and conducting hull inspections internally for usability determination or forensic examination.
- Archaeologists may be interested in the capability to systematically explore, map, and recover artifacts from wreck interiors. Artifacts recovered from inside wrecks are sometimes the only way to identify the wreck.
- The commercial salvage industry may be interested in the identification of wrecks as well as the location and recovery of objects within wrecks.
- Exploration organizations may be interested in the development of the technologies and processes necessary for wreck interior exploration.

Despite the potential for this capability, very few options exist for granting the explorer or salvager access to these remote places. One new and rapidly developing technological field, however, offers promise. Unmanned undersea vehicles may be the key to unlocking the mysteries of these unreachable places.

In Chapter I, the exploration of shipwreck interiors by an AUV is presented as a challenging and important potential mission for a number of key stakeholders, including the Department of the Navy. The absence of an existing solution for this mission is described. A brief synopsis of the history of shipwreck exploration, the specific importance of shipwreck interior exploration, a background on unmanned underwater vehicles (UUVs) and a discussion of AUVs set the stage for an enhanced understanding of the design reference mission (DRM) of Chapter II.

In Chapter II, the DRM describes the Soviet nuclear submarine *Komsomolets,* the background of her sinking, important characteristics of her construction and the environment in which she rests. A hypothetical reference mission is offered, detailing a specific objective and describing potential intelligence collection targets. Following the DRM, four high-level alternatives are discussed in detail. The benefits and drawbacks of traditional human shipwreck penetration, human shipwreck penetration using atmospheric suits, remotely operated vehicle (ROV) shipwreck penetration, and the covert raising of the submarine itself are all established. Following this, the decision to proceed with an AUV system solution to the mission is justified and the preliminary mission planning starts. After laying out the key assumptions, the following high-level essential tasks for the mission are established:

1. The submarine will launch the vehicle from depth to preserve the operation’s secrecy.
2. The vehicle will navigate to the hull opening, stabilize, and enter the wreck.
3. As the vehicle enters the wreck, it will record the environment using appropriate sensors.

4. The vehicle will systematically record its position as it additively builds the interior map of the submarine.

5. The vehicle will propel itself in a manner that causes minimal environmental disturbance.

6. When an internal space (compartment) has been mapped, the vehicle will maneuver to the next search area and continue the exploration.

7. When the vehicle encounters an obstacle, it will determine the appropriate action to defeat that obstacle, execute the task, and continue or abort the search as necessary.

8. The vehicle will recognize a target of opportunity and collect, or mark that opportunity for future collection, on the map. If operating on a tether, the vehicle may be commanded to manipulate or collect objects, or return to the crew for any reason.

9. If operating untethered, the vehicle will monitor its health and remaining power and return to the crew if unable to continue its mission, upon reaching a minimum power threshold, or upon completion of the mission.

The resulting nine tasks become the bedrock for the remaining research effort. The principal constraints are discussed, outlining first the expected operating conditions during the submarine loading and transport phase, the submarine launch phase, the target exploration phase, and the recovery phase. Logistic considerations and time constraints are followed by an assessment of expected environmental threats to the mission and the vehicle itself. These include entanglement, silt-out, strong and unpredictable currents, abrasion puncture and shock damage, temperature and pressure variations, toxic substances, corrosion, failure to collect the required data, and the loss of mission secrecy due to signature at the target site.

In Chapter III, the problem space is developed, beginning with the potential stakeholder's effective needs. The resulting needs analysis begins by identifying the stakeholders and carefully considering the value each could receive from an AUV solution to the problem. The needs are refined into effective needs statements for each stakeholder. The chapter concludes with the development of the scope of the mission. The purpose of the effort, division of

future life cycle responsibilities among systems engineering, program management, and Defense Department personnel, and operational context—culminating in the creation of an operational concept graphic, context diagram and definitions, follows. Within the discussion of project scope, the relevant concerns and objectives are developed. The identification of principal concerns begins with a list of the characteristics of a perfect vehicle and a discussion of the key concerns of an actual AUV solution. The system objectives are then discussed, with a mention of the system capabilities outside the scope of the effort of this thesis.

The literature review, contained in the second half of Chapter III, provides detailed discussion of the architecture of some of the most relevant existing AUV systems. The vehicle descriptions and methodologies for DEPTHX, HAUV, ARROWS (including U-CAT) and ACQUAS provide the answer to the critical research question: What are the characteristics of the architecture and methodology employed by existing AUVs for the exploration and mapping of other unexplored three-dimensional environments? Following this analysis, the advantages and disadvantages, with respect to wreck interior exploration, of each vehicle's architecture are generated in four tables. Five primary gaps are identified as follows:

1) vehicle size, shape and weight,

2) vehicle propulsion and control capability,

3) vehicle localization and mapping capability,

4) vehicle data collection, storage and processing capability, and

5) vehicle autonomous decision-making capability.

Chapter IV entails the general functional analysis and requirements generation. The resulting functional decomposition results in 11 primary functions, with sub-functions up to two levels down decomposed from these. In keeping with standard systems engineering discipline, the functions are then mapped back to the effective needs. A requirements analysis follows, resulting in

the generation of 38 general requirements, which are then mapped to the high-level essential tasks. Non-functional requirements are then explored, examining the system attributes of modularity, autonomy, vulnerability, reliability, availability, maintainability, testability, adaptability, affordability, compatibility, interoperability, modifiability, portability, recoverability, reusability, and usability. This results in the generation of 39 non-functional requirements. All requirements are then mapped back to the original stakeholder needs, and seven key performance parameters are established.

1. The vehicle shall be sufficiently small to transit the target submarine (TS) interior, sufficiently smooth to resist snagging on debris, and sufficiently lightweight to be portable by two men.

2. The vehicle shall be capable of autonomous propulsion, with sufficient agility and smoothness for complete environmental sensor coverage throughout the TS interior, without creating unacceptable silt-out conditions and while maintaining continuous awareness of the return route.

3. The vehicle shall continuously map and record the TS interior with sufficient visual resolution and mapping precision to ensure useful intelligence collection.

4. The vehicle shall be capable of sufficient processing capacity or tether-management to permit a complete mapping of the TS interior.

5. The vehicle shall be capable of deciding, autonomously, when and how to defeat an obstacle, collect a target of opportunity, or return to the host submarine (HS).

6. The system shall be interoperable with the host sub in all mission phases.

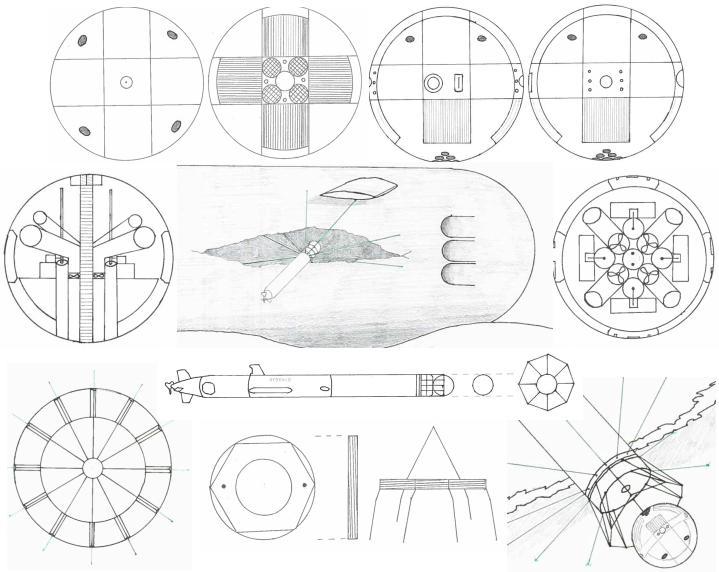
7. The system shall be capable of preserving the secrecy of the mission.

Chapter V harvests the effort sown in the first four chapters by synthesizing one possible architectural solution to the DRM. The chapter begins with an examination of five key architectural tradeoff considerations. After discussing the advantages and disadvantages of tethered and untethered vehicles, vehicle size, vehicle shape, propulsion method, and the use of light

detection and ranging (LIDAR) and sonar, a wreck interior exploration vehicle (WIEVLE) architecture is developed, as shown in Figure 1. The physical architecture elements are described first, followed by the functional architecture elements. The architectural elements are then mapped to the general functional requirements of Chapter IV. The chapter concludes with recommendations for possible future versions of the vehicle. Based on the analysis of existing systems and the problem space, the author recommends that future architectures include the following characteristics:

- small outer dimensions (approximately the size of a basketball)
- smooth, preferably round, solid outer surfaces with flush-mounted sensors
- minimum weight
- tunnel thrusters, or guarded propellers
- maximum sensor freedom of motion and field of view
- minimal required maneuvering for sensor positioning
- robust, reliable and precise mapping and localization capability
- robust and conservative autonomous decision making capability

Figure 1: Wreck Interior Exploration Vehicle (WIEVLE) Architecture



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I. INTRODUCTION

This chapter seeks to build the foundation of this thesis by providing the reader with a brief background to the history of shipwreck exploration, the importance of shipwreck interior exploration, and the context of the work—to include the objective, research questions, and contribution of the study. The chapter closes with the scope, limitations, assumptions, and methodology employed.

A. BACKGROUND

The exploration of shipwrecks has captivated the adventurous for centuries. Technological constraints have limited the exploration of ships lost to the deep until recently in human history. The following sections provide insight into the historical struggle to unlock the mysteries within shipwrecks and the direction of current technological efforts.

1. A Brief History of Shipwreck Exploration

What began as free-diving (diving without the use of air-supply equipment) for goods lost in relatively shallow wrecks transformed over centuries into increasingly sophisticated diving operations. Around 460 BC, Herodotus described a Greek diver named Scyllis who salvaged sunken treasure for the Persian King Xerxes (Acott 1999). Large, heavy diving bells later began to enable divers to breathe for limited periods at deeper depths, thus allowing them to accomplish more salvage work. Around 384–322 BC, Aristotle recorded the use of a diving bell by Alexander the Great (Acott 1999). Little advancement occurred during the next 2,000 years. Acott (1999) states that in 1616, Kessler's diving bell allowed divers to walk on the seabed. Using a diving bell, Treileben and Peckell salvaged 42 cannons in 1640 from the *Vasa*, a Swedish ship, which sank to 132 ft. Acott further states that in 1825, James developed what was likely the first self-contained dive suit. In 1829, Dean conducted salvage work on the

Carn Brae Castle—the first known use of suited divers for salvage work (Acott 1999).

Mysterious illnesses had been occurring for some time with salvage divers working in bells and suits. Divers who worked for too long at depth would often return to the surface to experience crippling pain in their joints, causing them to bend their hands, arms and legs—leading to the name “the bends” for the mysterious illness. The first use of this term occurred during the construction of the Brooklyn Bridge circa 1873, where divers worked at length at depths of approximately 78 ft. (Acott 1999). Acott (1999) states that in 1915, the U.S. Navy published its Diving Tables, which suggested a maximum depth of 300 ft. for dives. These tables were used in the salvage of the *F4* submarine, at a depth of 306 ft., in 1916. Peress developed an atmospheric (or one-atmosphere) diving suit, known as the *Tritonia*, in 1930 and demonstrated its use at Byfleet, England, and at Loch Ness. In 1935, James Jarret dove on the *Lusitania* using the *Tritonia*, at a depth of 304 ft. (Acott 1999). In 1939, Momsen and Wheland published operational heliox decompression schedules. Using this mixture of oxygen and helium, 36 men were rescued from the *USS Squalus*, a submarine that sank to a depth of 240 ft. (Acott 1999).

The mystery and danger of the deep continued to lure explorers from around the world. Diving technology had not yet advanced sufficiently to allow explorers access to the interiors of wrecks. Then, in 1943, Jacques-Yves Cousteau and Emile Gagnan developed the first self-contained underwater breathing apparatus (SCUBA) unit, the *Aqua Lung* (Acott 1999). Not long after the *Aqua Lung* came onto the market, divers began seeking shipwrecks for the adventure and the profits to be made from the salvage of artifacts. In saltwater environments, wooden ships decay quickly; however, many steel-hulled vessels and fresh-water wrecks remain intact long after sinking, allowing divers the opportunity to venture inside. Since many of the desirable artifacts for recovery lay inside these wrecks, divers soon began to enter them—sometimes never to return alive. This is shipwreck penetration exploration. Compared to external

shipwreck survey, the rewards for such exploration, as well as the risks, are great.

2. Importance of Shipwreck Interior Exploration

Today, shipwreck interior exploration is important for reasons beyond the simple thrill of traveling to an extreme environment. The capability to explore shipwreck interiors is potentially beneficial to a number of organizations, including the Department of Defense, the archaeological community, the commercial salvage industry, and agencies concerned with the exploration of marine environments, such as Woods Hole Oceanographic Institute. The following list details some specific examples of the benefit of wreck interior exploration for each of these types of organizations.

- The Department of Defense may be interested in the collection of intelligence from foreign wrecks, the location and salvage of certain objects within wrecks, conducting rescue operations for survivors within new wrecks and conducting hull inspections internally for usability determination or forensic examination.
- Archaeologists may be interested in the capability to systematically explore, map, and recover artifacts from wreck interiors. Artifacts recovered from inside wrecks are sometimes the only way to identify the wreck.
- The commercial salvage industry may be interested in the identification of wrecks as well as the location and recovery of objects within wrecks.
- Exploration organizations may be interested in the development of the technologies and processes necessary for wreck interior exploration.

Despite the potential for this capability, very few options currently exist for granting the explorer or salvager access to these remote places. One new and rapidly developing technological field, however, offers promise. Unmanned undersea vehicles may be the key to unlocking the mysteries of these unreachable places.

3. Unmanned Undersea Vehicles

Unmanned undersea vehicles (UUVs) are a type of unmanned vehicle, similar to unmanned aerial vehicles (UAVs) or unmanned surface vehicles (USVs), all of which are often collectively referred to, albeit non-technically, as drones. UUVs are further divided into two primary categories; remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). ROVs, which have been in operation for decades, depend upon a human operator to pilot the vehicle, and they are typically connected by a fiber optic tether to the host station, which may be located on platforms such as a dock, boat, or submarine. ROVs are generally used for close-quarters operations. The AUV, by contrast, is a much newer form of technology that does not principally rely on a human operator. AUVs are particularly well suited for open-ocean survey missions. The degree of autonomy of an AUV may be variable, depending on the level of control desired.

The development of UUV technology is particularly important to the U.S. Navy. The Deputy Assistant Secretary of the Navy and OPNAV N77 (Submarine Warfare Division) chartered the *Unmanned Undersea Vehicle Master Plan* (UUVMP) in 2000. This document was updated in 2004 with expanded mission and technology recommendations, using *Sea Power 21* for guidance. The latest update has not been made public. Of note, this thesis is directly relevant to two of the nine sub-pillar capabilities established in the UUVMP document: Intelligence, Surveillance, and Reconnaissance (ISR), which ranks first on the list in importance, and Inspection and Identification, which ranks fourth. Of the six recommendations established by the UUVMP, four are particularly relevant to this work: 1) the development of a man-portable (<100lbs) class of UUV, 2) the development of standards and implementation of modularity, 3) the increase of UUV technology experimentation, 4) the fielding of these systems in the fleet.

4. Importance of AUVs

The use of an AUV becomes necessary when a vehicle is required to make decisions and execute tasks without the direct command of a human operator. In the exploration of unknown extreme environments, AUVs are often a crucial tool. An extreme environment is one that is unsupportive of human life, thereby requiring significant technological intervention to protect the explorer from the environment, or requiring complete substitution of the robot for the human explorer. The shipwreck interior environment, the exploration of which is central to this thesis, is an extreme environment. The specific threats posed to a diver or vehicle within the shipwreck interior, as well as the capability gaps of existing technology toward achieving this objective, will be discussed in detail in a later chapter. Some shipwreck interiors are possible to explore using a human explorer with appropriate training and equipment, but many are not. Some AUVs can also operate without the use of a tether, which has drawbacks, but provides the significant advantage over ROVs of reducing the entanglement hazard. Although the use of an AUV to explore shipwreck interiors has not, to the author's knowledge, truly been achieved, the use of an AUV would eliminate the risk of loss of life to the wreck while presenting the potential for efficient interior exploration; thus, it is of great importance to this study.

B. CONTRIBUTION

A sound understanding of the objective of this work, in addition to the relevant research questions it hopes to answer, is necessary before addressing the contribution of this work to the body of knowledge.

1. Objective

The intent of this thesis is to develop, using the systems engineering process, a functional analysis and a set of requirements, key performance parameters, and high-level architectural tradeoffs for an AUV capable of shipwreck interior exploration.

2. Research Questions

The following questions are addressed in this thesis:

- What type of challenging AUV mission might be of interest to the Department of the Navy?
- What high-level alternatives exist for such a mission?
- What are the high-level essential tasks for such a mission?
- What are some of the potential stakeholder's effective needs?
- What would the scope of such a mission look like?
- What are the relevant concerns and objectives?
- What are the characteristics of the architecture and methodology employed by existing AUVs for the exploration and mapping of other unexplored three-dimensional environments?
- What are the corresponding capability gaps?
- What are some of the expected mission constraints, operating environments and threats?
- What are the functions and requirements of an effective AUV solution?
- What key tradeoffs should be considered in the architecture synthesis?

3. Importance to the General Body of Knowledge

This thesis is intended to provide a systematic approach to the development of an AUV architecture suitable for the exploration of shipwreck interiors. The study will provide a set of design requirements, architectural considerations that may prove beneficial for the future development of such a vehicle.

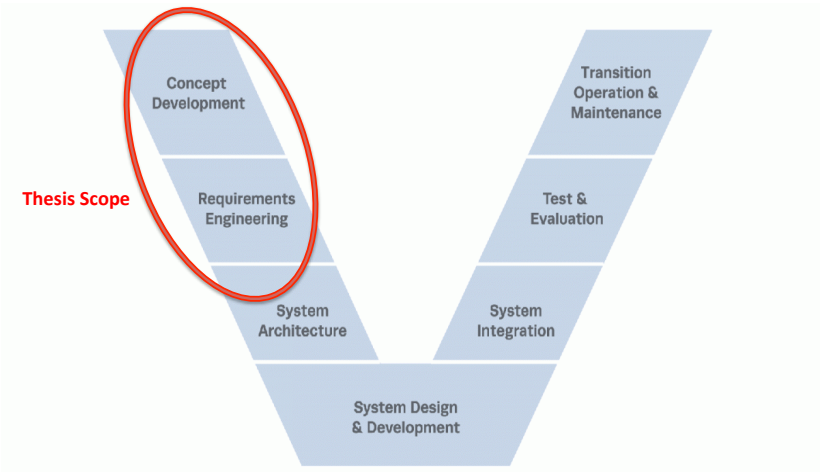
C. SCOPE, LIMITATIONS AND ASSUMPTIONS

Familiarity with the scope, limitations, and assumptions of this thesis will serve as a useful roadmap to the reader and, therefore, deserve brief discussion before developing the research methods in the next section.

1. Scope

The scope of this thesis is contained within the upper-left half of the systems engineering V-diagram shown in Figure 1.

Figure 1. Systems Engineering Life Cycle V-Model



Adapted from: MITRE. 2015. "The Evolution of Systems Engineering." Accessed Nov. 7. http://www.mitre.org/publications/systems-engineering-guide/systems-engineering-guide/the-evolution-of-systems.

The concept development begins with the design reference mission and high-level analysis of alternatives. The stakeholder analysis and project scope define the concept boundaries and objectives. Next, the functional analysis leads to the generation of requirements. Finally, from the requirements, key performance parameters, and architectural tradeoffs are analyzed. This area in the systems development life cycle was chosen as the focus of this work because the lack of AUVs designed for the purpose of wreck interior exploration, or even remotely capable of it, makes the architectural development interesting, highly flexible, and important. The preliminary and detailed design of the resulting AUV architecture would be a fascinating natural progression of this work. It is the author's hope that such a work will benefit from this study.

2. Limitations

Few AUVs exist with anything close to the capabilities required for conducting a wreck penetration mission. Since AUVs themselves are a relatively new technology, little literature exists on the subject of their potential use to explore wreck interiors. That which does is largely represented in the AUV exploration and mapping systems literature review of Chapter III. The author also has limited first-hand experience in the operation of AUV technology. It is the author's hope that this work's references will prove helpful for the AUV system designer seeking knowledge of the technology and techniques required of wreck interior exploration.

3. Assumptions

The intended audience for this thesis is the system engineer, domain engineer, or acquisitions officer interested in the development of an AUV solution to shipwreck interior exploration. A general understanding of the systems engineering discipline is also assumed.

D. METHODOLOGY

The goal of this thesis is to implement the systems engineering process in order to achieve a high-level architectural design for an AUV capable of shipwreck penetration, mapping and surveillance. The primary guidance for the approach pursued in this thesis came from the textbooks *Systems Engineering and Analysis, Fifth Edition*, 2011 by Blanchard and Fabrycky, and *The Art of Systems Architecting, Third Edition*, 2009 by Maier and Rechtin, as well as lecture notes from the courses SE3100, Fundamentals of Systems Engineering, taught by Professor Fotis A. Papoulias and SE4150, System Architecting, taught by Professor Gregory A. Miller at the Naval Postgraduate School in 2014. The principal effort of the thesis lies in the systematic and thorough application the individual tasks of the systems engineering process to the specific reference mission and the communication of the results in the most effective format available. Furthermore, much effort also rests in the capturing of as many

possibilities for a given task as possible. One example is the list of logistical constraints at the end of Chapter III. Many other items could certainly appear on a comprehensive list for a fully developed system. This list simply represents the author's best guess at the considerations most applicable to this work. The remainder of the effort generally lies in the artistic organization of the results of each analysis in a way that is most helpful in communicating the clearest view of the problem space as it develops.

In Chapter II, the process begins with a design reference mission (DRM), a high-level analysis of alternatives, mission planning considerations and the generation of a high-level essential task list. The problem space will then be explored in Chapter III, beginning with an analysis of stakeholder needs and an exploration of the project scope. The literature review will then explore four novel AUVs, identifying important architecture and methodology considerations. Research for the literature review, and other sections containing technology research, is conducted through topic searches using the search engine Google Scholar to locate the relevant academic papers and journal entries. The work by Fairfield et al. is particularly useful for understanding the implementation of simultaneous localization and mapping (SLAM) methodologies of autonomous vehicles operating in unknown three-dimensional environments. The work by Durrant-Whyte et al. is also helpful toward this end. Finally, the work by Salumae et al. is beneficial for insight into the physical design of a wreck-penetration-capable AUV. The literature review incorporates the ideas put forward by these and other authors and organizes the effort toward the goal of defining the requirements of a sophisticated AUV with a specific and demanding mission.

Following the literature review, the capability gaps between the existing and needed technology will be examined. The constraints will be developed, identifying operational conditions and threats. In Chapter IV, a functional decomposition and requirements generation will lead to measures of effectiveness and key performance parameters of an appropriate system

architecture. In Chapter V, architecture tradeoffs will be considered. Finally, in Chapter VI, the conclusion and recommendations for future work will be made.

II. DESIGN REFERENCE MISSION

In this chapter, the design reference mission, upon which the remainder of the thesis is based, is developed. This reference mission enables the subsequent development of a high level analysis of alternatives, general mission planning and the identification of constraints.

A. INTRODUCTION

A design reference mission (DRM) is a systems engineering tool used to assist the development of a new system by providing a representative mission profile. The DRM generated in this section will serve as the basis for the problem space exploration, and the functional analysis and design requirements, to follow. Numerous potential missions for an autonomous vehicle, capable of the internal exploration of shipwrecks, exist. The following reference mission is based upon the circumstances surrounding an actual sinking that occurred in 1989. The details of that event are given in the following section. This particular reference mission was chosen because it represents an extraordinary, rather than most likely, opportunity for the use of an AUV, and, thus, provides the basis for the design of a highly versatile AUV. The wreck described in the following section presents an incredibly challenging mission—far beyond the capability of humans and ROVs. Nevertheless, in order to justify the use of the AUV in a disciplined manner, other possible high-level alternatives will be considered immediately following the reference mission.

B. BACKGROUND

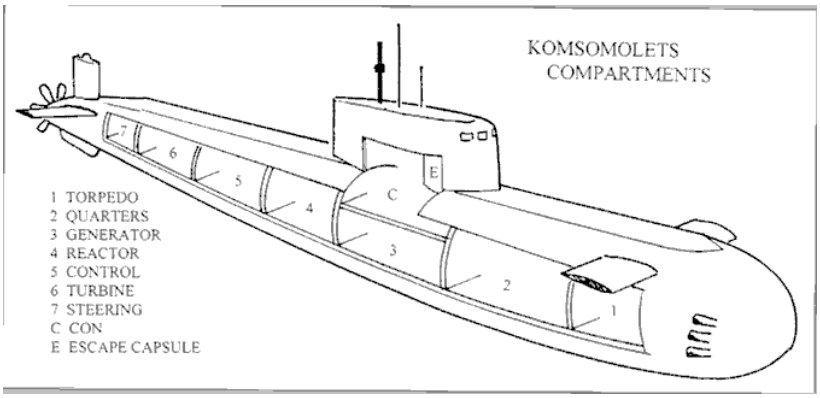
On April 7, 1989, the *Komsomolets* (K-278), a Russian nuclear attack submarine operating in the Norwegian Sea, went down after unsuccessfully fighting a fire in its aft compartment #7 (see Figure 1 under *Target Description*) caused by a ruptured high-pressure air line (Montgomery 1995). Montgomery (1995) notes that the disaster, which killed 42 of 69 crewmembers, sparked intense interest in the intelligence community. The submarine was carrying two

torpedoes with plutonium warheads. The potential for radiation leakage has since caused significant environmental concern. The *Akademik Mstislav Keldysh* oceanographic rescue vessel found *Komsomolets* two months after it sank using its submersibles, *Mir 1* and *Mir 2* (Montgomery 1995). In 1991, the explorers using the *Mir* submersibles determined that the pressure hull was breached in several places, the reactor was slowly leaking, and the torpedo tube hatches were open. Subsequent surveys, using technology including cameras developed at Woods Hole Oceanographic Institute, found additional damage, including a 20 ft. crack in the torpedo compartment hull, possibly caused by an explosion of hydrogen gas leaked from storage batteries. Montgomery also notes that in order to prevent further radiation contamination, the Russian government decided in 1994 to seal the submarine with a gelatinous compound of unknown composition.

C. TARGET DESCRIPTION

According to the Federation of American Scientists (2000), The Russian Navy commissioned *Komsomolets*, the first Russian Project 685 *Plavnik* (Mike-class) submarine in 1984. The technologically advanced double-hulled submarine, described by the Federation as 117.5 m. long, 107 m. at the beam, with an 8–9 m. draft, was to become a test-bed for new technologies, capable of delivering torpedoes as well as conventional or nuclear cruise missiles. The boat is divided into seven compartments, as depicted in Figure 2.

Figure 2. K-278 Structural Layout



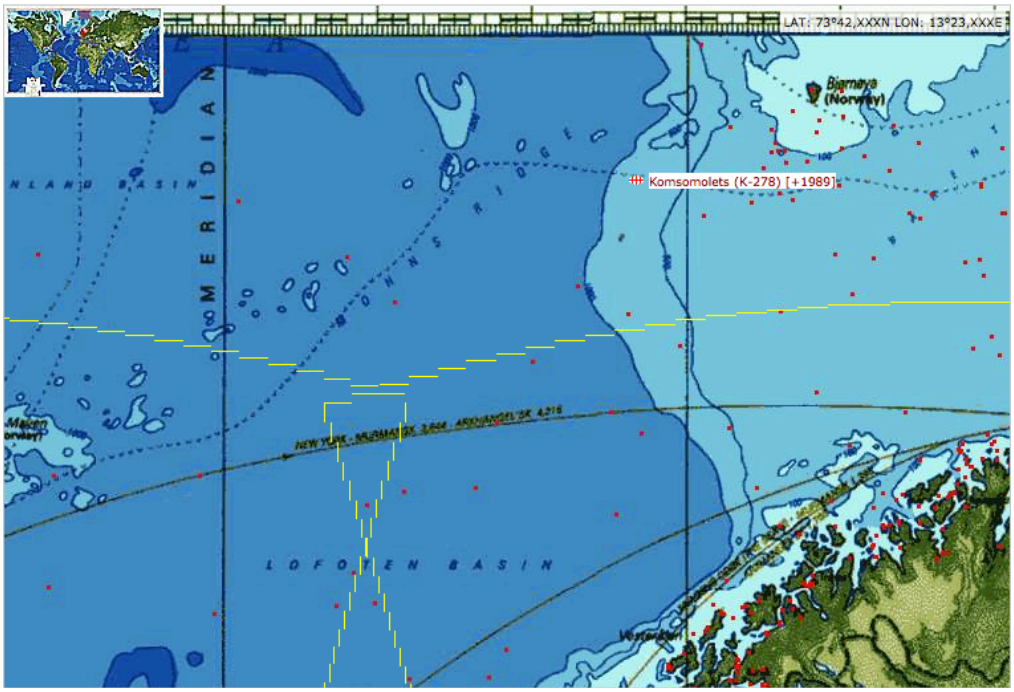
Source: Federation of American Scientists. 2000. "Project 685 Plavnik Mike Class." http://fas.org/man/dod-101/sys/ship/row/rus/685.htm.

The Federation of American Scientists also notes that the submarine was capable of diving to greater depths than any other military submarine—in excess of 3,000 ft.—due to the strength of its double hull, including an inner hull made of titanium. It is believed that the boat used a single 190 MW OK-650 b-3 pressurized water reactor in combination with two steam turbines with a maximum output of 47,000 shp and a single 7-blade screw (Federation of American Scientists 2000). The boat is assumed to have been capable of carrying an unknown number of SS-N-15 Starfish RPK-2 Viyoga and SS-N-16 Stallion missiles with conventional or nuclear warheads. The boat has six 21 in. torpedo tubes that were capable of firing conventional or nuclear-warhead torpedoes. The Federation of American Scientists also writes that the submarine may have employed the Snoop Head surface search radar and the Shark Gill active sonar.

D. ENVIRONMENT DESCRIPTION

K-278 is located approximately 180 miles south of Medvezhy Island (Sagalevitch 1995) on the floor of the Norwegian Sea (approximate LAT: °73°42 LON: 13° 23) as shown in Figure 3 (The Wreck Site 2015):

Figure 3. K-278 Wreck Location



Source: Wreck Site. 2015. "Komsomolets (K-278)[+1989]." Accessed Oct.14. http://www.wrecksite.eu/wreck.aspx?115318.

The continental slope in the area is approximately 1 degree (Hoibraten, Haugan and Thoresen 2003). Hoibraten et al. note that the boat rests at a depth of 1,697 m. on top of approximately 40 m. of sediment. Radiation levels in the surrounding water are low, but may increase as time progresses and materials corrode. The local currents at the site vary, but average approximately 0.2 m/s; the highest velocity recorded was 1.5 m/s. The same authors also note that the temperature at the wreck site is approximately -0.8 deg. C. The total ambient water pressure at this depth is approximately 2,500 psi (Calctool 2008).

E. REFERENCE MISSION

The reference mission for this thesis will incorporate the historic *Komsomolets* target at its actual location in the context of the following clandestine scenario:

Intelligence community sources have recently intercepted the encrypted distress signals of a Russian nuclear submarine. After a subsequent, rapid

search by air and surface assets, the wreck of a Mike-class submarine has been located (an image of the wreck is shown in Figure 4). Valuable intelligence may be recovered from a covert systematic exploration and mapping of the interior of the wreck. An external survey, conducted via a tethered ROV launched from a U.S. submarine shows a large hole in the hull around the boat's midsection, but due the depth of the wreck, the extreme environmental conditions, and the myriad hazards associated with internal exploration, the use of divers is outside the limits of current technology.

Figure 4. Sunken Mike Class Submarine

Source: Federation of American Scientists. 2000. "Project 685 Plavnik Mike Class." Accessed Oct. 14. http://fas.org/man/dod-101/sys/ship/row/rus/685.htm.

The Defense Intelligence Agency wishes to collect platform-specific intelligence from the interior spaces of the target submarine. This may include video reconnaissance of various instruments in separate compartments. Small physical objects of interest have also been identified that may contain valuable intelligence if recovered, and if one or more of these "targets of opportunity" are discovered, a recovery of the object is desired. Additionally, a previously unknown protuberance has been spotted near the bow, upon external survey, that may contain new sensor technology. It is critical that the precise location of all recorded objects of interest be known. To preserve secrecy, it is also critical

that the exploration be conducted at depth and in minimal time, leaving no visible trace of exploration if possible.

1. Primary Objective

The primary objective is to penetrate the submarine and collect intelligence, while mapping the interior spaces.

2. Potential Intelligence Collection Targets

Intelligence sources express specific interest in visual intelligence, which may be collectable via sensors such as cameras, which may include:

- engineering space monitors and equipment, including reduction gear specifics, such as the diameter of shafts and the number of teeth on gears
- SONAR room monitors and equipment
- radio room monitors and equipment
- missile control room monitors and equipment
- control room monitors and equipment, including the periscope
- torpedoes

Further, the sources indicate additional valuable intelligence may be obtained via the recovery of small targets of opportunity, including:

- countermeasures
- emergency distress beacons
- removable media (such as targeting disks) or manuals

F. HIGH-LEVEL ANALYSIS OF ALTERNATIVES

With the DRM established, it is now prudent to consider the potential alternatives to AUVs. This analysis of high-level alternatives aims at the early identification of as many solutions, no matter how radical, as possible. The candidates should be analyzed to in order to justify the selection of the initial design path to pursue. In this section, four high-level alternatives—traditional

human shipwreck penetration, human shipwreck penetration with the aid of atmospheric suits, use of ROVs, and raising the target submarine—will be briefly analyzed by examining their major benefits and drawbacks. Upon conclusion, the selection of the most promising alternative will become the first major design decision and determine the course of the work to follow.

1. Traditional Human Shipwreck Penetration

Perhaps the most obvious option for the exploration and mapping of shipwrecks is the use of human divers. Shipwreck penetration and exploration has, until recently, been the exclusive domain of a very advanced, elite type of diver generally referred to in the diving community as a "technical diver" or "wreck penetration diver" to differentiate the diver from recreational divers who may explore the exteriors of shipwrecks, but do not engage in diving in conditions where decompression is required, the use of a reel and line for navigation is required, or where the escape route is not naturally illuminated. A wreck penetration diver, using closed-circuit rebreathing equipment, is depicted in Figure 5.

Figure 5. A Traditional Wreck Penetration Diver

Source: Richie Kohler. 2015. "A Life Underwater." Accessed Nov. 4. http://www.richiekohler.com/gallery/a-life-underwater/nggallery/page/1.

Wreck-penetration technical divers go to these extreme environments for various reasons, including among them the recovery of artifacts for archeological study or personal gain, the identification of an unknown wreck, and the simple thrill of going to a place so extreme that only a handful of people can venture there and survive. The latter type are like an aquatic version of those who ascend Mt. Everest—in fact, entering the shipwreck *Andria Doria* has been commonly referred to as "the Mount Everest of scuba diving" for years in the technical diving community.

a. Benefits of Traditional Human Shipwreck Penetration

The techniques of wreck-penetration diving have been thoroughly studied and refined over many years, and much knowledge, often written in blood, has been added to the discipline. Until the advent of ROVs, the only way to explore the interiors of shipwrecks was to send a human into that dark and dangerous abyss. Once inside, wreck divers have generated maps, recovered valuable artifacts, and even acquired the data necessary to determine the wreck's name. Thus, the principal benefit of human exploration is that the power of human cognition can be directly inserted into the extreme environment. One need not depend on the robustness of an autonomous vehicle's decision-making algorithm, or on the ability of a remote operator to visually identify a target through degraded media collected by sensors. Certainly, under present technology, the capability of a human diver's problem-solving judgment exceeds that of the autonomous vehicle—but that may not always be so.

b. Drawbacks to Traditional Human Shipwreck Penetration

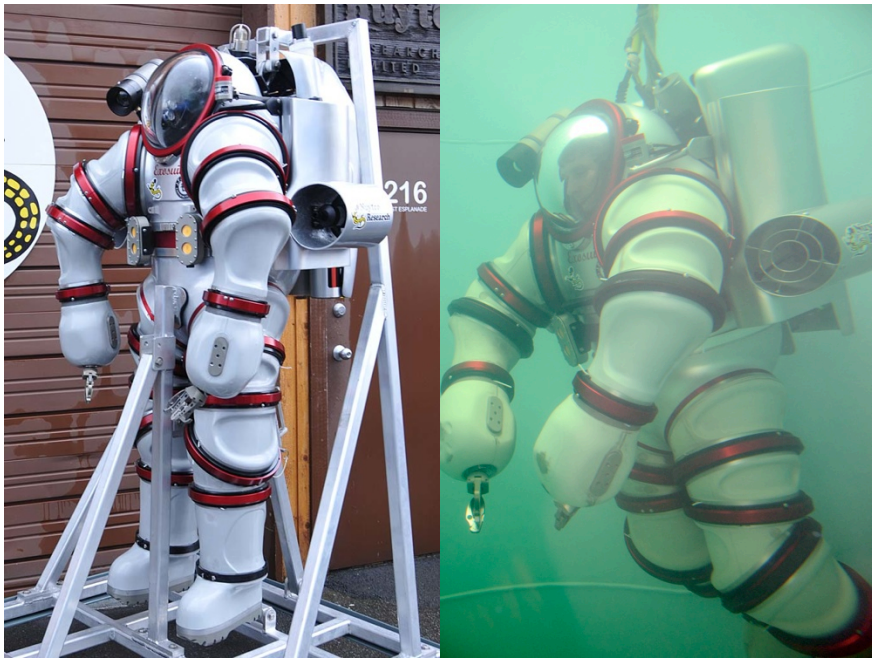
Although the potential benefits are significant, the risk to the diver is extremely high. Altered mental state due to extreme stress and adverse physiological responses to breathing gas mixtures at depth are very real possibilities. Entanglement, limited visibility due to sediment disturbance, injury from cuts and abrasions on sharp wreckage, limited air supply, entrapment due to structural collapse and simply becoming lost are some examples of the many

threats to the diver. The maximum depth technical divers may venture to, which varies greatly depending on the individual diver's equipment and capabilities but is generally much less than a thousand feet, is a significant limiting factor.

2. Human Shipwreck Penetration using Atmospheric Suits

Atmospheric suits enable divers to operate under a single atmosphere of ambient pressure by physically resisting the external water pressure with a hard, exoskeleton-like suit. The complexity of the suit, particularly in the architecture of the joints and internal life-support system, makes these suits relatively expensive and bulky. The atmospheric suit has been around for decades, but recent advancements have made them much more efficient. One of the latest and most advanced designs, the Exosuit, produced by Nuytco Research Ltd., is a particularly capable atmospheric suit. The Exosuit is depicted in Figure 6.

Figure 6. Exosuit Atmospheric Diving System



Source: Nuytco Research Ltd. 2015. "Products: Exosuit The Future of Ocean Exploration." Accessed November 9. http://nuytco.com/products/exosuit/.

a. Benefits of Human Shipwreck Penetration Using Atmospheric Suits

The benefits of diving, in general, with an atmospheric suit are substantial—particularly when a human is needed to directly execute tasks and great depths or lengthy missions are required. The Exosuit is rated to a maximum operating depth of 1000 ft. and uses a carbon dioxide scrubber that can operate for 50 hours (Nuytco 2015). The atmospheric suit eliminates many of the dangers of traditional human technical diving discussed previously. By eliminating the pressure of the water from the diver's chest, the diver is able to breathe air at normal atmospheric pressure. The dissolution of gas in the blood and tissues of the body is not accelerated, and the need to decompress, as well as the threat of the bends or adverse reaction to increased-partial-pressure breathing gasses is eliminated. The Exosuit uses an A536 aluminum alloy shell (Nuytco 2015). The nature of an exoskeleton suit also reduces the chances of injury to the diver from direct contact with the environment.

b. Drawbacks to Human Shipwreck Penetration Using Atmospheric Suits

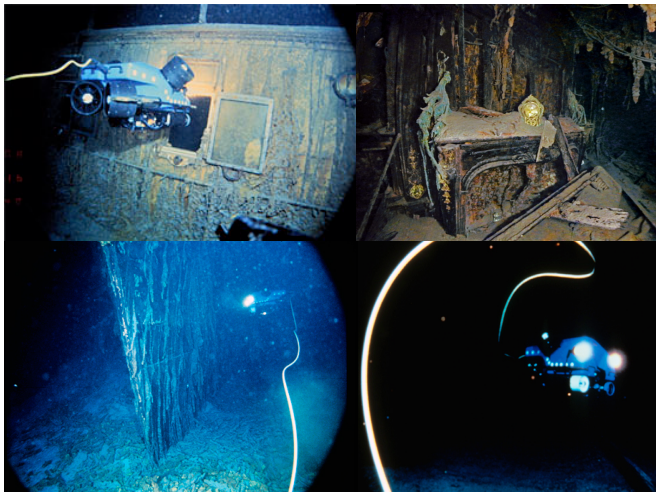
The most obvious drawback to the use of such a suit for the exploration of shipwreck interiors, however, is the bulkiness and corresponding lack of maneuverability required for such an environment. The Exosuit is significantly lighter than predecessor atmospheric suits. Nevertheless, it still weighs between 500 and 600 lbs, depending on the configuration (Nuytco 2015). The bulkiness of the life-support system on the back of the suit, combined with the tether, makes the Exosuit incapable of typical shipwreck penetration missions. It is conceivable that such a system could be used to explore wreck interiors where large, generally entanglement-free areas exist, such as an open hanger deck of an aircraft carrier. It is also conceivable that atmospheric suit technology may continue to advance, producing even lighter, more flexible, and less bulky systems than the Exosuit. Significant advancements, however, seem unlikely given that the need for atmospheric suits is typically driven by the commercial

diving industry, largely servicing open-ocean industrial systems like gas and oil platforms. This type of work, where deep water and lengthy missions combine with the need for direct human intervention in tasks, is ideal for current atmospheric suits and does not demand the extremely low-profile suit that would be necessary for wreck penetration missions.

3. ROV Shipwreck Penetration

Remotely Operated Vehicles are an obvious option for the exploration of wreck interiors. Few ROVs, however, have ever been flown inside a wreck. Perhaps the most famous ROV to be flown inside a wreck was *Jason Junior*, or *JJ*, which was operated remotely via tether from the mini-submersible *Alvin* while exploring the wreck of the *RMS Titanic* in 1986. *JJ* is depicted in Figure 7 along with some of the remarkable images it captured inside that most famous wreck. Although it was an incredible piloting feat, *JJ's* flight into the Titanic was restricted to relatively large, open spaces such as the main stairwell—far more benign than the interior of a submarine.

Figure 7. ROV *Jason Junior's* Exploration of *Titanic's* Interior Spaces



Adapted from: Woods Hole Oceanographic Institute. 2010. "A Titanic Tale: Sellers, William. 2010." A Titanic Tale: A Former Alvin Pilot Recalls His 1986 Dives On the Shipwreck." *Oceanus Magazine*, Sept. 2. Accessed Nov. 9, 2015. http://www.whoi.edu/oceanus/feature/a-titanic-tale; National Geographic. 2015. "Unseen Titanic—Gallery: Then and Now." http://ngm.nationalgeographic.com /2012/04/titanic/cameron-gallery#/5.

a. Benefits of ROV Shipwreck Penetration

ROVs have been used to explore the exteriors of many shipwrecks. The principal benefit to the use of an ROV lies in the ability to control the vehicle directly through the communication link provided by its tether. The operator has access to real-time information, which may include sonar imaging data and high-definition video. The human operator can fly the vehicle, maneuvering around obstacles, collecting samples, and returning to the base station as the operator sees fit. Less processing power and physical space on the vehicle need be devoted to navigation, since the tether can connect the vehicle to essentially limitless processing power at the base station. ROVs are a generally cheaper solution when compared to AUVs, and have been operating effectively in less challenging environments for many years. These benefits make a solid case for an enhanced ROV architecture as a solution to this reference mission.

b. Drawbacks to ROV Shipwreck Penetration

Despite the many benefits of ROVs, significant drawbacks plague this option. The principal drawback to the ROV is also one of its main advantages—the tether. The tether presents a substantial hurdle for the safe penetration of a shipwreck. The risk of entanglement or damage to the tether is severe. If the tether is damaged, complete loss of the vehicle may occur, unless another means of communication, such as through-water radio-frequency communication, is available. Wireless communication through a wreck presents additional logistical concerns. Furthermore, should the tether become entangled, the host vessel is in danger of becoming anchored to the wreck if the tether-jettisoning mechanism fails. Another concern is the lack of sufficient situational awareness for the pilot to successfully navigate the wreck interior. ROVs are typically flown visually, either by direct observation of the vehicle, or through a real-time video feed from the vehicle. If the vehicle stirs up debris within the wreck, or if the field of view is too narrow, the vehicle could become lost or entangled within the wreck.

4. Covert Raising of the Submarine

The covert raising of a soviet submarine was attempted in 1974. The *Glomar Explorer* was designed as a part of an effort by the CIA, code-named *Project Jennifer,* to retrieve the Soviet K-129, a Golf-class diesel submarine that sank in 1968 in approximately 17,000 ft. of water 750 miles from Hawaii (Schindler 2015). According to Schindler, the U.S. Navy intercepted encoded transmissions that indicated that an explosion had taken place, but the submarine was likely mostly intact. The submarine carried a number of nuclear missiles and torpedoes (Schindler 2015). The *Glomar Explorer*, funded by Howard Hughes, was to operate under the cover story of manganese mining operations. The *Glomar Explorer* and a Soviet Golf-class submarine are depicted in Figure 8.

Figure 8. The *Glomar Explorer* and a Soviet Golf-Class Submarine

Adapted from: The National Security Archive, The George Washington University. 2010. “Project Azorian: The CIA’s Declassified History of the Glomar Explorer.” Accessed Nov. 9, 2015. http://nsarchive.gwu.edu/nukevault/ebb305/.

The enormous vessel employed a giant claw designed to lift the submarine. Upon securing the prize within the claw, the entire wreck would be hauled up by cables to a “moon pool” hidden within the *Glomar Explorer* (Schindler 2015). Schindler notes that the operation, however, did not entirely succeed, as the claw became damaged during an impact with the ocean floor and subsequently failed after raising the submarine about a third of the way to

the surface. Part of the submarine was recovered, along with some intelligence, but most of the prize was lost (Schindler 2015).

a. Benefits of Covertly Raising the Submarine

The primary benefit raising the submarine is the more complete collection of contents of the vessel—at least as much of the vessel as is actually recovered. With an intact vessel safely brought into government custody, the systematic, thorough retrieval of material can be conducted. Large items, otherwise unobtainable, such as missiles, torpedoes, reduction gear, or even whole reactors can be obtained. Having the intact submarine is the gold standard for a collection effort.

b. Drawbacks to Covertly Raising the Submarine

The primary drawback of raising the submarine is the sheer magnitude of the effort involved. The expense of a capable host vessel is amplified by the enormous support required and difficulty of keeping such a large operation secret. The simple fact that it has been tried before also decreases the probability of covertly implementing this alternative.

5. Alternative Selection

The severity of this reference mission drives a solid case for the design of a suitable AUV. The depth of the target (in excess of 5,000 ft.) and narrowness of passageways prevents the use of human divers—even those incorporating atmospheric suits. The depth of penetration into, and complexity of, the wreck's interior severely restricts the use of traditional ROV technology. Raising the submarine, a task of immense proportion, would almost certainly jeopardize the effort due to the highly visible nature of such an operation. The decision to proceed with the AUV design effort is justified.

G. MISSION PLANNING

With the selection of an alternative established, general mission planning should be commenced in order to identify the principal assumptions and tasks that will guide the effort.

1. Assumptions

To begin formulating a systematic solution to this assigned task, it is necessary to frame a set of initial assumptions:

- The vehicle is to be launched and recovered covertly, preferably at depth from a large, manned, submersible asset such as a submarine.
- The target submarine is reasonably intact; damage inflicted to the structure from the initial casualty that caused the sinking, as well as the violence of the sinking itself, has not caused the vessel to completely crush or break apart, thus, the vehicle has sufficient internal spaces to explore.
- The submarine has been precisely located, and an external survey, using the vehicle itself or other technology, has been conducted.
- An opening in the hull, large enough for the AUV to enter, exists. If an open hatch or damaged hull opportunity does not exist, a breach of sufficient size to allow vehicle access must be created in advance.

2. High-Level Essential Task List

To successfully execute the assigned mission, the vehicle must possess a number of key capabilities that will be formalized in the requirements analysis to follow. In order to achieve a robust functional analysis, critical aspects of the mission execution must be established. The following high-level essential task list provides the starting point for a functional analysis in support of the primary objective:

1. The submarine will launch the vehicle from depth to preserve the operation's secrecy.
2. The vehicle will navigate to the hull opening, stabilize, and enter the wreck.

3. As the vehicle enters the wreck, it will record the environment using appropriate sensors.

4. The vehicle will systematically record its position as it additively builds the interior map of the submarine.

5. The vehicle will propel itself in a manner that causes minimal environmental disturbance.

6. When an internal space (cavity) has been mapped, the vehicle will maneuver to the next search area and continue the exploration.

7. When the vehicle encounters an obstacle, it will determine the appropriate action to defeat that obstacle, execute the task, and continue or abort the search as necessary.

8. The vehicle will recognize a target of opportunity and collect, or mark that opportunity for future collection, on the map. If operating on a tether, the vehicle may be commanded to manipulate or collect objects, or return to the crew for any reason.

9. If operating untethered, the vehicle will monitor its health and remaining power and return to the crew if unable to continue its mission, upon reaching a minimum power threshold, or upon completion of the mission.

H. CONSTRAINTS

The system must be designed with great consideration for the constraints of the mission. These constraints include a combination of expected operating conditions, logistics considerations, time requirements and threats.

1. Expected Operating Conditions

System operating conditions are defined as “the variables of the operational environment or situation that may affect performance. Conditions impact the ability to perform a task.” (NPS SE3100 Module 2, Slide 22, Spring 2014 Lecture). This section examines the expected operating conditions of the vehicle during the four major phases of the mission.

a. Submarine Loading and Transport Phase

After procurement, the system, and all the necessary support systems, will be transferred to the host submarine. During the transit, the system will likely experience changes in temperature and humidity as it is moved on or off of the submarine. The components will be transported through relatively small hatches, carried through passageways, and hauled up and down ladder wells; thus, it is likely that the system components, in their transportable configuration, will need to be relatively small, and may be inadvertently subjected to shock along the way. During the submarine transport phase, the vehicle and support systems will be expected to be storable in the minimum space practical. Upon deployment for the mission, the vehicle and supporting systems will be unpacked and set up for operations. Interoperability and compatibility with the shipboard environment is crucial to mission success.

b. Submarine Launch Phase

At the beginning of the mission, the vehicle will be launched from the submarine and subjected to rapid changes in temperature and pressure. As the host submarine will be limited in the depth at which it can descend and keep station, the journey to the target submarine is likely to entail a significant change in depth and may require a significant lateral distance to travel as well. The conditions experienced during this phase may include significant increased pressure corresponding to depth change, strong currents with the potential for directional changes, and salinity changes, which may affect buoyancy and sonar operating characteristics.

c. Target Exploration Phase

The target exploration phase begins when the vehicle penetrates the outer hull of the submarine and enters the interior environment. This phase can reasonably be assumed to be the highest-risk phase. The interior sea conditions may be similar to the last stages of the submarine launch phase, at the entrance to the wreck, with an increased risk of entanglement, silt-out, strong and

unpredictable currents, abrasion, puncture and shock damage, and toxic chemicals. Each of these threats will be discussed in turn shortly. The vehicle must operate autonomously once the penetration commences, unless it operates on a tether. The vehicle will continuously localize as it maps the interior, collecting intelligence data via sensors or physical collection until it reaches a decision to return. Upon exiting the hull, the target exploration phase is complete and the recovery phase begins.

d. Recovery Phase

The recovery phase is essentially the reverse of the launch phase—beginning with the vehicle's return to the host submarine. The vehicle must renegotiate all the hazards of currents, pressure, salinity, and buoyancy change, and return to a precise physical location on the host submarine without impacting the submarine's hull or fouling its propulsion system along the way. The physical docking or loading of the vehicle into the submarine presents a risk for shock and physical damage. Once the vehicle is recovered, and before being brought into human contact, it must be tested for radiation or hazardous material contamination, if exposure to such material is suspected, and decontaminated as necessary The data collected must be retrieved from the system and processed. The vehicle must be inspected, cleaned, serviced, repaired and refitted for redeployment or stowed for sea as appropriate. The recovery phase is complete when the vehicle has been brought aboard safely and the collected data has been processed.

2. Logistics

The following list delineates the primary logistics concerns for the mission-execution phase of the system's life cycle.

- packaging for transportation to the submarine facilities
- packaging for transportation onboard the submarine
- submarine interoperability requirements, particularly power and servicing

- hazardous-materials storage compliance for shipboard storage
- maintenance tools, expendables, and procedures
- operator training resources
- spare parts
- data processing tools
- manpower

Each of these items should be considered, with respect to the stakeholder's needs, during the creation of the system requirements.

3. Time Constraints

Although specific time constraints will be dependent on the individual mission, and a prediction of such requirements is outside the scope of this work, the nature of the reference mission requires that the mission be executed with minimal delay. The sensitivity of the mission necessitates the rapid exploitation of the target with the minimum opportunity for the adversary to discover the compromise. The loitering of the host submarine in the wreck vicinity increases the risk to the boat and its crew. Since the vehicle may be required to execute multiple sorties in order to provide adequate intelligence, the process should be initiated as soon as it is safe to do so. The time-sensitive nature of the mission necessitates deliberate planning during the system preliminary design phase to ensure high usability, capability, and reliability.

4. Threats

During the mission-execution phase, the vehicle will be subjected to a host of environmental conditions that may destroy the vehicle or ruin the mission. The interior environment of a shipwreck, especially the one detailed in the DRM, is extreme, and the risk of loss of the vehicle is very high. A thorough understanding of the threats to the vehicle and the mission is essential to a survivable design.

a. Threats to the Vehicle

Any shipwreck interior should be considered a potential operating environment for this system in order to maximize operational flexibility. The general characteristics of shipwreck environments are well known through the experience of technical wreck-penetration scuba divers.

Figure 9. A Submarine Wreck Interior

An example shipwreck interior. This image was taken inside U-869, a WWII German U-boat wreck. Note the complexity of the structure and the hazards imposed to divers and vehicles via entanglement and sediment disruption. Source: Richie Kohler. 2015. “U-869 Gallery.” Accessed Nov. 4. http://www.richiekohler.com/gallery/u-869-gallery/.

The shipwreck interior, such as the one depicted in Figure 9, which has killed divers, is indeed a hostile world. Its lethal factors include:

Entanglement: The sea begins reclaiming the elements of a ship immediately upon her sinking. The increased ambient pressure, along with the violence of the event that caused the sinking, and the crash of the vessel as it impacts the seabed all damage the physical integrity of the wreck. Currents carry

debris and sediment throughout the spaces. Oxidation takes effect rapidly as surfaces never intended for immersion in salt water become exposed under high pressure. Coral and other sea life begin to inhabit and break down the structure. Even in a fresh wreck that has not had a significant period of time to deteriorate, the vessel will likely be oriented on the seabed in a way other than that which it was designed, causing gravitational stresses and a shifting of furniture and other debris, blocking passageways and turning the structure into a labyrinth. The breakdown of the structure causes myriad opportunities for entanglement and other entrapment of vehicles. This is perhaps the greatest risk faced by a vehicle (or diver) attempting to penetrate the wreck.

Silt-out: The ocean currents will begin depositing sediment into the wreck interior as soon as the spaces flood. Over time, the oxidation and breakdown of the materials inside the wreck will further the accumulation. This buildup of sediment is easily disturbed, and when it is, it tends to billow out and fill the cavities of the wreck, quickly reducing the visibility. When human divers penetrate shipwrecks, this disturbance creates a potentially lethal situation should the diver become separated from his guide line. The disturbed curtain of silt becomes opaque quickly, even with the aid of lights. Indeed, lights can often make the situation worse, as the light reflects off of the particles in suspension near the diver or vehicle creating a brown or black glow. Examples abound of this exact phenomena killing wreck-penetration and cave divers. Silt-out is equally dangerous to the successful execution of an AUV penetration mission. The capability to conduct reconnaissance will depend on the use of sensors such as video, sonar or Light Detection and Ranging (LIDAR) imaging—a capability that will be destroyed if the environment is sufficiently disturbed.

Strong/Unpredictable Currents: Local currents occur from the effects of tides, wave action, larger ocean currents and other effects. These currents may be significant during the transit to the submarine entrance. A great deal of power or alternate method of delivery may be required to get the vehicle to the target entrance location efficiently. Once inside the wreck, the vehicle may be subjected

to varied local currents as seawater moves unpredictably through the structure. The Venturi effect may cause a slight current to accelerate through narrowed passageways, possibly creating turbulent effects that may complicate vehicle control. Changes in current flow within the wreck may produce an unanticipated silt-out situation. If the vehicle is subjected to significant currents during the mission, battery capacity and propulsion power will be of great concern.

Abrasion, Puncture and Shock Damage: Myriad opportunities exist for contact between the vehicle and the host or target submarine. During the mission, contact with substances as varied as sharp, jagged metallic structure, monofilament fishing nets, biological gelatinous material, aquatic plants and animal life, oil or fuel deposits, coral, sediment, shredded synthetic materials, and loose piping and wiring are all possible. Any sizeable vehicle will move with sufficient momentum to cause structural damage if it impacts a sharp, hard surface. If the vehicle is tethered for any portion of the penetration operation, and that tether is pulled through the wreck, the tether will almost certainly be subjected to severe risk of severing or abrading.

Temperature Variations: The vehicle will be subjected to temperature variations inherent in deploying from a shipboard environment with an approximate ambient air temperature in the mid 60-degree Fahrenheit range to ocean water that may be near, or even slightly below, freezing. The vehicle may also travel through thermocline layers en route to the target. A rapid temperature change may adversely affect the vehicle in ways such as increasing stress on vehicle components, changing sonar behavior, reducing battery life and power available, reducing material elasticity, and degrading sensor operation.

Pressure Variations: It is commonly accepted that a depth of 33 feet of seawater produces the equivalent of one atmosphere of ambient pressure. Most shipwrecks, therefore, exist at depths of many atmospheres of ambient pressure. At the depth of K-278 (1700 m. or approximately 5,577 ft.), the vehicle must undergo a pressure increase of approximately 169 atmospheres (170 atmospheres of total pressure, or 2,500 psi). Any vacuum or volume of

compressible fluid, such as an air cavity within an exposed sensor, not sufficiently reinforced, may implode.

Toxic Substances: As mentioned previously, the hazards of the shipwreck interior may include fluids and semi-solids as well as solid matter. Deposits of petroleum products such as lubricating oil, grease and fuel, decomposing bodies, and nuclear contamination may be encountered.

Corrosion: As most shipwrecks of interest for the system can be expected to occur in saltwater, corrosion prevention will be a significant concern. Ocean salinity varies significantly from sea to sea. As salinity increases, so does the corrosive effect on the system.

b. Threats to Mission Success

The success of the mission is dependent on much more than the survival of the vehicle. Considerations for the risk of mission failure, given that the vehicle survives to be recovered, include:

- **Failing to collect the required data**: An inability to properly map the target while executing the mission, or generating a map, but silting out the environment so much that it prevents the collection of video, are two possible concerns.
- **Compromising the collected intelligence due to vehicle signature at the target**: Any trace of physical evidence, such as hull breaches or abandoned equipment, may compromise the mission.

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III. PROBLEM SPACE EXPLORATION

In this chapter, the problem space will be examined, in detail, to develop the foundation necessary for a robust architecture synthesis.

A. INTRODUCTION

The first task in this development is the identification of the system stakeholders and their needs. The stakeholder's primitive desires will be refined and condensed into a set of effective needs statements. From the resulting set of effective needs statements, the scope of the project will be defined. In this critical step, system development and implementation responsibilities are divided among the appropriate stakeholders and the corresponding boundaries of the system architects are established. The operational environment and other key system attributes are defined, allowing the context and critical system interfaces to be established. With this knowledge, the principal design concerns are identified early, and in-scope and out-of-scope design capabilities are established in order to prevent scope creep. A review of the applicable literature for existing relevant systems is then presented, with a close examination of the architecture and capabilities of four appropriate AUVs. Following this analysis, the capability gaps are identified. At this point, the design concerns identified in the scope discussion may be validated upon comparison with the actual capability gaps of existing systems. Finally, the system constraints are examined through analysis of the expected operating conditions during each of the four mission phases, logistics concerns, time requirements, and threats to the system and the mission.

B. STAKEHOLDER NEEDS ANALYSIS

The analysis of the needs of system stakeholders is a crucial step in the systems engineering process. Without a thorough understanding of the actual, or effective, needs of stakeholders, the system architects risk developing a solution to the wrong problem. Even with a basic, or primitive, list of stakeholder wishes, the lack of careful consideration of the circumstances behind those wishes may

result in striving toward a sub-optimal solution founded on the natural bias of the stakeholder or the design team. In this section, an analysis of the needs of likely stakeholders is performed, in each case culminating in a needs statement summarizing and condensing the individual stakeholder's effective needs into a single sentence.

1. Stakeholder Identification

A stakeholder may be defined as anyone with a vested interest in the system. This typically includes, at a minimum, clients, users, analysts, and others directly involved in the life cycle of the system. Identification of the system stakeholders is the first step in the stakeholder needs analysis. With a system of the scale and complexity required of this mission, the complete stakeholder list is likely very lengthy. An analysis of the needs of principal stakeholders will suffice, within the scope of this thesis, for the generation of a robust set of design requirements. The author anticipates the following principal stakeholders, and their respective interests, in the context of this DRM (the author makes no claim to the actual interests of any stakeholder in this list):

Intelligence Agencies

- CIA – The Central Intelligence Agency is interested in the collection of intelligence related to Russian strategic assets and the development of new methods to exploit or counter those assets.
- DIA – The Defense Intelligence Agency is interested in the collection of intelligence that may increase the organization's understanding of the capabilities of specific Russian submarine technology.
- DOE – The Department of Energy is interested in the collection of intelligence related to the propulsion and strategic weapons capabilities of the Russian M-class submarine.
- ONI – The Office of Naval Intelligence is interested in the collection of intelligence related to the lethality and survivability of the Russian M-class submarine, the tactics employed by the M-class submarine, as well as the tracking and deception of this and other types of Russian submarines.

Naval Agencies

- COMNAVSUBFOR – The Commander, Naval Submarine Forces is interested in the doctrine, organization, training, materials, leadership and education, personnel, and facilities (DOTMLPF) aspects of the mission that impact the naval submarine community mission, assets and personnel.
- EOD – The naval Explosive Ordinance Disposal community is interested the system's potential for supporting EOD missions and reducing risk through enhanced situational awareness.
- ND – The Navy Diver community is interested in the system's potential for supporting diver missions and reducing risk through enhanced situational awareness.
- Acquisitions – The naval acquisitions community is interested in the DOTMLPF aspects of the system life cycle.

Oceanographic, Exploration, and Research Agencies

- Agencies, such as the National Oceanic and Atmospheric Association (NOAA), Woods Hole Oceanographic Institute (WHOI), and the Office of Naval Research (ONR) are interested in all aspects of the exploration of extreme underwater environments.

Product Development Team

- The system and its subsystems and supporting systems will integrate the products of numerous manufacturers. Among these include the developers of the vehicle's frame, sensors, supporting power and communications equipment, training and operating software, computers, monitors and other logistic equipment.

2. Stakeholder Needs

The purpose of this section is to identify the effective needs of the above stakeholders and derive from them a set of robust needs statements. Typically, primitive needs are refined into effective or capability needs after thorough stakeholder interviews and analysis by the systems engineering team. In this thesis, however, the effective needs are assumed, since, to the author's knowledge, no request for such a system has been published; thus, there are no actual written primitive needs to refine. In a following section, these effective needs will be further transformed into specific engineering requirements.

a. Intelligence Agencies

The intelligence community is primarily concerned with the collection of technical intelligence on the target, as specified in the stakeholder list. The principal areas of concern for the intelligence community can be categorized as follows:

- **Secrecy**: The specific process by which the collection occurs is generally of less importance to the analyst, but it is vital that the collection itself remains secret.
- **Repeatability**: It is desirable for the collection process to be repeatable, should a similar opportunity present itself in the future. A proven new method of intelligence collection may also open up new avenues for collection in other areas.
- **Quality**: Intel analysts need the quality of the information to be as high as possible. The quality of the intelligence collected depends on a number of factors, most importantly, resolution and location precision.

Lessons learned from the successful outcome of the mission may allow analysts to better understand how to protect our own systems from a similar exploitation by an adversary.

Intelligence Agencies Needs Statement: *The intelligence agencies need a system capable of collecting high-quality technological intelligence inside sunken vessels while preserving secrecy, and maintaining the capability to repeat the mission as required.*

b. Naval Submarine Forces Community

The submarine community is primarily concerned with the ability of the system to fulfill its requirements in a manner that imposes *limited cost* to the community's ability to conduct its primary mission: anti-submarine warfare (ASW), or land attack. The principal concern of the submarine commander is the safety of his submarine and crew. Should the commander be tasked with this auxiliary mission, his concern will lie chiefly with his ability to ensure the safety of the platform while executing the assignment as efficiently and effectively as

possible. As the ability to ensure platform safety, as well as mission success, hinges greatly on the ability of the submarine to remain undetected, it is reasonable to assume that the submarine should conduct the operation submerged. The associated needs can be categorized as follows:

- **Interoperability**: The system and its support systems should be fully interoperable with the shipboard storage capacity, power supply, hazardous materials (HAZMAT) requirements, heating and cooling requirements, and acoustic stealth requirements.
- **Physical space**: Given the extremely restricted space of a submarine, the system and its support systems should require as little physical space onboard the submarine as possible.
- **Manpower and training**: The system, and the support systems, should require as few operators and as little training as possible.
- **Mission impact**: The system should create the smallest possible impact on existing platform missions.
- **Risk**: The system should produce the least increase in risk possible to the platform, its crew, and the mission. The mission should be executed while the submarine is submerged. The launch and recovery of the vehicle should be conducted in a manner that prevents the potential for flooding submarine spaces or fouling the boat's propulsion system. The system and its support should contain minimal hazardous or flammable materials.

Naval Submarine Forces Community Needs Statement: *The naval submarine community needs a system capable of conducting the assigned mission, with minimal impact to the primary platform missions and safety, while possessing complete interoperability with host submarine systems, and requiring minimal storage and operating space, manpower and training, mission alteration, and risk.*

c. Naval EOD Community

The EOD community is primarily concerned with the system's potential to support typical EOD missions, to include the surveillance of dangerous submerged spaces. As the organization responsible for the removal and disposal of unexploded ordinance, the EOD community, along with the navy diver

community, is well familiar with the use of remotely-operated and autonomous vehicles. In the context of this reference mission, the EOD community needs the system to be capable of detecting potentially hazardous materials and conditions, while presenting minimal hazards to the operators. The EOD community needs can be categorized as follows:

- **Situational Awareness (SA)**: If EOD divers are to be sent into the exploration environment itself on similar, shallower, missions, the operators need the system to provide maximum situational awareness in the operating environment.
- **Risk**: Risk to the system operators should be minimized through maximum interoperability with the shipboard environment and use of minimally hazardous materials.

Naval EOD Community Needs Statement: *The EOD community needs a system that maximizes support for EOD missions by maximizing operator situational awareness through the detection and localization of hazardous materials and conditions while minimizing risk to operators.*

d. Navy Diver Community

In the context of this mission, the navy diver community's needs are similar to the needs of the EOD community. Although not traditionally concerned with the handling of explosives, an increase in situational awareness delivered by the system is certainly of great use in support of traditional navy diving operations. The diver community is also in need of systems that enhance the effectiveness of activities such as salvage operations, deep-submergence operations, and the inspection and repair of ship and submarine hulls and equipment.

Navy Diver Community Needs Statement*: The navy diver community needs a system capable of enhancing diver operations by maximizing situational awareness and minimizing risk to divers.*

e. Acquisitions Community

The acquisitions community needs to acquire a system that achieves the assigned mission with the highest performance for the lowest cost over the system life cycle. This need typically requires a close examination of system attributes, commonly referred to as the "ilities," familiar to systems engineers.

Acquisitions Community Needs Statement: *The acquisitions community needs a system capable of achieving the assigned mission objective with maximal performance and minimal cost.*

f. Oceanographic, Exploration and Research Agencies

The oceanographic, exploration and research agencies need a system that enables the attainment of knowledge of extreme marine environments and the development of the necessary tools and techniques for exploring them. The successful accomplishment of the mission, as outlined in the DRM, could lead to the collection of important marine environment data. Additionally, this stakeholder needs to understand the effectiveness of hardware and software algorithms in the accomplishment of the mission, as it could aid in the development of alternative systems for use in other environments.

Oceanographic, Exploration and Research Agencies Needs Statement: *The oceanographic and exploration agencies need a system that enables the discovery of new environmental knowledge, new exploration hardware and software algorithms, and new exploration tactics, techniques, procedures (TTPs).*

g. Product Development Team

In general, the product development team needs to accomplish the objective as set forth by the principal stakeholder—the DIA. In doing so, it must design the system with concern for the complete system life cycle. Capability, demonstrated in the effectiveness of the system in executing the items in the high-level essential task list, must be maximized for minimal monetary and

schedule cost. Additionally, the team needs to design a system with the flexibility to ensure the product's attractiveness to future customers.

Product Development Team Needs Statement: *The product development team needs the system to satisfy the primary objective via the high-level essential task list while maximizing performance, flexibility, and desirability and minimizing cost and production time.*

The stakeholder needs are summarized in Table 1.

Table 1. Stakeholder Needs Summary

Stakeholder	**Needs**
1. Intelligence Agencies	1.1. Operational secrecy 1.2. Mission repeatability 1.3. High-quality intelligence collection
2. Naval Submarine Forces Community	2.1. Capability to execute assigned mission objective 2.2. System/Host interoperability 2.3. Minimal space requirements 2.4. Minimal manpower and training requirements 2.5. Minimal host-platform mission impact 2.6. Minimal host-platform risk
3. Naval EOD Community	3.1. Maximal SA enhancement 3.2. Minimal risk to operators
4. Navy Diver Community	4.1. Maximal operational support 4.2. Minimal risk to divers
5. Acquisitions Community	5.1. Capability to execute assigned mission objective 5.2. Maximum system performance 5.3. Minimal cost to government
6. Oceanographic, Exploration, and Research Agencies	6.1. New physical system elements for research 6.2. New exploration methods
7. Product Development Team	7.1. Capability to execute assigned mission objective 7.2. Maximum system performance 7.3. Maximum flexibility 7.4. Maximum desirability 7.5. Minimal production cost

C. SCOPE

The delineation of project scope aids in the generation of requirements, which, when fully articulated, guard against scope creep.

1. Purpose

The scope of the design should delineate the boundaries of the solution space for the stakeholder's needs. It should define what is inside and outside the sphere of influence of the systems engineer. Interfaces and information flows should be identified. Upon the completion of this section, the capabilities that the systems engineer should design toward, as well as those that he should not, should be identified.

The highest-level decision in the design process was completed in the previous chapter, upon the conclusion of the high-level analysis of alternatives. After considering potential forms of data retrieval from the interior of the wreck, to include sending human divers, using ROVs, or raising the submarine, the design of an AUV was decided upon as the most feasible option. Thus, it was from this starting point that the preliminary mission planning and the resulting high-level essential task list grew.

The use of an autonomous vehicle to explore the wreck necessitates the research of existing systems designed for this or similar tasks. That is the purpose of the following section. From this analysis, the determination of capability gaps will provide insight into the principal areas of focus for the upcoming architecture synthesis. At this time, it is prudent to determine the areas of responsibility for the systems engineer in this project effort.

2. Responsibilities

The DOD acquisitions community uses the acronym DOTMLPF to enhance understanding of the magnitude of the effort required to undertake a particular project. The doctrine, organization, training, materiel, leadership and education, personnel and facilities required to develop, produce, sustain, and

dispose of a new system during its life cycle can be roughly assigned to three entities—the systems engineering team, the program management team, and the principal stakeholders who will purchase and use the system. For this AUV development project, the responsibility can be delegated as shown in Table 2.

Table 2. Project Division of Responsibility

	Consideration	Meaning	Responsibility
D	**Doctrine**	**How will the system be employed?**	**Systems Engineering**
O	Organization	How will the project effort be divided?	Program Management
T	**Training**	**How will the user train to use the system?**	**Systems Engineering**
M	**Materiel**	**What logistics are needed to use the system?**	**Systems Engineering**
L	Leadership and Education	Who will be in charge of the operation and training?	DOD
P	Personnel	Who will be assigned to the project?	DOD
F	Facilities	What facilities will be needed to use the system?	DOD

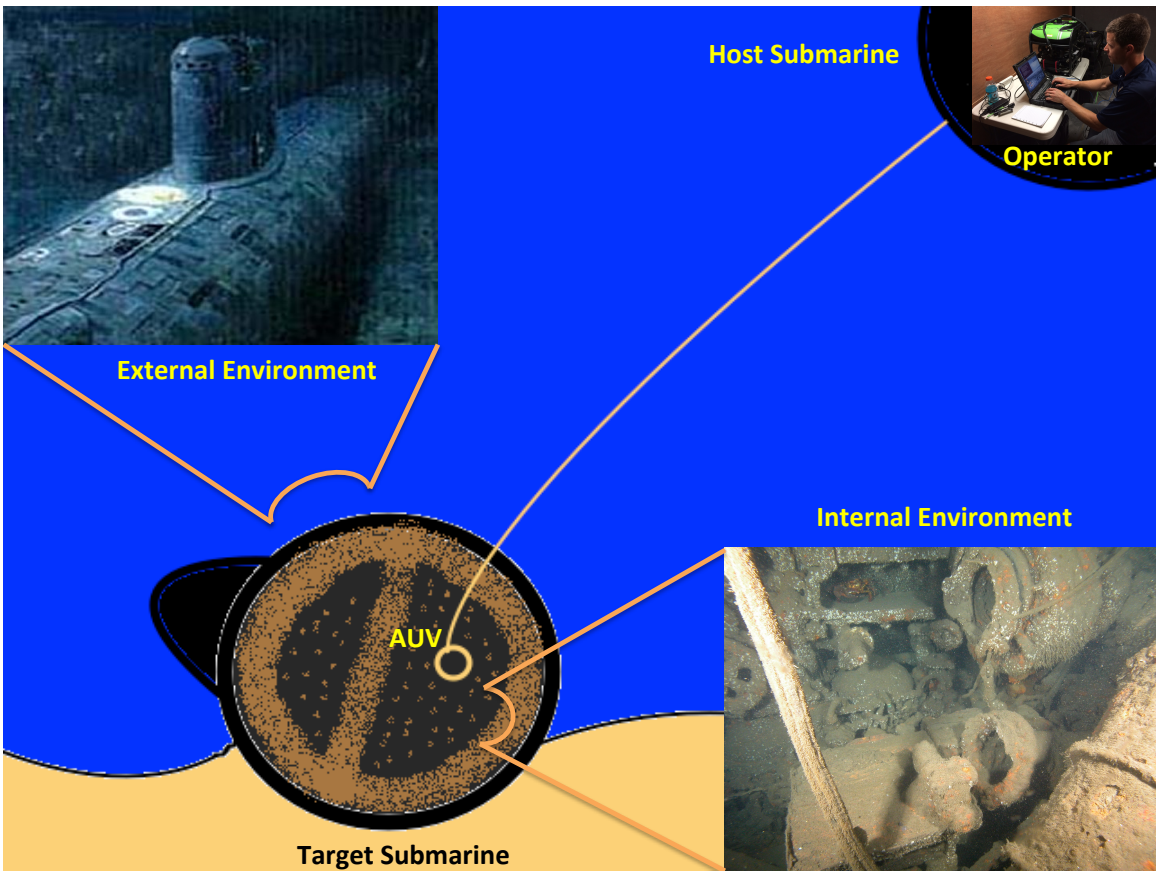
Note that the three principal areas of concern for the systems engineering team, and for the purpose of this thesis, include doctrine, training, and materiel. How the system will be employed, how the user will train to use the system, and the logistics needed to support the system are directly related to system architecture.

3. Context

It is necessary to clarify the system boundary. At this point, the system boundary shall be defined as the operational environment, the vehicle itself, the supporting physical systems, the necessary logistics, and the doctrine and training necessary for system operation. The operational environment includes the host submarine, the open ocean between the host submarine and the target

submarine, and the interior spaces of the target submarine, as shown in the operational concept graphic view given in Figure 10.

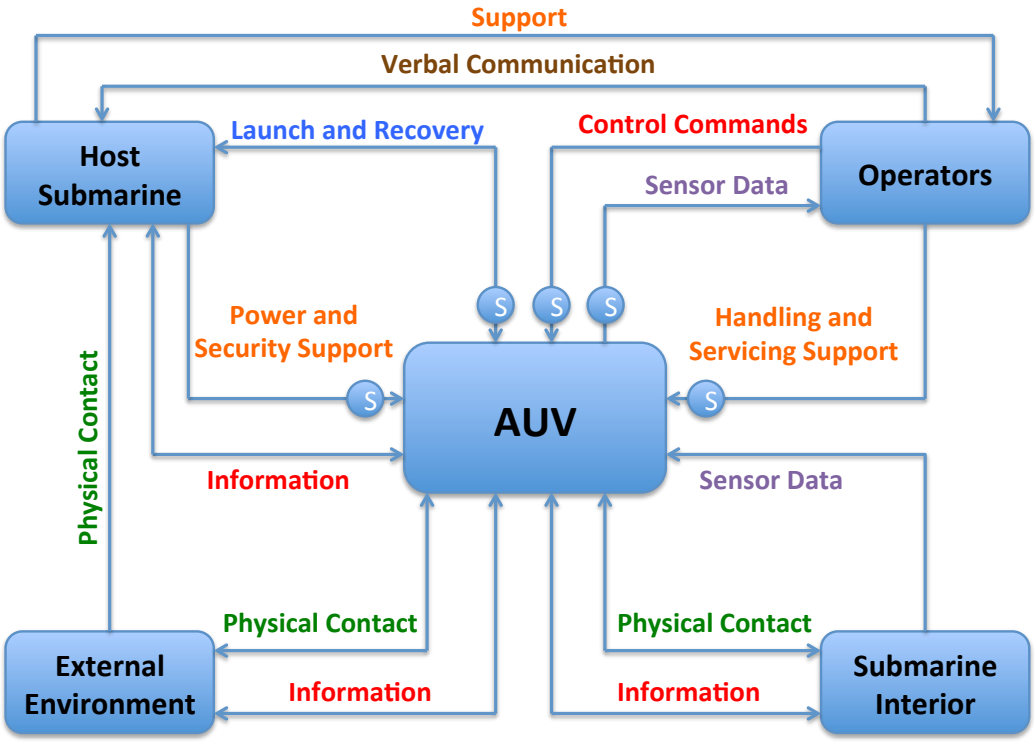
Figure 10. Operational Concept Graphic



Adapted from: Richie Kohler. 2015. "U-869 Gallery." Accessed November. http://www.richiekohler.com/gallery/u-869-gallery/; Federation of American Scientists. 2000. "Project 685 Plavnik Mike Class." Accessed Oct.14, 2015. http://fas.org/man/dod-101/sys/ship/row/rus/685.htm.

The context diagram view, shown in Figure 11, identifies the principal physical constituents of the operational environment and the corresponding interface relationships. Related interfaces are categorized by colors to augment conceptualization. Six of the interfaces occur through the physical support systems (located onboard the host submarine) and are indicated by the blue circle with white "S." This physical support system includes such items as computers, monitors, tether, piloting controls and similar hardware and software.

Figure 11. Context Diagram



4. Definitions

The definition of the operating environment, vehicle, and support system is helpful in delineating system boundaries.

- **The operating environment is**: The host submarine, the target submarine, and the open ocean between them
- **The operating environment is not**: The external support facilities and modes of transportation to and from the host submarine
- **The vehicle is**: The AUV responsible for wreck penetration and surveillance
- **The vehicle is not**: Any delivery system, autonomous or not, that does not penetrate the wreck, or any umbilical cord or similar interface with systems external to the target submarine
- **The supporting system is**: All system components carried onboard the host submarine except the vehicle itself

- **The supporting system is not**: Any physical part of the vehicle or training and maintenance supplies not carried onboard the host submarine

5. Identification of Principal Concerns

Continuing the exploration of the problem space, it is useful to ask, “Given the mission, what might a perfect vehicle look like?” By identifying the optimal design characteristics, the resulting list of attributes enables the architect to more easily understand the project’s most significant architectural challenges, as well as the likely areas of concern.

Characteristics of the Perfect Vehicle

- costs little
- requires little training to operate
- requires no operational impact to the host submarine
- leaves no trace behind on the target submarine
- has an unlimited electrical power supply
- completes the mission rapidly
- has unlimited processing power and speed
- never gets lost—maintains perfect localization capability
- makes perfect obstacle decisions
- never silts out the environment
- collects perfect sensor data
- launches and recovers seamlessly with the host submarine

This wish list likely contains few, if any, feasible items; however, from it the following preliminary key concerns can be identified:

Key Concerns

- risk
- interoperability

- electrical power
- data-processing power
- decision-making fidelity/autonomy
- maneuverability
- anti-silt-out propulsion
- sensor capability

Certainly, as the complexity and cost of the vehicle increases, so does the risk associated with the very real possibility of losing the vehicle inside the wreck. Interoperability of the vehicle with the host submarine is also a non-trivial matter. As the caretaker of one of the nation's most powerful and expensive war assets, the submarine commander builds his career upon conservative operations and strict adherence to protocol. The vehicle must adhere to the resulting potentially stringent interoperability requirements. Electrical and processing power—both key concerns for obvious reasons—will be largely dependent on the key design decision of whether or not to incorporate the use of a tether. The use of a tether may spawn arduous tether-management concerns to avoid entanglement within the wreck. The use of a tether also greatly increases system decision-making capability by linking the vehicle to a human operator. Additionally, the tether may provide power and reduce the necessary physical space allocated to the vehicle's battery. Forgoing the use of a tether will remove this particular entanglement concern and likely increase the vehicle's agility; however, it will also introduce the problem of limited onboard data-processing capacity. Software development will be a major challenge, as the decision-making capacity of autonomous vehicles is limited, and the challenges imposed by defeating obstacles in the interior environment is not trivial even for human divers. Similarly, translation and attitude control without the disturbance of sediment and the implementation of sensors with the resolution necessary to accomplish the mission will contribute much to the challenges of the engineering team.

6. System Objectives

Now that an understanding of the responsibilities, context and principal design concerns for the mission has been established, a list of desired capabilities, or objectives, that the architects can design to should be developed. This preliminary list is not comprehensive, but rather, the best starting point for the iterations to follow.

System Objectives

- interoperability with the host sub in all required mission phases
- ability to transit to (or be transported to) the target submarine
- ability to transit the interior spaces of the target submarine
- ability to map and record the interior spaces
- ability to identify small physical targets of opportunity
- ability to determine how, or whether to attempt to, collect a target of opportunity
- ability to conduct a comprehensive search
- ability to determine how, or whether to attempt to, overcome an obstacle

Similarly, it is important to identify some capabilities that, although inherently good, are outside the scope of the stakeholder's effective needs and, therefore, not desirable to expend design effort upon. Avoiding designing for these capabilities, which are listed below, and other, similar distractions, is key to preventing scope creep, regardless of how technologically interesting the results might be.

System Capabilities outside the Scope of the Effort

- ability to transit long-distance open water space
- ability to defeat heavy obstacles
- ability to collect large artifacts

The ability to transit long distances in open water, i.e., much longer than the required distance between the host submarine and target wreck, may increase flexibility, but would require significantly greater power capacity or tether lengths. Similarly, the ability to defeat heavy obstacles, such as the ability to breach a hull, or collect large artifacts, would likely require excessive size or power capacity for the primary mission of interior exploration.

D. AUV EXPLORATION AND MAPPING SYSTEMS LITERATURE REVIEW

In this section, the architectures of four key AUVs will be examined.

1. Introduction

The four AUVs discussed in this section were chosen because their designs are the closest in existence to achieving a shipwreck-penetration capability. Their architectures vary widely, as do their costs and capabilities. To the author's knowledge, these few systems are the most relevant AUVs currently in existence. AUV technology is, after all, relatively new. Through a thorough examination of the available literature regarding these systems, their successes, and their shortcomings, a better understanding of the capability gaps, and their corresponding requirements, can be attained.

2. DEPTHX

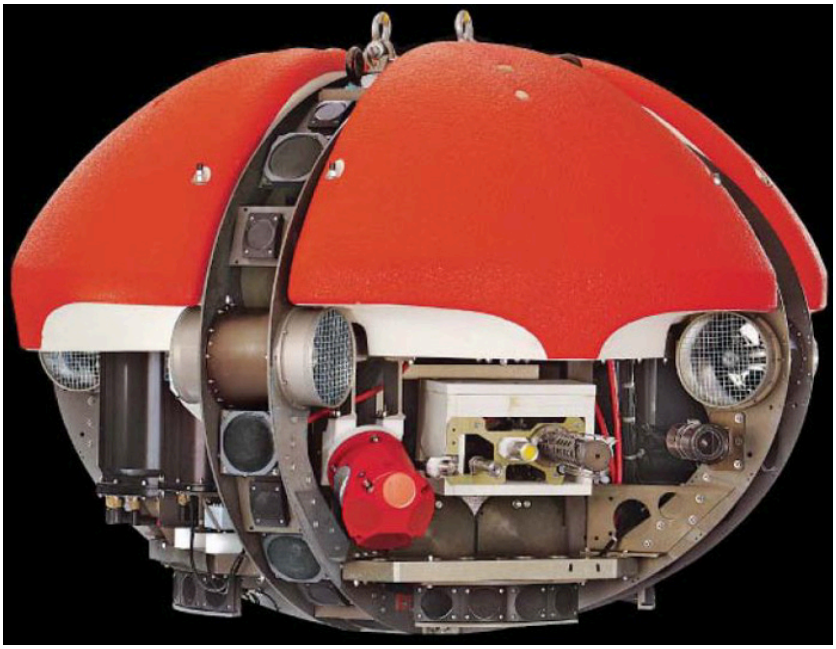
The Deep Phreatic Thermal Explorer (DEPTHX) autonomous underwater vehicle, created by Stone Aerospace, has been used to map the Zacaton underwater sinkhole (cenote) in Tamaulipas, Mexico (Stone Aerospace 2010).

a. Vehicle Description

DEPTHX is one of two generations of AUVs developed by Stone Aerospace. DEPTHX was designed to explore extreme environments such as the deep hydrothermal vents and sub-glacial lakes in Antarctica (Stone Aerospace 2010). The vehicle was designed to explore these areas for the first time—thereby testing the ability of a fully autonomous system to explore and

map true 3D environments where no previous maps have been developed or navigation aids deployed (Stone Aerospace 2010). According to Stone Aerospace, the vehicle was developed as part of a NASA effort toward a mission to explore a sub-surface ocean on Europa. Additionally, the company claims the vehicle achieved three remarkable accomplishments, including being the first mobile robot to implement 3D-SLAM, the first AUV to explore a subterranean cavern and produce a map of it, and the first robot to decide, autonomously, when, where, and how to collect specimens (Stone Aerospace 2010). The fully-assembled vehicle is shown in Figure 12.

Figure 12. DEPTHX

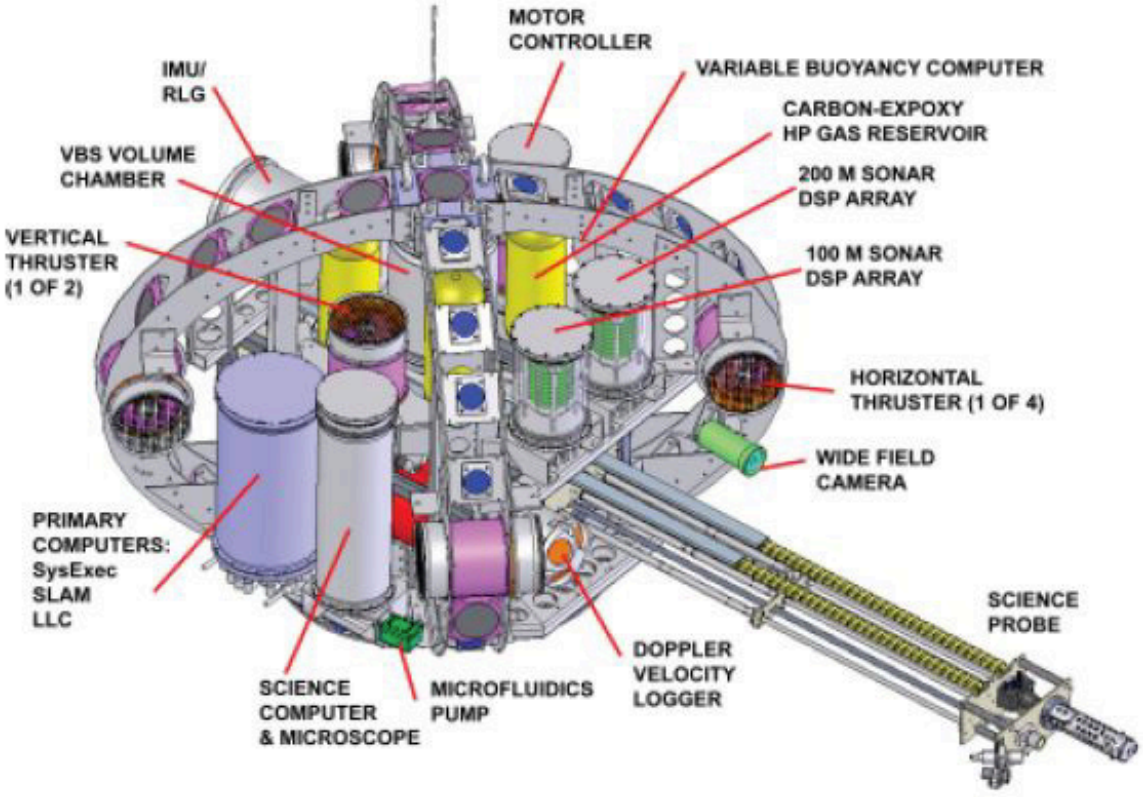


Source: Stone Aerospace. 2010. "DEPTHX (DEep Phreatic THermal eXplorer)." Accessed Oct. 19, 2015. http://www.stoneaerospace.com/products-pages/products-DEPTHX.php.

The vehicle's axisymmetric, ellipsoid shape is ideally suited to SLAM and prevents snagging on objects (Stone Aerospace 2010). The vehicle's major axis is 2 m., its minor axis is 1.5 m., and its total weight is 1.35 metric tonnes (Stone Aerospace 2010). The vehicle's center of mass is significantly separated from the center of buoyancy, permitting resistance to pitch and roll and allowing the

vehicle to be modeled as a 4 DOF, uncoupled system (Stone Aerospace 2010). The internal component architecture is shown in Figure 13.

Figure 13. DEPTHX Internal Architecture



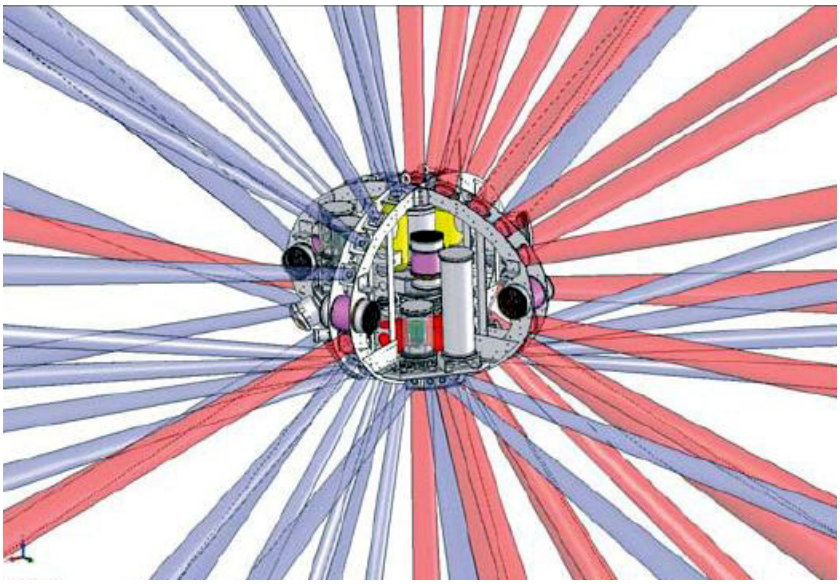
Source: Stone Aerospace. 2010. “DEPTHX (DEep Phreatic THermal eXplorer).” Accessed Oct. 19, 2015. http://www.stoneaerospace.com/products-pages/products-DEPTHX.php.

The vehicle is designed for precise movements in the X,Y,Z, and yaw degrees of freedom (Stone Aerospace 2010). Yaw and pitch are intentionally damped for instrument-position stability. The vehicle uses two independent systems for navigation—the dead-reckoning sensor suite and 3D SLAM sensors (Stone Aerospace 2010). The DEPTHX dead-reckoning sensor suite includes the Honeywell HG2001 inertial measurement unit (IMU), an RDI Navigator 600 Doppler velocity log (DVL), two Paro-scientific Digiquartz depth sensors, and a conductivity, temperature, and depth (CTD) sensor (Fairfield et al. 2007). The CTD sensor measures the local speed of sound in order to correct DVL velocity

measurements. The quality of the dead-reckoning solution can be very good (0.5% of distance traveled), however, over the course of a multi-hour mission, the error will increase to unacceptable levels in operations in tunnel systems (Fairfield et al. 2007). According to Fairfield et al., the dead-reckoning sensors provide excellent measurements in pitch, roll, yaw, and depth (z). Only the x and y coordinates remain highly dependent on the SLAM methodology, which is discussed in the next section (Fairfield et al. 2007).

The DEPTHX pencil-beam sonar array produces a constellation of ranges surrounding the vehicle (Fairfield et al. 2007). A total of 54 sonar sensors are used in three separate great circles around the vehicle. Design of the sonar beams in a circle around the vehicle is very important for the SLAM methodology because, unlike cylinder arrays, circular arrays allow the sensors to observe features the vehicle has already mapped (Fairfield et al. 2007). Fairfield et al. note that the inability to observe previously-mapped features causes additive error in SLAM. Feature detection is difficult, nonetheless, because the array does not have the point density, resolution, or update rate of a laser scanner (Fairfield et al. 2007). Despite the difficulties, DEPTHX demonstrates a SLAM accuracy of approximately one meter within a 500 m. cube (Stone Aerospace 2010). A depiction of the sonar coverage of the DEPTHX arrays is given in Figure 14.

Figure 14. Acoustic View of the DEPTHX Arrays



Source: Stone Aerospace. 2010. "DEPTHX (DEep Phreatic THermal eXplorer)." Accessed Oct.19, 2015. http://www.stoneaerospace.com/products-pages/products-DEPTHX.php.

Processing power was limited, at the time of the Fairfield et al. 2007 article, to 1 Gb of RAM and 1.8 GHz processor speed (Pentium M). The SLAM update rate is limited to the sonar array cycle time of 1 Hz. Fairfield et al. state that sensor degradation or failure is coped with by continuing in a localization-only mode that does not update maps, or by adjusting the particle count to maximize the number of particles. The Rao-Blackwellized particle filter is combined with evidence grids for map representation (Fairfield et al. 2007).

b. Methodologies

Dead Reckoning*:* Fairfield et al. state that inertial, depth, and Doppler-velocity sensors are typically used by AUVs for the task of dead-reckoning navigation. According to the authors, most navigation systems for underwater vehicles also incorporate Kalman Filters (Fairfield et al. 2007). These filters combine the inertial measurements with Doppler velocity. While operating with access to the surface, GPS updates are typically used to reduce drift error. According to Fairfield et al., Long Baseline (LBL), beacon-based positioning

systems can also serve this task. In the exploration of restricted, 3D environments such as caves or wrecks, however, LBL or GPS navigational assistance is unavailable, thus, other methods are necessary.

SLAM Methodology*:* Simultaneous Localization And Mapping (SLAM) is a key methodology for the use of autonomous vehicles to localize and map areas for exploration (Durrant-Whyte and Bailey 2006). Using SLAM, an autonomous vehicle can generate a map of its environment and simultaneously deduce its location from that map. Both the vehicle trajectory and the landmark locations are estimated without any prior knowledge of the location. Since neither the vehicle nor landmark locations are precisely known, a probabilistic approach is used in the methodology (Durrant-Whyte and Bailey 2006). Error between the true and estimated landmark positions is common and due to sensor error, which is particularly problematic under water, and the uncertainty of vehicle location at the time of the landmark observation. Thus, the landmark localization errors are highly correlated. The correlations between estimates of landmark positions increase monotonically with increasing observations. According to Durrant-Whyte et al., this is a critical revelation; understanding of the relative position of landmarks continually improves, no matter the path of the vehicle. The SLAM problem has several solutions, which are described in the following paragraphs. These solutions provide a representation of the observation model as well as the motion model in order to allow efficient computation of time and measurement updates (Durrant-Whyte and Bailey 2006).

EKF SLAM*:* The most common solution is the Extended Kalman Filter (EKF), which uses a linearized state-space model and incorporates Gaussian noise (Durrant-Whyte and Bailey 2006). EKF SLAM is very well known, as extended Kalman filters have been commonly used in other navigation and tracking problems. However, according to Durrant-Whyte et al., it has several drawbacks, including:

- **Convergence**. Initial vehicle position and observation uncertainties determine a lower bound toward which individual landmark position variances converge.
- **Computational Effort**. The joint-covariance matrix and all landmarks must be updated upon each observation, leading to a quadratic computational growth with the quantity of landmarks.
- **Data Association**. When the vehicle returns and re-observes landmarks after traveling a long distance, EKF SLAM is vulnerable to incorrect association of landmarks to observations. This is especially true in environments where complex landmarks look different when viewed from different directions.
- **Nonlinearity**. Inconsistent solutions can be generated when using a linearized model of nonlinear observation and motion models.

FastSLAM: An important alternative to EKF SLAM is the Rao-Blackwellized particle filter, also known as FastSLAM (Durrant-Whyte and Bailey 2006). This method describes the vehicle's motion model as a collection of samples of more general non-Gaussian distributions. According to Durrant-Whyte et al., FastSLAM is a fundamental design shift for recursive probabilistic SLAM. This method is based on Monte Carlo sampling, also known as particle filtering. Maps produced via FastSLAM represent a collection of independent Gaussian distributions, with linear complexity (Durrant-Whyte and Bailey 2006). This key property is the reason for its speed. Nevertheless, FastSLAM suffers degeneration caused by an inability to forget past measurements. FastSLAM empirical results, in actual outdoor environments, demonstrate accurate map-making capability in practice (Durrant-Whyte and Bailey 2006).

Marine SLAM*:* Fairfield et al. describe their use of SLAM to bound inherent dead reckoning error and allow the use of a completely self-contained vehicle to map an underwater environment (Fairfield et al. 2006). The resolution needed to recognize features is difficult to achieve in underwater sensors. According to Fairfield et al., a number of strategies for implementing underwater SLAM have been developed, including:

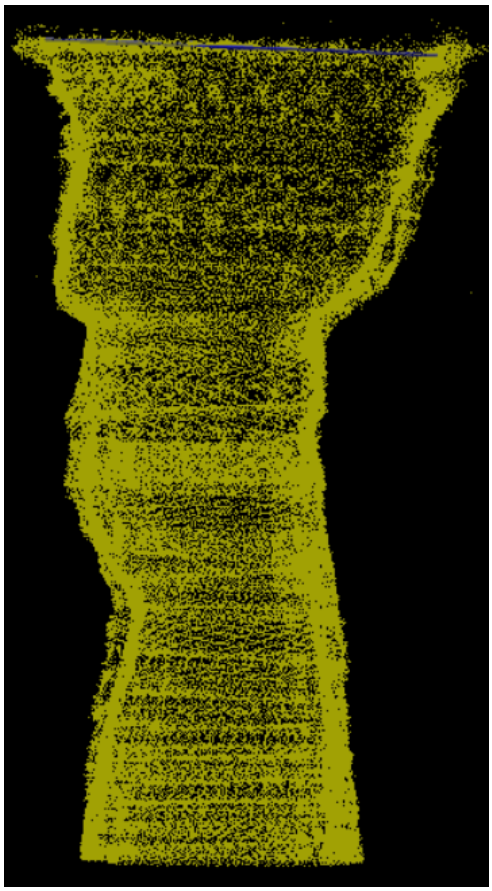
- Use of tunnel cross-section (slide) images derived from sonar. This method works as long as the environment is tunnel-shaped.

Scanning sonars are effective where free-floating artificial features exist.

- Video mosaicing, along with combined sonar and vision-based feature detection works well in well-lit, clear water.
- Synthetic Aperture Sonar (SAS) has been used in a range-and-bearing variant of SLAM effective for large, monotonous regions of water.

A 3D SLAM map of the first 200 m. of the Zacaton cenote generated from the DEPTHX sonar sensors is shown in Figure 15.

Figure 15. 3D SLAM Map of the of the Zacaton Cenote



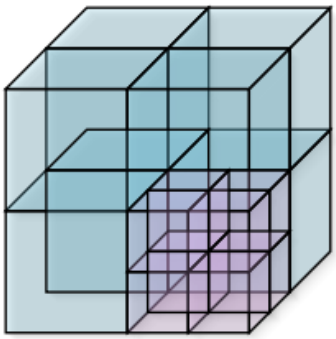
Source: Fairfield, Nathaniel, George Kantor, and David Wettergreen. 2006. "Towards Particle Filter SLAM with Three Dimensional Evidence Grids in a Flooded Subterranean Environment." ***In*** *Proceedings 2006 IEEE International Conference* on *Robotics and Automation,* 2006, 3575–3580.

SLAM vehicle position error was shown by Fairfield et al. to be a significant improvement over simple dead reckoning. Fairfield et al. note that it is also important that the position error is bounded, unlike dead reckoning error, which, predictably, continues to grow with time. Handling the large quantities of data needed to generate high-resolution maps of 3D environments, and the necessary performance of underwater sensors to achieve that performance, is a significant concern (Fairfield et al. 2006). A solution to the organization of data is discussed in the next section.

3D Evidence Grids and Octree Data Storage*:* An evidence grid (also called an occupancy grid) is a world-view representation in which space is divided into cubic volume elements called voxels (Fairfield et al. 2007). Fairfield et al. explain that the voxels, which contain occupancy evidence generated from the vehicle's sensors, are arranged in a grid. Because of the increased number of storage cells, upgrading a 2D evidence grid to a 3D grid is data intensive. Independence is assumed between neighboring voxels and individual sonar measurements. The independence assumption is necessary to prevent the evidence grid from becoming intractable, but the cost is noisy maps in response to measurement ambiguity (Fairfield et al. 2007).

The magnitude of the data required to update 3D occupancy maps, especially at the rates needed for near real-time SLAM, require a data structure more efficient than the uniform array (Fairfield et al. 2007). An octree is such a solution. In an octree, the environment is divided into eight cubes. Each cube can be further broken into eight more sub-cubes and so on until the finest resolution required is reached (Fairfield et al. 2007). Figure 16 illustrates the octree principle.

Figure 16. Octree Data Structure



Source: Fairfield, Nathaniel, George Kantor, and David Wettergreen. 2007. "Real-time SLAM with Octree Evidence Grids for Exploration in Underwater Tunnels." *Journal of Field Robotics* 24, no. 1 (2007): 3–22.

Octree data storage significantly reduces the large data-capacity requirements of 3D SLAM since any given environment contains a great deal of homogenous space. Any large homogenous portion of space can be represented by one octnode, thus truncating children octnodes of the same value (Fairfield et al. 2007).

3. HAUV

According to Vaganay et al., the Hovering Autonomous Underwater Vehicle (HAUV) project began in 2002 as a joint effort of the Bluefin Robotics Corporation (Bluefin) and the Massachusetts Institute of Technology Sea Grant AUV Laboratory (MIT-SG) under the funding of the Office of Naval Research (ONR).

a. Vehicle Description

The purpose of the first prototype, which incorporated Dual Frequency Identification Sonar (DIDSON) as its primary search sensor, was to autonomously conduct searches of naval ship hulls using a hull-relative navigation methodology and identify potential threats such as mines and improvised explosive devices (IEDs) (Vaganay et al.). HAUV-1A and HAUV-1B were the result of this effort, participating in demonstrations from 2006–2009. Direction from the U.S. Navy's PMS-408 office, via the Explosive Ordnance Disposal Hull Unmanned Underwater

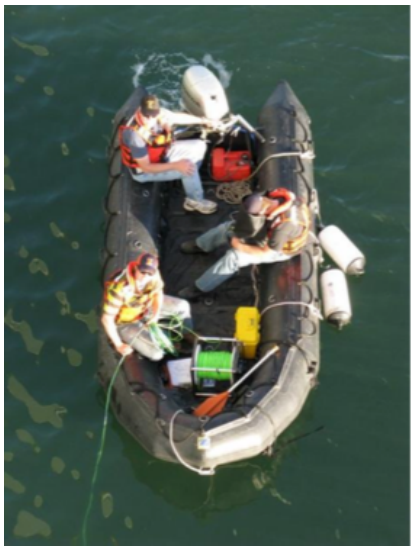
Vehicle Localization System (EOD HULS) program, resulted in the 2008 delivery of HAUV-2, which incorporated a dual-axis sensor rotation capability. Vaganay et al. state that further refinement in speed capability, weight reduction, and the ability to direct the sonar to either starboard or port, led to a dramatic form change and the birth of HAUV-3, shown in Figure 17.

Figure 17. HAUV-3

Source: Vaganay, Jerome, Kyle Guilbert, Leo Gurfinkel, Kimberly Shurn, Larry Simpson, and Mike Szegedi. “Hovering Autonomous Underwater Vehicle: A Hull Search System in Procurement in the U.S. Navy,” presented at AUVSI Unmanned Systems North America Conference, Las Vegas, Aug. 6-9, 2012

The vehicle was designed to be launched from a small boat, such as a Combat Rubber Raiding Craft (CRRC) or Rigid Hull Inflatable Boat (RHIB) (Vaganay et al.). The operator team consists of three crewmembers; the vehicle operator, the coxswain, and the tender, as shown in Figure 18.

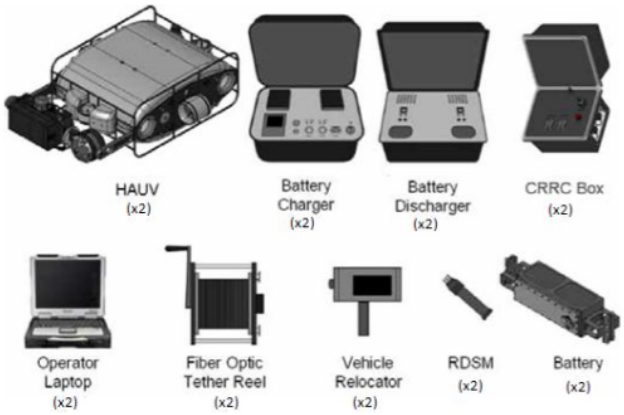
Figure 18. HAUV Small Boat Operations



Source: Vaganay, Jerome, Kyle Guilbert, Leo Gurfinkel, Kimberly Shurn, Larry Simpson, and Mike Szegedi. "Hovering Autonomous Underwater Vehicle: A Hull Search System in Procurement in the U.S. Navy," presented at AUVSI Unmanned Systems North America Conference, Las Vegas, Aug. 6-9, 2012

The HAUV-3 hull-inspection system incorporates the vehicle and a battery charger, battery discharger, CRRC box, operator laptop, fiber optic tether and reel, vehicle re-locator, Removable Data Storage Module (RDSM) and battery, with each item duplicated for redundancy, as shown in Figure 19.

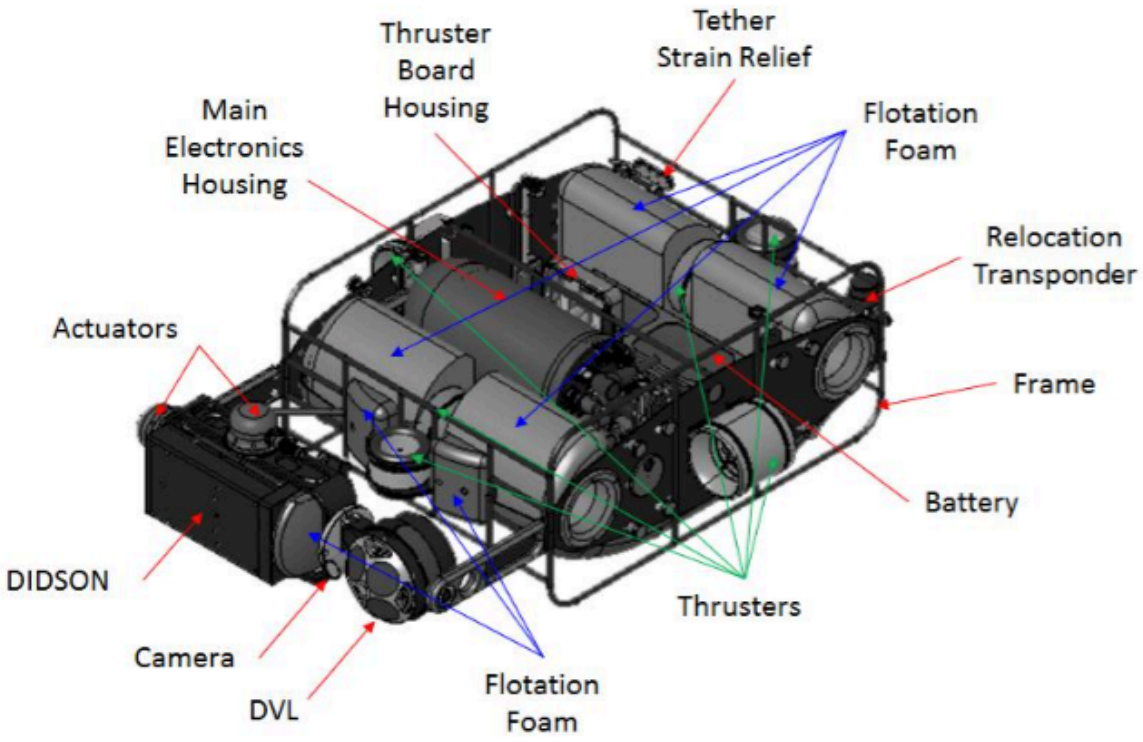
Figure 19. HAUV and Support System Components



Source: Vaganay, Jerome, Kyle Guilbert, Leo Gurfinkel, Kimberly Shurn, Larry Simpson, and Mike Szegedi. "Hovering Autonomous Underwater Vehicle: A Hull Search System in Procurement in the U.S. Navy," presented at AUVSI Unmanned Systems North America Conference, Las Vega, Aug. 6-9, 2012.

The CRRC box powers the fiber-optic reel, which allows for Ethernet connectivity through the fiber-optic cable. The RDSM is removed from the vehicle after recovery to download data. Battery run time is greater than 3.5 hours, and a spare is typically included in the kit for extended operations (Vaganay et al.). The vehicle's components are shown in Figure 20.

Figure 20. HAUV Vehicle Components



Source: Vaganay, Jerome, Kyle Guilbert, Leo Gurfinkel, Kimberly Shurn, Larry Simpson, and Mike Szegedi. "Hovering Autonomous Underwater Vehicle: A Hull Search System in Procurement in the U.S. Navy," presented at AUVSI Unmanned Systems North America Conference, Las Vegas, Aug. 6-9, 2012.

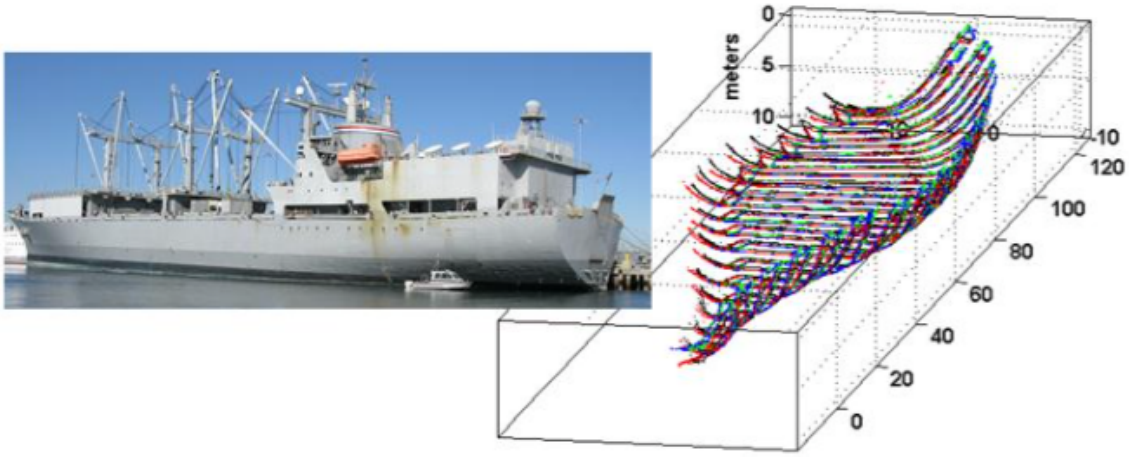
Each component is mounted within an aluminum frame, which includes grip points and skids for ease of launch and recovery (Vaganay et al.). Control of all degrees-of-freedom in movement—except roll, which is hydrostatically stable—is provided through the vehicle's six thrusters. Seven pieces of foam provide buoyancy. Upper and lower fairings protect the vehicle's battery and main electronics housing. Two rotary actuators control the movement of the

payload tray, which is supported in front of the vehicle with two arms (Vaganay et al.). Vaganay et al. state that the vehicle will right itself if flipped over in the water since the upper-mounted main electronics housing is light and the lower-mounted battery compartment is heavy compared to the other components mounted near the vehicle's midline. The battery and main electronics housing can be switched, however, allowing operations of the vehicle in an upside-down position. Allowing the vehicle to operate in either orientation is advantageous since it allows the DIDSON sonar to be located on the right or left side of the vehicle as necessary in order to always be aimed at the hull ahead of the path of the vehicle as it scans (Vaganay et al.).

b. Methodology

The ship hull can be divided into two regimes—complex and non-complex areas (Vaganay et al.). Non-complex areas consist of flat, simple hull sections such as the ship's sides and bottom. Complex areas consist of high-curvature and protuberance-laden areas such as propellers, rudders, and sonar domes. According to Vaganay et al., the HAUV uses a hull-relative, Doppler Velocity Log (DVL) method for navigation and control when mapping non-complex search areas. This method allows for high-resolution sonar imaging without the need to deploy external navigation beacons or other external navigation aids (Vaganay et al.). By automatically maintaining the DVL sensor orientation normal to the ship's hull and maintaining a constant stand-off distance, the AUV's position can be determined by integrating the hull-relative velocity. The imaging sonar is automatically pointed at an optimal grazing angle with the hull (Vaganay et al.). The AUV automatically executes surveys, forming slice images, from stern to bow or vice versa, as shown in Figure 21.

Figure 21. HAUV Layered Survey



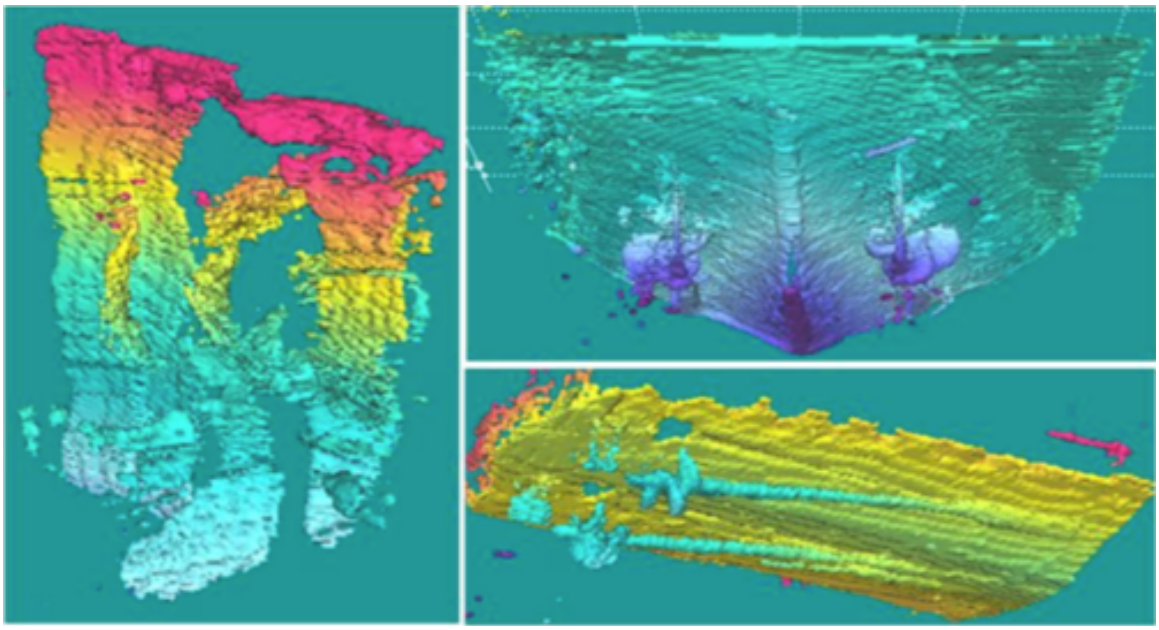
Source: Vaganay, Jerome, Kyle Guilbert, Leo Gurfinkel, Kimberly Shurn, Larry Simpson, and Mike Szegedi. "Hovering Autonomous Underwater Vehicle: A Hull Search System in Procurement in the U.S. Navy," presented at AUVSI Unmanned Systems North America Conference, Las Vegas, Aug. 6-9, 2012.

Vaganay et al. state that the sonar images are transmitted via a fiber optic tether to provide the operator with real-time data. If the operator is suspect of a particular area, autonomous operations can be suspended and the vehicle manually controlled (Vaganay et al.). When manual control is activated, the vehicle will hold its position relative to the hull and then allow the operator to move the vehicle up and down or right and left while the vehicle maintains an automatic, safe-standoff distance from the hull. If desired, the operator may override the standoff distance to drive the vehicle closer to the point of interest and employ the use of a low-light camera. Should the object need to be neutralized, the vehicle can hold position while a diver descends along the tether line to the object. The vehicle can be commanded to resume automatic mapping at any time (Vaganay et al.).

According to Vaganay et al., the complex areas remain an area of concern for HAUV developers. This is an area of ongoing research by Bluefin and ONR's Confined Area Search Group (Vaganay et al.). In complex environments, HAUV-3 points the DVL at the seafloor, allowing the vehicle to navigate relative to it, since complex areas do not allow a reliable DVL lock. The Dual Frequency

Identification Sonar (DIDSON) used by HAUV-3 can also be set to profiling mode instead of imaging mode (Vaganay et al.). In profiling mode, a special lens focuses the vertical aperture to 1 degree instead of 14 degrees, resulting in the generation of a 30-degrees by 1-degree plane of 96 beams. The vehicle moves relative to the structure while operating DIDSON, and the sonar profiles are stacked in a reference frame created from the vehicle's navigation data (Vaganay et al.). An example of 3D reconstruction of a complex area on a ship is shown in Figure 22.

Figure 22. 3D DIDSON Profile Reconstruction



Source: Vaganay, Jerome, Kyle Guilbert, Leo Gurfinkel, Kimberly Shurn, Larry Simpson, and Mike Szegedi. "Hovering Autonomous Underwater Vehicle: A Hull Search System in Procurement in the U.S. Navy," presented at AUVSI Unmanned Systems North America Conference, Las Vegas, Aug. 6-9, 2012

The principal disadvantage of the 3D reconstruction is the inherent lack of detail, and corresponding inability to detect small targets, due to data filtering and smoothing (Vaganay et al.).

Vaganay et al. state that another application considered for the vehicle is the inspection of water-conveyance tunnels. Currently, ROVs carry out this task,

but they require continuous piloting by the operator and are less capable of assuring complete coverage (Vaganay et al.). The HAUV could conduct this mission with a modification of the DIDSON mount, allowing for 360-degree rotation in the pitch and roll axis. The vehicle would then be capable of holding its position in the tunnel center using its DVL, while scanning the tunnel walls via the rotation of the DIDSON sensor (Vaganay et al.). The HAUV would travel forward through the tunnel repeating the DIDSON scan at intervals less than the sensor's field of view, thus ensuring complete wall coverage. A live-scan feed would be provided to the operator during the mission, and, upon discovering an item of interest, the operator may command the vehicle to close on the contact to capture video data, then resume the scan when complete (Vaganay et al.).

4. ARROWS

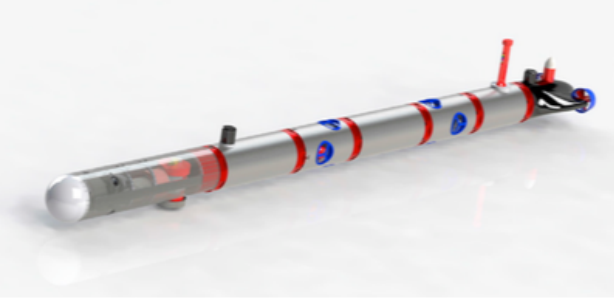
The Archaeological Robot Systems for the World's Seas (ARROWS) project began in September of 2012 under the coordination of the Universita di Firenze, Italy (Allotta et al. 2015). The project objective was the development of a cooperative, heterogeneous team of AUVs for the execution of a complete, autonomous archaeological mission.

The framework incorporates three new AUVs—Marine Tool for Archaeology (MARTA), A_Size AUV, and U-CAT (Allotta et al. 2015). These vehicles were developed upon the needs of archaeologists. The ARROWS team was challenged with the task of adapting existing offshore gas-oil industry and military security industry technologies toward low-cost AUV solutions for archaeological problems in various sea environments. A number of technologies, including multi-beam echo-sounder and side-scan sonar, were incorporated in the design to provide necessary flexibility under various visibility conditions (Allotta et al. 2015). The needs of the archeological community also drove the requirement for precision mapping, with positional errors less than a meter. The various capabilities were distributed on different vehicles, resulting in a cooperative, heterogeneous network of vehicles. Modularity was a key design

principle (Allotta et al. 2015). Most interestingly, one of the requirements for ARROWS is the capability to penetrate shipwrecks, which was achieved, in part, by the U-CAT vehicle described below. This capability was deemed important to the archaeological community in order to help identify wrecks and determine the cause of their sinking (Allotta et al. 2015). At the time of this writing, a full report on the results of the integration of the ARROWS vehicles and the success of the overall mission has not been released. Full trials were scheduled for early 2015 (Allotta et al. 2015). The following paragraphs detail the individual ARROWS vehicles.

MARTA, developed at the University of Florence, is a modular AUV, allowing for customizable configurations for various archaeological environments (Allotta et al. 2015). The largest of the three vehicles, with a length of approximately 3 meters, diameter of 7 inches, and a weight of approximately 90kg, MARTA is still capable of being launched over the side of a small boat (Allotta et al. 2015). Five degrees of freedom (minus roll) are controlled through six thrusters—two rear, two lateral, and two vertical. In order to move near the seabed without disturbing silt, the vehicle can also control pitch and vertical translation via two buoyancy modules on the bow and stern (Allotta et al. 2015). According to Allotta et al., MARTA, shown in Figure 23, has a max depth of 150 m., max autonomous time of four hours, and hovering capability.

Figure 23. MARTA



Source: Allotta, Benedetto, Riccardo Costanzi, Alessandro Ridolfi, Carlo Colombo, Fabio Bellavia, Marco Fanfani, Fabio Pazzaglia et al. 2015. “The ARROWS Project: Adapting and Developing Robotics Technologies for Underwater Archaeology.” IFAC-PapersOnLine 48, no. 2: 194–199.

MARTA modules include two buoyancy control modules, as previously mentioned, two ODROID-XU main computers, two acoustic modems, one SensorTechnics depth sensor, one Xsens MTi-G-700 GPS/IMU, one KVH 1-axis DSP-1750 Fiber Optic Gyro (FOG), one NavQuest 600 Micro Doppler Velocity Log (DVL), one RF Solutions radio modem, six MaxAmps LiPo batteries, one magnetic activation switch, NESNE motor drivers, and mission-specific equipment (Allotta et al. 2015). Mission-specific sensors include a Teledyne BlueView M900 2D forward-looking sonar, mounted on the nose, or an Ocean Tools C-laser Fan, four illuminators, and two Basler Ace cameras (Allotta et al. 2015).

A_Size AUV is essentially similar to MARTA, with an emphasis on minimal size (Allotta et al. 2015). According to Allotta et al., the vehicle, shown in Figure 24, capitalizes on the ARROWS network, which schedules tasks to platforms and manages those platforms in real-time through integrated control software, allowing the vehicles to cooperate and maximize individual vehicle capabilities.

Figure 24. A_Size AUV

Source: Allotta, Benedetto, Riccardo Costanzi, Alessandro Ridolfi, Carlo Colombo, Fabio Bellavia, Marco Fanfani, Fabio Pazzaglia et al. 2015. “The ARROWS project: adapting and developing robotics technologies for underwater archaeology.” IFAC-PapersOnLine 48, no. 2: 194–199.

U-CAT is an experimental biomimetic AUV designed with the ultimate goal of shipwreck penetration for data collection (Allotta et al. 2015). Penetration of shipwrecks is typically a dangerous task, performable only by technical divers. As an experimental platform, a principal objective was low-cost design (Allotta et al. 2015). The key benefit of a low-cost, experimental, shipwreck-penetration

autonomous vehicle is the reduction of the financial risk from loss of the vehicle. U-CAT does not operate with DVL, imaging sonars, or other expensive sensors (Allotta et al. 2015). The developers state that the use of fully autonomous navigation inside a shipwreck is “far beyond the state of the art, especially when using low cost sensing solutions.” (Allotta et al. 2015, p. 197). Salumae et al. state that AUV technologies are often unsuitable for real-world applications outside of the heavily-funded oil and defense industries. This is due to a lack of available funding for activities such as archaeology as well as the general immaturity of the technology (Salumae et al. 2014). Typically, archaeologists employ ROVs or divers for detailed inspection of shipwrecks—a risky endeavor for humans, and a very limited task for ROVs due to the risk of tether entanglement (Salumae et al. 2014). According to Allotta et al., this understanding drives the conservative employment of U-CAT in relatively-simple scenarios, such as being hand-delivered into a room in a shipwreck by a diver, allowing U-CAT to record the room, followed by a return to the diver via a beacon carried by the diver. These scenarios will allow the developers to identify promising techniques and technologies for use in more complex scenarios, such as shipwreck interior mapping, at a later date (Allotta et al. 2015). The U-CAT vehicle is depicted in Figure 25.

Figure 25. U-CAT (First Prototype)

Source: Salumae, Taavi, Rasmus Raag, Jaan Rebane, Andres Ernits, Gert Toming, Mart Ratas, and Maarja Kruusmaa. 2014. “Design principle of a biomimetic underwater robot U-CAT.” *Oceans-St. John’s,* pp. 1–5.

The needs of archaeologists operating in two areas—the Mediterranean and Baltic Sea—were analyzed (Salumae et al. 2014). These areas were chosen due to their very different sea conditions in order to demonstrate the vehicle's usability. The Mediterranean Sea has generally higher visibility, salinity, depths, and temperature. The Baltic Sea typically has lower depths, visibility, and large temperature gradients (Salumae et al. 2014). The stakeholder-needs analysis resulted in a set of general requirements for U-CAT, listed below (Salumae et al. 2014):

- Recording video of shipwreck interiors to assess general wreck conditions and identify interesting objects is the main task.
- The vehicle should be as maneuverable and small as possible, with low entanglement risk, in order to penetrate confined spaces.
- The vehicle must be untethered when operating inside the wreck, but include an ROV mode for tethered flight to a specific point, such as a wreck entrance hole.
- The vehicle must be affordable to archaeologists to enable the potential use of multiple vehicles with an acceptability of loss of a vehicle.
- The vehicle must be simple enough to operate without special robotics training and suitably ergonomic for deployment from a small boat with limited crew.
- The vehicle must be capable of operating at depths of at least 100 m.
- The vehicle must be capable of speeds of at least a meter per second in order to cope with currents.
- The vehicle must be capable of at least two hours of operation time.

The resulting vehicle weighs 17 kg and has a 100 m. maximum depth (Allotta et al. 2015). The biomimetic fins are perhaps the vehicle's most distinctive feature. The highly-maneuverable vehicle uses four oscillating flippers, placed to provide control over all 6 degrees of freedom (Allotta et al. 2015). Allotta et al. postulate that inside a wreck, flippers are advantageous to propellers because they are less likely to disturb sediment or become entangled. To the

author's knowledge, this claim has not been experimentally verified. The four fins are angled inward so that the fin's thrust vectors are not collinear (Salumae et al. 2014). Allowing each fin to oscillate independently around one axis, in any direction, is what allows the vehicle to achieve 6 degrees of freedom (Salumae et al. 2014). A principal disadvantage to fins, however, is the difficulty in achieving the steady motion necessary for most sensors. The ARROWS team is working to limit the U-CAT oscillations to only one degree of freedom (Allotta et al. 2015).

U-CAT's architecture includes two AMT buoyancy compensators. These compensators change the vehicle's volume through the movement of two pistons. Maintaining neutral buoyancy by movement of the pistons in response to changes in temperature and salinity can save a lot of energy (Salumae et al. 2014). Although pitch and roll is limited in the vehicle by designing the center of buoyancy above the center of mass, moving the pistons independently can change the center of buoyancy position fore or aft (Salumae et al. 2014). U-CAT also contains a beacon-localization system to allow navigation to homing beacons mounted on the wreck's exterior by a diver (Allotta et al. 2015). Additionally, U-CAT carries 8 obstacle-avoidance echo-sounders, an IMU, an Applicon acoustic modem, a depth sensor, illuminators, a camera, a computer (with a 1 GHz Quad-Core ARM cortex A9 processor), brushless, 60 W DC motors, NESNE Electronics motor drivers, and a 540 Wh battery allowing for an operating time of at least 4 hours (Allotta et al. 2015).

Salumae et al. state that the principal problem with conventional AUV exploration of shipwrecks is the size and expense of the vehicle. Penetration of the wreck simply generates too much risk for the owner of an expensive AUV to accept (Salumae et al. 2014). Salumae et al. also consider the size of typical AUVs to be too large for effective wreck exploration. These are the concerns that led to the development of the small, simple, inexpensive U-CAT (no explicit cost, however, was given).

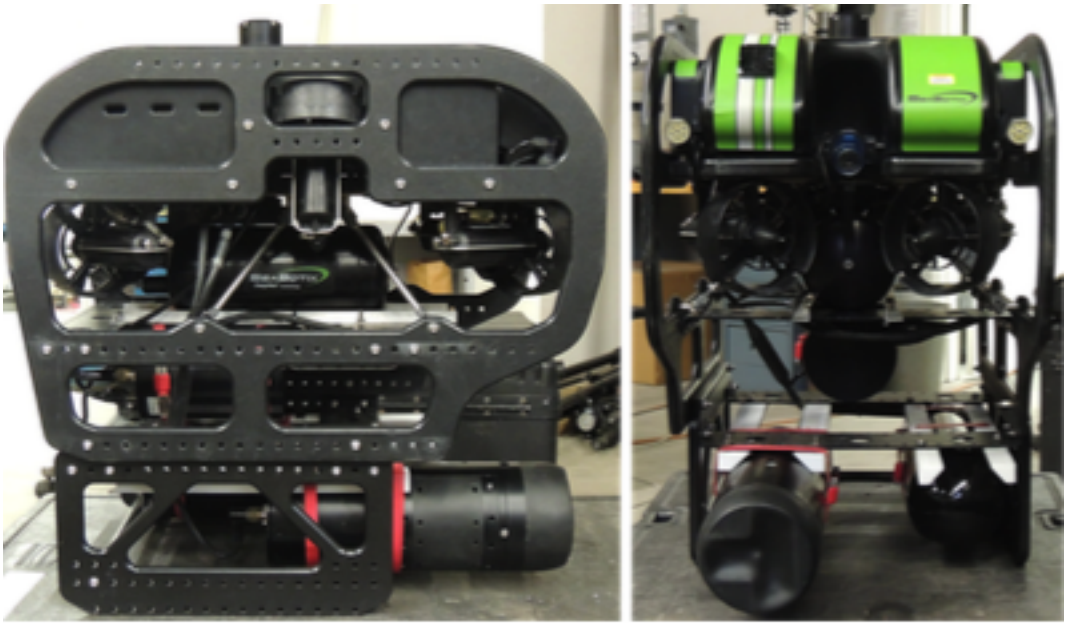
5. ACQUAS

The Agile Close-Quarters Underwater Autonomous System (ACQUAS) is a hover-capable autonomous underwater vehicle research platform developed at the Naval Postgraduate School (NPS) Center for Autonomous Vehicle Research (CAVR) in Monterey, California.

a. Vehicle Description

ACQUAS was developed specifically for the purpose of enabling autonomous operations in close quarters with other objects, the seafloor, or human divers—a realm traditionally relegated to ROVs or divers (Du Toit 2015). According to Du Toit, since close-quarters operations (CQO) represent new territory for the AUV realm, a unique set of requirements is necessary. ACQUAS is a tethered vehicle, which is very beneficial for platform testing, but presents challenges for CQO operations (Du Toit 2015). The vehicle, shown in Figure 26, is a modified SeaBotix vLBV300 miniature ROV platform.

Figure 26. ACQUAS



Source: Du Toit, Noel E. 2015. "The Agile Close-Quarters Underwater Autonomous System, ACQUAS." Naval Postgraduate School (unpublished manuscript).

ACQUAS is depth-rated to 300 m. and is controllable via an operator control unit, communicating through a fiber-optic cable (Du Toit 2015). The complete system consists of a surface power supply, tether, vehicle, and the operator control unit. Sensor data is transmitted to the operator through ethernet-based communication protocols. Du Toit further explains that the open-frame platform design allows for easily swapping sensors. The vehicle can be transported with two people and operated from confined spaces such as small boats or docks. ACQUAS has four degrees of freedom, provided through two vertical thrusters and four statically vectored horizontal thrusters. The approximate vehicle dimensions are 24 in. x 15 in. x 15 in., with a mass of 18.1 kg (38.1 kg with sensors) in air (Du Toit 2015). The vehicle's maneuverability and size are particularly suitable for CQO. The vehicle's adjustable camera and lighting system feeds high-definition video in real time to the operator station. The vehicle also employs a simple grasper for basic tasks (Du Toit 2015).

b. Methodology

To execute its autonomous missions, ACQUAS must both localize and map its environment. According to Du Toit, the localization capability for autonomous control is provided through a number of sensors. A Greensea Systems Fiber-Optic Gyro (FOG) based INS is integrated with a GPS and DVL to provide seafloor-relative velocity information. The FOG based INS is an Ethernet-capable system that combines gyro, accelerometer, and magnetic compass information. The required localization augmentation for the relative INS solution may be provided by GPS or an acoustic beacon system (Du Toit 2015). Du Toit further explains that although such a beacon system can provide geo-rectified location fixes, the system must be set up ahead of time. DVL, however, is a localization augmentation option that typically provides higher-accuracy tracking in the short term. In addition to precise localization, CQO require that the system operate in complicated, 3D environments (Du Toit 2015). Forward-looking imaging sonars, which can look ahead of the vehicle, even in turbid water, help address this issue. ACQUAS uses two BlueView P900 imaging sonars—one

vertically mounted and one horizontally mounted—to provide mapping information (Du Toit 2015). Additionally, the vehicle uses a high-frequency, micro-bathymetric sonar (MB2250), mounted sideways, for profiling. The high-resolution data provided can then be used to develop 3D maps of the environment (Du Toit 2015).

E. CAPABILITY GAP

Examination of the capabilities of the DEPTHX, HAUV, U-CAT, and ACQUAS vehicles reveals a technological growth that is as exciting as it is promising. The rapid progress of 3D-SLAM and DVL navigation technology, in combination with increasingly capable sensors and vehicle-control technology, is rapidly closing the gap between the existing and needed capability to effectively explore shipwreck interiors. Although the architectural requirements have not yet been analyzed, it is possible and useful to identify some of the key disadvantages of each system at this stage in order to better understand some of the challenges that must be the overcome during the design solution. The primary advantages and disadvantages of the AUVs, relative to shipwreck-penetration missions, are listed in Tables 3, 4, 5 and 6.

Table 3. DEPTHX Shipwreck Penetration-Relative Advantages and Disadvantages

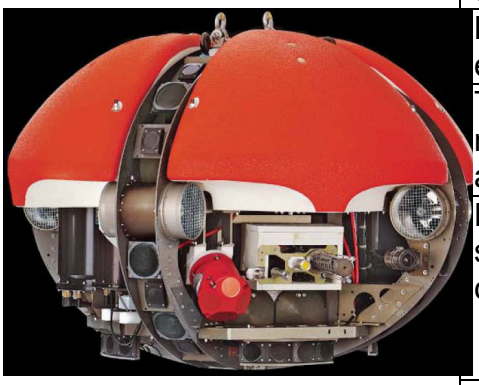
DEPTHX	Advantages	Disadvantages
	Fully-autonomous mapping capability via 3D-SLAM	Very large – 2 m. x 1.5 m. ellipsoid
	Low-snag, axisymmetric ellipsoid shape	Very heavy – 1.35 metric tonnes
	Two independent navigation systems – DR and SLAM	No real-time data transmission
	Robust sensor suite – sonar, video, sample collection	Some mapping degradation suffered due to inability to forget past measurements
	4 DOF – X,Y,Z,Yaw	No silt-out reduction design effort

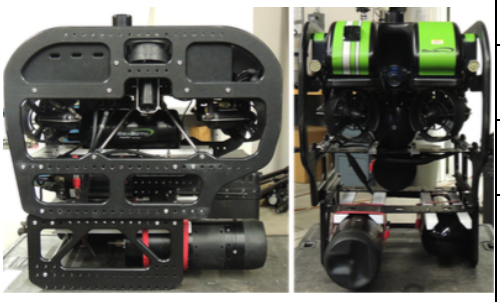
Table 4. HAUV Shipwreck Penetration-Relative Advantages and Disadvantages

HAUV	Advantages	Disadvantages
	Fully-autonomous mapping capability, specifically designed for ship hulls, via DIDSON imaging	Required tethered operations restrict maneuverability
	Hull-relative DVL navigation methodology	DIDSON imaging sonar axis must remain approximately normal to ship's hull
	Launchable from confined spaces, such as a small boat	3D target reconstruction lacks detail due to smoothing
	5 DOF - (minus roll)	Complex areas do not allow reliable DVL lock
	Real-time data transmission via fiber-optic tether	No silt-out reduction design effort
	Manual control capable	

Table 5. U-CAT Shipwreck Penetration-Relative Advantages and Disadvantages

U-CAT	Advantages	Disadvantages
	Specifically designed for shipwreck penetration	Little sensory capability – video data collection only
	Relatively low cost	Beacon-dependent navigation
	Highly maneuverable – 6 DOF (Holonomic)	Unsteady movements due to fin propulsion
	Capable of tethered and untethered operations	
	Small vehicle size and weight ideal for shipwreck penetration	
	Fins minimize silt-out and snagging risk	
	Simple operation	
	In-water data compression and WIFI transmission	

Table 6. ACQUAS Shipwreck Penetration-Relative Advantages and Disadvantages

ACQUAS	Advantages	Disadvantages
	Fully-autonomous mapping capability via BlueView imaging sonars	Required tethered operations restrict maneuverability
	Manual control capable	No silt-out reduction design effort
	Highly-modularized platform	
	Robust, modular sensor suite: sonar, video, sample collection	
	4 DOF – X,Y,Z,Yaw	
	Real-time data flow	

The principal obstacles to overcome can be segregated into four primary categories: 1) vehicle size, shape and weight, 2) vehicle propulsion and control capability, 3) vehicle localization and mapping capability, 4) vehicle data collection, storage and processing capability, and 5) vehicle autonomous decision-making capability.

1. Vehicle Size, Shape and Weight

The typical AUV is too large to effectively maneuver inside the structure of a shipwreck. Of the AUVs considered, only U-CAT is small enough for easy maneuvering inside a typical structure. The size of the vehicle must be small enough to navigate narrow ship corridors and spaces, many of which will be degraded, and be easily manipulated and launched by humans in the constrained environment of a launching platform such as a submarine. It must also, however, be large enough to permit carrying sufficient sensors to conduct the mission. The vehicle's weight, in and out of the water, is a significant factor as well. The vehicle should be as lightweight as possible out of water for ease of use by human operators and as lightweight as possible in water to conserve energy. Conservation of energy, in the form of reduced propulsion requirements, is necessary both to extend battery life and to limit the disturbance of visibility-destroying fine sediment inside the shipwreck. Increased weight would lead to increased thrust requirements to alter the vehicle's momentum resulting in greater disruption of water and silt.

The shape of the vehicle is important for a number of reasons. Typical AUVs employ a generally square frame that provides easy equipment mounting, as is the case with the highly modular ACQUAS. DEPTHX is unique in employing an ellipsoid shape, beneficial for the implementation of its 3D-SLAM architecture. A generally smooth, ergonomic, aerodynamic shape would be beneficial to reduce snagging and drag. In summary, typical AUV architecture falls short of shipwreck-penetration capability because it is too big to fit inside a shipwreck

environment, too small to carry the necessary sensors for mapping and navigation, and is not smooth enough to prevent snagging.

2. Vehicle Propulsion and Control Capability

Of the vehicles considered, only U-CAT was designed specifically for shipwreck penetration missions; however, its four-fin propulsion system currently causes significant oscillations. Typical hovering-capable AUVs employ small thrusters for translation and attitude control, resulting in much smoother movements. This is generally acceptable in the open-ocean environment where the disruption of sediment—generally referred to as “silt-out” in the diving community—and entanglement in wires and other debris is of little concern. These environmental considerations are, however, extremely significant in the shipwreck environment. The vehicle must be capable of fine, steady, and precise movements to negotiate the hazards of the environment without silting it out. U-CAT is also the only vehicle examined with a full six DOF. It is worth noting, however, that DEPTHX, HAUV and ACQUAS do not require all six DOF due to the flexibility of their sensor architecture. A full six DOF may not necessarily be required. In summary, current AUV architecture falls short of shipwreck-penetration capability because either it presents too great a silt-out and entanglement hazard or it produces movements that are too rough for onboard sensors.

3. Vehicle Localization and Mapping Capability

Of the vehicles considered, DEPTHX, incorporating 3D-SLAM, presents an attractively-sophisticated localization and mapping method. Alternatively, the imaging sonar and DVL navigation solution employed by HAUV and ACQUAS is attractively simple. Each, unfortunately, fall short in the precision required for the acceptable mapping of shipwreck interiors – in the case of 3D-SLAM, due to the estimation errors of the sonar returns, and, in the case of DIDSON sonar imaging, due to the smoothing errors of complex areas. For the DEPTHX mission to the Zacaton cenote, the size and the relatively smooth nature of the cenote

walls did not require mapping precision to the degree that would be necessary to retrieve valuable intelligence from the interior of a submarine wreck. Similarly, the majority of the ship hull area typically searched by HAUV is simple, smooth and flat. The entirety of the submarine interior would be categorized as complex using the HAUV mapping algorithm, and, worse yet, no smooth surface will likely exist below these areas to allow for a DVL lock. Thus, this navigation and mapping methodology would currently allow for neither successful navigation nor mapping in the shipwreck interior environment. U-CAT, unfortunately, can neither navigate truly autonomously (homing beacons are necessary) nor generate useful maps (only a video camera is employed). It may simply be used as a means of recording images of the interior spaces as long as homing beacons are pre-positioned along the hull or on an accompanying diver. In summary, current AUV architecture falls short of shipwreck-penetration capability because it employs a navigation methodology unsuitable for the environment, or it employs a mapping capability insufficiently precise for the environment.

4. Vehicle Data Collection, Storage and Processing Capability

The autonomous localization and mapping problem is computationally complex. A typical hovering AUV, such as HAUV or ACQUAS, employs a tether to transfer data in real-time to an operator, typically with access to greater computer processing power through the support station than the vehicle has itself. If the vehicle operates untethered, it will likely be more maneuverable, but it will require increased onboard data processing power, as is the case with DEPTHX. If the vehicle operates tethered, however, the onboard processing power requirement will be significantly reduced, the operator will have greater control (thereby reducing the risk of vehicle loss), and the operator will be able to collect real-time data without the need to recover the vehicle first (reducing mission-loss risk). Operations using tethers would, however, greatly limit the penetration capability of the vehicle without significant innovation. In summary, typical AUV architecture falls short of shipwreck-penetration capability because it fails to adequately incorporate either sufficient onboard processing capacity or an

adequate tether-management solution for the extreme environment of a shipwreck interior.

5. Vehicle Autonomous Decision-Making Capability

The capability of the vehicle to make decisions autonomously is critical to the successful exploitation of the shipwreck. As previously mentioned, DEPTHX has demonstrated its ability to autonomously decide when, where, and how to collect environmental specimens. DEPTHX, however, was designed to operate in spaces much less confined than a shipwreck interior, and some problems unique to the shipwreck environment must be overcome through autonomous decision-making capability. The collection of physical targets is one example. To successfully collect a target, the vehicle must first identify a potential target and then determine whether or not to attempt to collect it, or mark it for future collection—perhaps by another vehicle in a system-of-systems architecture. Another example of a key decision-making task is the determination of how to overcome a physical obstacle. The four possible choices the vehicle may make when encountering an obstacle are: to go around the obstacle, to move the obstacle, to destroy the obstacle, or to abort the effort and decide on a new course. All of the vehicles previously examined are autonomous, capable of navigating independent of human control. None, however, were specifically designed with these unique wreck-interior exploration decision-making capabilities. In summary, typical AUV architecture falls short of shipwreck-penetration capability because it lacks the ability to autonomously decide when and how to collect target objects and negotiate obstacles unique to the shipwreck interior environment.

IV. FUNCTIONAL DECOMPOSITION AND REQUIREMENTS GENERATION

The generation of requirements and key performance parameters (KPPs) are an essential part of a system's engineering approach toward an architectural solution that satisfies the primary objective.

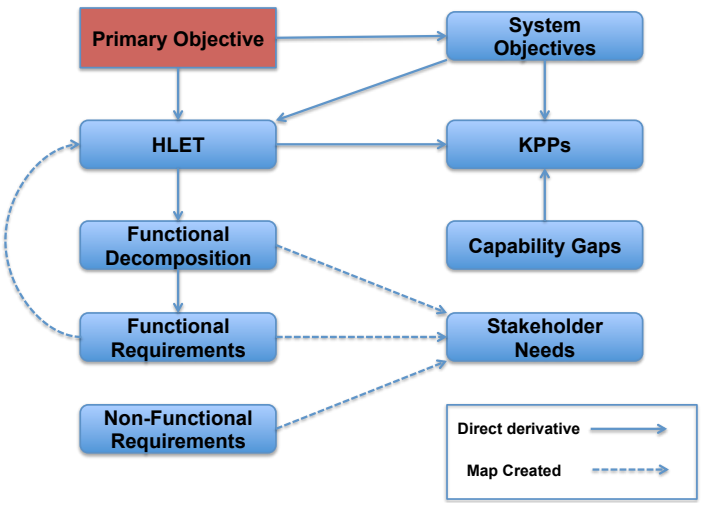
A. INTRODUCTION

This chapter begins with a functional decomposition of the high-level essential tasks (HLET) generated from the preliminary functional decomposition of the primary objective. Recall the primary objective from the DRM:

The primary objective is to penetrate the submarine and collect intelligence, while mapping the interior spaces.

From this primary objective, and the supporting system objectives, the KPPs will be generated. The functional decomposition, functional requirements, and non-functional requirements will be mapped to the stakeholder effective needs. Similarly, the functional requirements will be mapped to the HLET. These relationships are depicted in Figure 27.

Figure 27. Systems Engineering Products Relationships



Through this systematic approach, a degree of thoroughness can be achieved even at the high-level architectural design phase. Additionally, the generation of mapping tables lessens the burden of traceability at later design stages, when the number of functions and requirements will be significantly greater.

B. FUNCTIONAL DECOMPOSITION

The following functional decomposition was derived from the elements of the HLET list created in Chapter II, in support of the primary objective. The purpose of this effort is to generate tasks that are as free from technological bias as possible. The high-level essential task list was created with the minimum possible technological direction in mind. Only the vehicle type (AUV) and the need for bathymetric mapping sensors hint at any specific technological solution. The HLETL analysis may be conceptualized as the first iteration of the following functional decomposition—the first “layer of the onion” in the iterative design process. The next iteration—a full, but general, functional decomposition—leverages the increased understanding of the problem space and the existing technology while keeping the functions as general and free of technological bias as possible. The functional decomposition continues the development of all HLET tasks with the exception of the eighth task, the collection of targets of opportunity, which will be postponed for a future iteration. The resulting decomposition, therefore, assumes only the following hardware: the host submarine (HS), target submarine (TS), exploration vehicle (AUV), delivery vehicle (DV), and sensor array (including mapping, video recording and light producing hardware).

1. Decomposition

1. HS launches the AUV from depth

    1.1. HS locates TS

    1.2. HS stabilizes in proximity to TS for launch

    1.3. HS launches DV

2. DV delivers the AUV to the wreck interior

    2.1. DV executes search of sea floor for TS

        2.1.1. DV descends to the appropriate altitude above the sea floor

        2.1.2. DV executes a search pattern

        2.1.3. DV detects the TS

    2.2. DV conducts an external survey of TS

        2.2.1. DV scans the hull exterior

        2.2.2. DV identifies a potential hull breach

    2.3. DV deploys AUV

        2.3.1. AUV undocks from DV

        2.3.2. AUV propels itself away from DV

    2.4. AUV begins searching interior spaces

        2.4.1. AUV commences the search pattern

3. AUV maps and records the environment

    3.1. AUV enables its sensor array to scan the environment

    3.2. AUV sensors collect data necessary for 3D map generation

    3.3. AUV collects video data

    3.4. AUV processes the sensor data to create a 3D map

4. AUV systematically localizes

    4.1. AUV records its location relative to known reference points

    4.2. AUV maintains a current escape path plan

5. AUV maneuvers within the wreck interior

    5.1. AUV hovers in a stable position as required

    5.2. AUV translates in the horizontal plane as required

5.3. AUV translates in the vertical plane as required

6. AUV moves between compartments

6.1. AUV determines the completeness of the current compartment map

6.2. AUV identifies compartment entrances

6.3. AUV records each location of new compartment entrance

6.4. AUV prioritizes each new compartment entrance

6.5. AUV returns to preferred entrance after completing current compartment

6.6. AUV passes through the new compartment entrance

7. AUV overcomes obstacles

7.1. AUV recognizes a physical obstacle

7.2. AUV determines appropriate response to obstacle

7.3. AUV executes response to obstacle

7.4. AUV determines post-obstacle profile

7.4.1. AUV continues exploration if possible

7.4.2. AUV aborts exploration if necessary

8. AUV decides when to return to DV

8.1. AUV returns to DV upon completing scan of all known compartments

8.2. AUV returns to DV when unable to continue compartment searches

8.3. AUV returns to DV upon reaching low-power threshold

8.4. AUV returns to DV upon suffering a critical casualty

9. AUV returns to DV

9.1. AUV returns to DV upon completing scan of all known compartments

9.2. AUV returns to DV when unable to continue compartment searches

9.3. AUV returns to DV upon reaching low-power threshold

9.4. AUV returns to DV upon suffering a critical casualty

10. DV returns to HS
    10.1. DV returns to HS
    10.2. DV docks with HS
11. Crew retrieves AUV exploration data
    11.1. Crew recovers DV with AUV
        11.1.1. Crew sanitizes DV and AUV as necessary
    11.2. Crew downloads exploration data from AUV

2. Function Map to Effective Needs

Table 7 maps the functions to the respective effective needs generated in the stakeholder analysis section. It is imperative that each function be associated with at least one specific need in order to prevent design creep.

Table 7. Functions to Needs Map

Function	Need	Function	Need
1	1.1, 2.1, 2.2. 7.1, 7.3	6.4	6.2, 7.1
1.1	2.1	6.5	6.2, 7.1
1.2	2.1, 2.2	6.6	7.1
1.3	2.1	6.7.2	7.1
2	6.1, 6.2, 7.1	6.7.3	7.1
2.1	6.1, 6.2, 7.1	7	4.1, 6.1, 6.2, 7.1, 7.2, 7.3
2.1.1	7.1	7.1	3.1, 6.2, 7.1
2.1.2	7.1	7.2	6.2, 7.1
2.1.3	7.1	7.3	6.2, 7.1
2.2	3.1, 6.1, 6.2, 7.1	7.4	6.2, 7.1
2.2.1	3.1, 6.1, 6.2,	7.4.1	6.2, 7.1
2.2.2	7.1	7.4.2	6.2, 7.1
2.3	6.1, 6.2, 7.1	8	1.2, 5.1, 7.1
2.3.1	7.1	8.1	7.1
2.3.2	7.1	8.2	7.1
2.4	1.3, 3.1, 5.1, 6.1, 6.2, 7.2	8.3	7.1
2.4.1	6.2, 7.1	8.4	7.1
3	1.3, 5.1, 6.1, 6.2, 7.1, 7.2	9	1.2, 5.1, 7.1
3.1	1.3, 6.1, 7.1	9.1	7.1
3.2	1.3, 6.1, 6.2, 7.1	9.2	7.1
3.3	1.3, 3.1, 4.1, 5.1, 7.1	9.3	7.1
3.4	1.3, 3.1, 4.1, 5.1, 6.2, 7.1	9.4	7.1
4	6.2, 7.1	10	1.2, 2.1, 2.2, 5.1, 7.1
4.1	6.2, 7.1	10.1	2.1, 7.1
4.2	7.1	10.2	2.1, 2.2, 7.1
5	4.1, 5.1, 6.1, 7.1	11	1.3, 3.1, 4.1, 5.1, 6.1, 7.1
5.1	7.1	11.1	2.1, 2.2, 7.1
5.2	7.1	11.1.1	2.2, 7.1
5.3	7.1	11.2	1.3, 2.1, 2.2, 5.1, 7.1
6	6.2, 7.1		
6.1	6.2, 7.1		
6.2	1.3, 6.2, 7.1		
6.3	6.2, 7.1		

C. REQUIREMENTS GENERATION

System requirements may be defined as, “a description of how the system should behave, or an essential attribute of the system.” (NPS SE3100 Module 2, Slide 53, Spring 2014 Lecture). The objective of the requirements generation process is to establish guidance for design while reducing the ambiguity of the

effective needs. Requirements pertain to capabilities, functions, constraints, performance and effectiveness. Requirements should be specific, measurable, attainable, realistic and time-bound or traceable—commonly termed “SMART”—and generally consist of an attribute or characteristic, a relationship and a value. The value may be binary—i.e., on or off, or capable or incapable, but it must measurable. Well-defined requirements reduce the risk of schedule slippage, cost overruns, technology bias and help to ensure that the design form follows the required function. The requirements for the system may be categorized as functional and non-functional. The specific numbers associated with each requirement in this thesis should be considered the author’s best guess for the design of a robust AUV solution to the DRM. The numbers in these requirements can be conveniently replaced in future work with values that reflect the product of actual stakeholder negotiations and the most current technological developments. Physical prototyping will also enable more refined values. The functional requirements, which are derived from the lowest-level functions (disregarding the parent functions) of the functional decomposition, are generated in the following section.

1. Functional Requirements

The strategy for the development of the functional requirements is to first consider, for each lowest-level function, what item the requirement pertains to, what the item is required to do, how soon it should begin doing it, how quickly it should execute the task, how accurately or precisely it should execute the task, or how well it should qualitatively execute the task. Once written, the requirement should be checked against the SMART guidelines.

1) F1.3. HS launches DV

FR1: DV shall be capable of launching from the HS at depths between sea level and 1,000 fsw.

2) F2.1.1. DV descends to the appropriate altitude above the sea floor

FR2: DV shall begin descending from the HS to the search pattern depth within 5 seconds of launch from the HS, at a rate of 5 ft. per second, slowing the descent as appropriate to enable stabilization at search pattern depth (+/-5 ft.), with no more than one overshoot, within ten seconds.

3) F2.1.2. DV executes a search pattern

FR3: DV shall begin the first leg of the pre-programmed search pattern upon stabilization at search pattern depth (+/-5 ft.) within 5 seconds.

4) F2.1.3. DV detects the TS

FR4: DV shall detect the TS during the search pattern, when the target is present, with a 99% probability of detection (P_d=.99).

5) F2.2.1. DV scans the hull exterior

FR5: DV shall descend to the scanning standoff distance of the TS within 5 seconds of detection at search pattern depth, at a rate of 3 fps, slowing as necessary to stabilize within one foot of standoff distance to the TS hull with no overshoot and commence the scanning pattern of the TS hull within 2 seconds of stabilizing at standoff distance (+/-1 ft.).

6) F2.2.2. DV identifies a potential hull breach

FR6: DV shall detect a potential hull breach from the scanning standoff distance with a 95% probability of detection.

7) F2.3.1. AUV undocks from DV

FR7: DV shall release AUV into the TS interior within 5 seconds of undocking command.

8) F2.3.2. AUV propels itself away from DV

FR8: AUV shall propel itself clear of DV by at least 6 inches within 5 seconds of undocking command.

9) F2.4.1. AUV commences the search pattern

FR9: AUV shall commence search pattern within 5 seconds of undocking command.

10) F3.1. AUV enables its sensor array to scan the environment

FR10: AUV shall be capable of complete coverage with its sensor array.

11) F3.2. AUV sensors collect data necessary for 3D map generation

FR11: AUV shall collect imaging data as necessary for 3D map generation.

12) F3.3. AUV collects video data

FR12: AUV shall collect high-definition (1080p) video data continuously during the mission.

13) F3.4. AUV processes the sensor data to create a 3D map

FR13: AUV shall process the sensor data as necessary to create a 3D map.

14) F4.1. AUV records its location relative to known reference points

FR14: AUV shall maintain a record of its location relative to known reference points throughout the mission.

15) F4.2. AUV maintains a current escape path plan

FR15: AUV shall maintain an updated escape path map throughout the mission.

16) F5.1. AUV hovers in a stable position as required

FR16: AUV shall be capable of attaining a hovering profile relative to an interior surface with less than 1 inch per second of forward/aft, lateral, or vertical drift, within 2 seconds of a hover command, in variable currents up to 5 fps with accelerations of 3 feet per second squared.

17) F5.2. AUV translates in the horizontal plane as required

FR17: AUV shall be capable of moving in any direction within the horizontal plane from a hover to a maximum in-water velocity of 5 fps in 2 seconds.

18) F5.3. AUV translates in the vertical plane as required

FR18: AUV shall be capable of moving in any direction within the vertical plane and accelerate from a hover to a maximum ascent and descent rate of 1 fps in 2 seconds.

19) F6.1. AUV determines the completeness of the current compartment map

FR19: AUV shall assess the completeness of the working map as the scan takes place and continue scanning the environment until complete (4π steradians) coverage has occurred.

20) F6.2. AUV identifies compartment entrances

FR20: AUV shall identify compartment entrances with a reliability of 95%.

21) F6.3. AUV records each location of new compartment entrance

FR21: AUV shall record the location of each new compartment entrance.

22) F6.4. AUV prioritizes compartment entrances

FR22: AUV shall prioritize compartment entrances for exploration in the following order: open, obstructed, closed.

23) F6.5. AUV returns to preferred entrance after completing current compartment

FR23: AUV shall begin maneuvering to the priority entrance of the new potential compartment, after completing the map of the current compartment, within 2 seconds of completion.

24) F6.6. AUV passes through the new compartment entrance

FR24: AUV shall attempt compartment entrance passage when within 1 horizontal foot of an open compartment entrance.

25) F7.1. AUV recognizes a physical obstacle

FR25: AUV shall identify a physical obstacle with a 99% probability of identification.

26) F7.2. AUV determines the appropriate response to the obstacle using a decision tree

FR26: AUV shall determine the appropriate response (discontinue exploration of the space, bypass the obstacle, move the obstacle, or destroy the obstacle) to the obstacle with a reliability of 95%.

27) F7.3. AUV executes response to obstacle

FR27: AUV shall execute the response to the obstacle within 3 seconds of identifying the obstacle.

28) F7.4.1. AUV continues exploration if possible

FR28: AUV shall recommence compartment exploration within 2 seconds of bypassing the obstacle.

29) F7.4.2. AUV aborts exploration if necessary

FR29: AUV shall abort the exploration of the compartment upon exhausting obstacle circumvention options.

30) F9.1. AUV returns to DV upon completing exploration of all known compartments

FR30: AUV shall commence returning to the DV within 3 seconds of determining all available compartment search space has been explored.

31) F9.2. AUV returns to DV when unable to continue compartment searches

FR31: AUV shall commence returning to the DV within 3 seconds of determining its inability to continue further compartment searches.

32) F9.3. AUV returns to DV upon reaching the low-power threshold

FR32: AUV shall commence returning to the DV within 3 seconds of determining its estimated return power requirement is within the programed safety margin of the remaining power reserve.

33) F9.4. AUV returns to DV upon suffering a critical casualty

FR33: AUV shall commence returning to the DV within 3 seconds of suffering a critical system casualty.

34) F10. AUV docks with DV

FR34: AUV shall dock with the DV with a reliability of 99%.

35) F10.1. DV returns to HS

FR35: DV shall begin ascending from the TS to the HS at a rate of 5 fps, slowing the ascent as appropriate to enable stabilization on docking profile (+/- 5 ft.) with no more than one overshoot, within ten seconds.

36) F10.2. DV docks with HS

FR36: DV shall initiate docking approach when within 20 horizontal feet of the DV recovery station, drive into the recovery station at a speed of 6 inches per second (+/- 2 inches per second) and within 5 degrees of the recovery profile.

37) F11.1.1. Crew sanitizes DV and AUV as necessary

FR37: DV and AUV shall be able to be sanitized for safe human exposure within 10 minutes of recovery.

38) F11.2. Crew downloads exploration data from AUV

FR38: Exploration data shall be downloadable within 15 minutes of recovery.

2. Functional Requirements Map to High-Level Essential Tasks

Table 8 maps the functional requirements to the respective HLET items generated in the mission planning section of Chapter II. It is a useful tool for ensuring that each primary task is appropriately represented by its corresponding design requirements. Note that only HLET 8, which will be addressed in future work, is missing from the map.

Table 8. Functional Requirements to High-Level Essential Tasks Map

FR	HLET	FR	HLET	FR	HLET	FR	HLET
1	1	11	3	21	4	31	9
2	2	12	3	22	4	32	9
3	2	13	4	23	6	33	9
4	2	14	4	24	6	34	9
5	2	15	4	25	7	35	9
6	2	16	5	26	7	36	9
7	2	17	5	27	7	37	9
8	2	18	5	28	7	38	9
9	2	19	4	29	7		
10	3	20	4	30	9		

3. Non-Functional Requirements

The strategy for the development of the non-functional requirements is to consider the stakeholder needs, context, and other aspects of the problem space while applying the same techniques used to generate the functional requirements to encompass the necessary system attributes. A target submarine test environment (TASTE) is anticipated for future prototype testing and is periodically referred to in the following non-functional requirement list in order to enable the measurement of certain system attributes.

Modularity

NR1: AUV frame and subsystems shall be modular.

Autonomy

NR2: DV shall be capable of autonomously navigating to the programmed wreck site, searching for the TS, conducting the TS hull inspection, inserting and extracting the AUV, and returning the HS.

NR3: AUV shall be capable of autonomously docking and undocking from the DV, navigating the TS interior and overcoming physical obstacles.

Vulnerability

NR4: AUV shall be free of edges rough enough to cause snagging by filaments greater than 0.5 mm. in diameter.

NR5: AUV shall be capable of translating through the TASTE without becoming entangled with 99% reliability.

NR6: DV shall be capable of delivering the AUV to the TS in the TASTE without becoming entangled with 99% reliability.

NR7: AUV shall be capable of translation through the TASTE without silt-out degradation in sensors with 85% reliability.

NR8: AUV shall be capable of translation through the TASTE with no damage to the AUV structure with a reliability of 99%.

NR9: DV and AUV shall be capable of withstanding 150% the maximum ambient operating pressure of the TS with no loss in functionality and no leaks with a 99% reliability.

NR10: DV and AUV shall be capable of performing all mission tasks in water temperatures ranging between -5 to 140 degrees F.

NR11: DV and AUV shall be capable of performing all mission tasks in the presence of toxic chemicals 150% higher in concentration than expected in the TS with 99% reliability.

NR12: DV and AUV shall be capable of performing all mission tasks in the presence of radiation levels 150% higher than expected in the TS with 99% reliability.

Reliability

NR13: AUV shall be capable of performing all mission tasks in the TASTE with an intelligence-collection reliability of 95%.

Availability

NR14: AUV and supporting systems shall be capable of performing all mission tasks in the TASTE with an availability of 95%.

Maintainability

NR15: AUV and supporting systems mean time between failures (MTBF) shall be greater than 100 hours.

NR16: AUV and supporting systems shall be capable of being maintained by the crew in less than one hour.

Testability

NR17: AUV and support system operation shall be testable in the TASTE.

Adaptability

NR18: AUV and support system shall be capable of normal operations in the following alternate submerged environments: surface ships, passenger aircraft, building structures, and underwater caves.

NR19: AUV and support systems shall be capable of a minimum of two hours operating time at the maximum translation speed.

Affordability

NR20: AUV and support systems production shall cost less than $5 million to production of the first vehicle.

NR21: AUV and support systems subsequent to the first operational system shall cost less than $2 million.

Compatibility

NR22: AUV and support system shall be capable of normal storage and operations, including support system power, launch, recovery, and maintenance aboard U.S. Navy submarine and surface ship platforms.

NR23: AUV and support system shall be capable of normal storage and operations, including support system power, launch, recovery, and maintenance aboard NATO submarine and surface ship platforms with a modification kit.

Interoperability

NR24: DV shall be deployable and recoverable from the HS.

NR25: AUV shall be deployable and recoverable from the DV.

NR26: AUV and support system shall be serviceable and transportable via the HS.

NR27: AUV and support system shall comply with HS hazardous materials (HAZMAT) safety requirements.

NR28: AUV and support system shall be storable within the designated HS storage space.

Modifiability

NR29: AUV and support systems shall be modifiable to operate from U.S. or NATO host vessels and to operate in the following alternate submerged environments: surface ships, passenger aircraft, building structures, and underwater caves.

Portability

NR30: AUV and support systems shall be portable, such that, within their storage cases, two men may move the entire system between assigned spaces on separate HS vessels on the same pier within an hour.

NR31: AUV and support systems shall be capable of transportation on MH-60S (helicopter) and fixed-wing cargo aircraft, unpressurized to an altitude of 10,000 ft. MSL.

NR32: AUV and support systems shall be capable of transfer via vertical replenishment (VERTREP) at sea from an MH-60S.

Recoverability

NR33: AUV shall dock with the DV with 99% reliability.

NR34: DV shall dock with the HS with 99% reliability.

Reusability

NR35: AUV shall be capable of 100 missions before replacement with a reliability of 95%.

NR36: DV shall be capable of 500 missions before replacement with a reliability of 95%.

NR37: DV and AUV shall leave no discernable visual trace of exploration (signature).

Usability

NR38: Crewmember training for AUV and support system operation shall be less than six months.

NR39: AUV and support systems shall be mission-capable with a two-man crew.

4. Key Performance Parameters

Key performance parameters (KPPs) are metrics for the most critical system performance goals. Identification of KPPs enhances the likelihood of synthesizing an architecture with maximum leverage for meeting the stakeholder needs.

Key Performance Parameters

1. The vehicle shall be sufficiently small to transit the TS interior, sufficiently smooth to resist snagging on debris, and sufficiently lightweight to be portable by two men.
2. The vehicle shall be capable of autonomous propulsion, with sufficient agility and smoothness for complete environmental sensor coverage throughout the TS interior, without creating unacceptable silt-out conditions and while maintaining continuous awareness of the return route.
3. The vehicle shall continuously map and record the TS interior with sufficient visual resolution and mapping precision to ensure useful intelligence collection.
4. The vehicle shall be capable of sufficient processing capacity or tether-management to permit a complete mapping of the TS interior.

5. The vehicle shall be capable of deciding, autonomously, when and how to defeat an obstacle, collect a target of opportunity, or return to the HS.

6. The system shall be interoperable with the host sub in all mission phases.

7. The system shall be capable of preserving the secrecy of the mission.

5. Functional and Non-Functional Requirements Map to Effective Needs

Table 9 maps the functional and non-functional requirements to the respective stakeholder needs. It is a useful tool for ensuring that each effective need is met by at least one corresponding design requirement.

Table 9. Functional and Non-Functional Requirements to Needs Map

FR	Need	NR	Need
1	2.1	1	5.3, 7.3, 7.4, 7.5
2	7.1	2	2.4, 2.5, 2.6, 3.2, 4.2, 7.2
3	7.1	3	2.4, 2.5, 2.6, 3.2, 4.2, 7.2
4	7.1	4	7.1, 7.2, 7.3
5	3.1, 6.1, 6.2, 7.1	5	7.1, 7.2, 7.3
6	7.1	6	2.2, 7.1, 7.2, 7.3
7	7.1	7	1.2, 5.2, 7.1, 7.4
8	7.1	8	5.2, 7.1, 7.4
9	6.2, 7.1	9	5.2, 7.2
10	1.3, 6.1, 7.1	10	5.2, 7.2
11	1.3, 6.1, 6.2, 7.1	11	5.2, 7.2
12	1.3, 3.1, 4.1, 5.1, 7.1	12	5.2, 7.2
13	1.3, 3.1, 4.1, 5.1, 6.2, 7.1	13	1.3, 2.1, 5.1, 7.1
14	6.2, 7.1	14	1.3, 2.1, 5.1, 7.1
15	7.1	15	1.2, 2.2, 2.4, 5.2, 7.4
16	7.1	16	1.2, 2.4, 5.2, 7.4
17	7.1	17	5.1, 5.2, 5.3, 7.2
18	7.1	18	1.3, 3.1, 4.1, 5.2, 7.4
19	6.2, 7.1	19	2.1, 4.1, 7.2
20	1.3, 6.2, 7.1	20	5.3, 7.5
21	6.2, 7.1	21	5.3, 7.5
22	6.2, 7.1	22	2.2
23	6.2, 7.1	23	2.2, 7.3, 7.4
24	7.1	24	2.2
25	3.1, 6.2, 7.1	25	7.3
26	6.2, 7.1	26	2.2
27	6.2, 7.1	27	2.2, 2.5, 2.6
28	6.2, 7.1	28	2.2, 2.3, 2.5, 7.4
29	6.2, 7.1	29	2.2, 7.3, 7.4
30	1.2, 7.1	30	2.2, 2.4, 2.5, 7.4
31	1.2, 7.1	31	2.2, 2.5, 7.4
32	1.2, 7.1	32	2.2, 2.5, 7.4
33	1.2, 7.1	33	7.1, 7.2
34	1.2, 7.1	34	1.2, 2.1, 2.2, 7.1
35	1.2, 2.2, 5.1, 7.1	35	1.2, 5.2, 5.3, 7.4
36	2.1, 2.2, 7.1	36	1.2, 5.2, 5.3, 7.4
37	2.6	37	1.1, 7.4
38	1.3, 2.1, 5.1, 7.1	38	2.4, 2.5, 5.3, 7.4
		39	2.4, 2.5, 5.3, 7.4

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V. ARCHITECTURE SYNTHESIS

In this chapter, the general functions and requirements of the previous chapter will be combined with the knowledge generated from the literature review and the capability gaps in order to arrive at one possible architectural solution to the problem of shipwreck interior exploration.

A. INTRODUCTION

The architecting process begins with an examination of some key design tradeoffs. With this knowledge, a physical and functional architecture is then developed. An assessment of potential future versions brings the chapter to a close.

B. ARCHITECTURAL DESIGN TRADEOFF CONSIDERATIONS

Before the synthesis of an architectural solution can begin, some key design tradeoff considerations must be discussed. Many architecture decisions will be made throughout the iterative design process, but some have such a significant impact on the design of the vehicle that they should be carefully considered as early as possible. In this section, five such tradeoffs will be considered.

1. Tethered versus Untethered Operations

The use of a tether has significant advantages and disadvantages and greatly impacts the physical and functional architecture of any AUV. In the confines of a wreck, the use of a tether has the advantage of allowing some key decisions to be made by a human operator instead of the autonomous logic of the vehicle's software. A tether may provide electrical power to the vehicle, thus reducing the necessary battery storage within the vehicle and allowing more internal space to be allocated to sensors, flight control, computer hardware and other subsystems. The tether may also serve as a means for finding the way out

of the shipwreck. Clearly, the advantages of tethered operations compel serious consideration.

The principal disadvantage of tethered operations, however, particularly in the shipwreck environment, is the entanglement hazard. If the tether is dragged through the wreck, it is likely to become entangled or damaged by the wreck structure. A loss of the tether could mean the loss of the vehicle itself, as is the case with ROVs, and this is one major reason why ROV operators rarely risk venturing inside shipwrecks. Although the risk of entanglement or damage to the tether could be reduced if the tether was dispensable from the vehicle itself, the increased weight and complexity of carrying an onboard tether spool would likely limit the performance of the vehicle. Should the vehicle be designed to drag the line through the wreck interior spaces, the weight of such a line would likely require increased translation power from the vehicle, thereby increasing the likelihood of sediment disruption in addition to the reduction in maneuverability. No matter how flexible and resilient such a line may be, a limit inevitably exists to the number of turns the vehicle could make through a wreck interior before the line snags, is damaged, or requires too much force to overcome the resistance. Additionally, should the tether become damaged and break or require jettison, leaving it behind could provide a signature that would be harmful to the secrecy of the mission.

2. Vehicle Size

The size of the vehicle is, in the case of this DRM, naturally constrained by the environment in which it must explore. Since the interior spaces of a ship or submarine are generally compact, the use of a large vehicle such as DEPTHX is obviously excluded. The average human, for whom most vessel compartments were designed, may still need to squeeze through various spaces—especially on a submarine—even in its original, un-sunk condition. The vehicle should, therefore, be generally smaller than a human. It is easy to imagine a small AUV propelling itself through the interior passages of a wreck. It is hard to imagine,

however, anything much larger than a basketball fitting through passageways and hatches, particularly when those passageways are partially obstructed. Much smaller vehicles, perhaps the size of a baseball, may be less likely to become entangled, but would also be incapable of carrying most useful sensors. The basketball and baseball, then, may be considered the rough maximum and minimum potential vehicle sizes given the current state of sensor technology. The tradeoff is straightforward—too big and the vehicle will be less capable of freely traveling inside the wreck, too small and the vehicle will be less capable of performing the required sensory functions.

3. Vehicle Shape

The vehicle's shape is a significant architectural decision. The vehicle's shape is important for multiple reasons, including its resistance to entanglement, the use of its internal space, the employment of its sensors, its modularity and the ease of its design and manufacture. A square or rectangular vehicle, such as HAUV and ACQUAS, enhance modularity and simplify control. A spherical or ellipsoid vehicle, such as DEPTHX, reduces the snagging potential on the wreck interior structure and enables the use of circularly mounted scanning sensors. Spherical and ellipsoid designs are, however, more difficult to manufacture and require an efficient use of internal space.

4. Propulsion Method

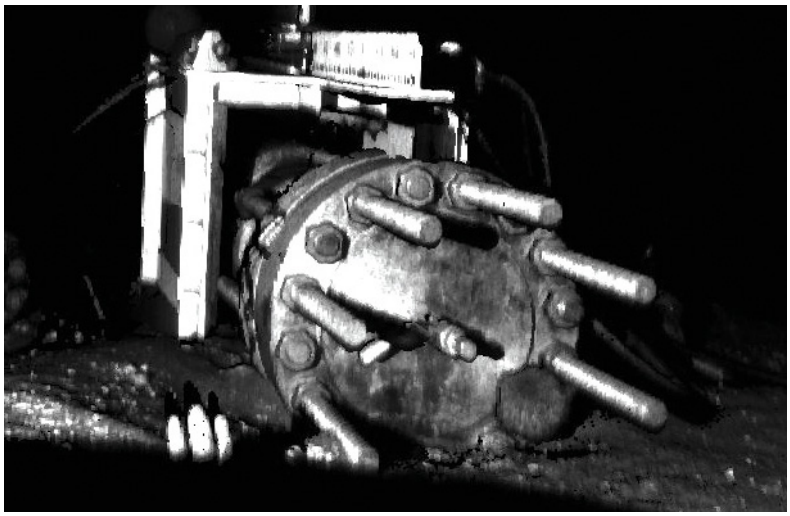
Multiple methods for propulsion exist. The use of propellers (or thrusters) is perhaps the most common. Propellers present the advantages of efficiency, simplicity, and controllability. Many options for propellers exist on the market. The thrust produced is generally predictable. Additionally, the vehicle motion is potentially very smooth under propeller propulsion. The principal disadvantage, particularly for wreck interiors, however, is the propeller's propensity for fouling on debris or becoming damaged by contact with objects. Techniques may be implemented, such as shielding the thrusters or burying them within tunnels, to help alleviate this problem. Another disadvantage is the harsh propeller wash

produced during operation, which may easily stir up sediment. A fin-propelled vehicle, such as U-CAT, has the advantage of minimizing silt-out conditions and fouling on debris. The primary disadvantage, however, is the difficulty with which steady motion is achieved.

5. LIDAR vs. Sonar

The shipwreck interior environment necessitates the use of aquatic mapping tools with great precision. Since the objects and passages within a shipwreck interior are generally small and highly complex compared to traditional objects for underwater mapping, such as ship hull exteriors, the sea floor, or cavern walls, the use of imaging tools capable of producing very high-resolution maps is necessary for effective wreck interior mapping and localization. Sonar has historically been the choice for bathymetric mapping. Sound beams expand rapidly compared to laser energy, however, and the resulting large sonar beam footprint translates into less densely populated point clouds (2G Robotics 2015a). Objects or details smaller than the corresponding footprint cannot be resolved. It is possible, however, to trade longer-range capability for higher-resolution capability. Light detection and ranging (LIDAR) is a newer technology with significantly increased resolution at ranges under five meters (2G Robotics 2015a). This significant range limitation is due to the rapid attenuation of light in water. LIDAR, therefore, is often incapable of fulfilling the needs of those seeking long-range underwater mapping technology. The shipwreck interior, with most scanning needs well under five meters, is ideally suited for laser scanning. The narrow beam produces multiple orders of magnitude greater resolution than sonar, resulting in far denser point clouds (2G Robotics 2015a). A sample LIDAR image of a spool with a flange, taken by 2D Robotics using a ULS-500 laser scanner at 90m depth in the North Sea, is shown in Figure 28.

Figure 28. Sample Laser Scanning Image



Source: 2G Robotics. 2015. “Spool Metrology with 2G Robotics ULS-500.” Accessed Dec. 11. http://www.2grobotics.com/spool-metrology-with-2g-robotics-uls-500/.

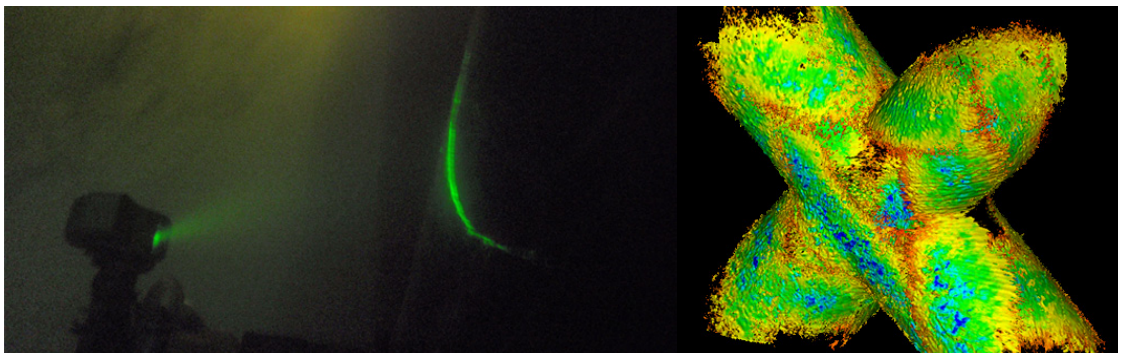
Unlike sonar, laser scanners are not adversely affected by false echoes in confined spaces. Laser scanners are, however, adversely affected by suspended particulate matter, since these particles scatter light. Nevertheless, software methods for silt filtering enable high-quality imagery even in the presence of some silt. The ULS-100, the smallest of three laser scanners produced by 2G Robotics, is an example of a potentially useful laser scanner for a wreck interior exploration AUV. The ULS-100 scanner is shown in Figure 29.

Figure 29. G Robotics ULS-100 Laser Scanner

Source: 2G Robotics. 2015. "ULS-100 Product." Accessed Dec. 11. http://www.2grobotics.com/products/underwater-laser-scanner-uls-100/.

This scanner has a maximum range of 1 m. with a 50-degree laser scan angle (2G Robotics 2015b). The scanner's range resolution is 0.30 mm. at 1 m., with a maximum sample rate of 2400 points per second. Figure 30 shows the ULS-100 in the process of scanning an offshore bracing jacket along with the resulting image.

Figure 30. ULS-100 Scanning Image



Adapted from: 2G Robotics. 2015. "ULS-100 Results." Accessed Dec. 11. http://www.2grobotics.com/products/underwater-laser-scanner-uls-100/.

C. WRECK INTERIOR EXPLORATION VEHICLE (WIEVLE)

In this section, an architecture design is presented. The solution is a system-of-systems approach that incorporates a modified version of the REMUS AUV, as the delivery vehicle for a spherical AUV, called the Wreck Interior

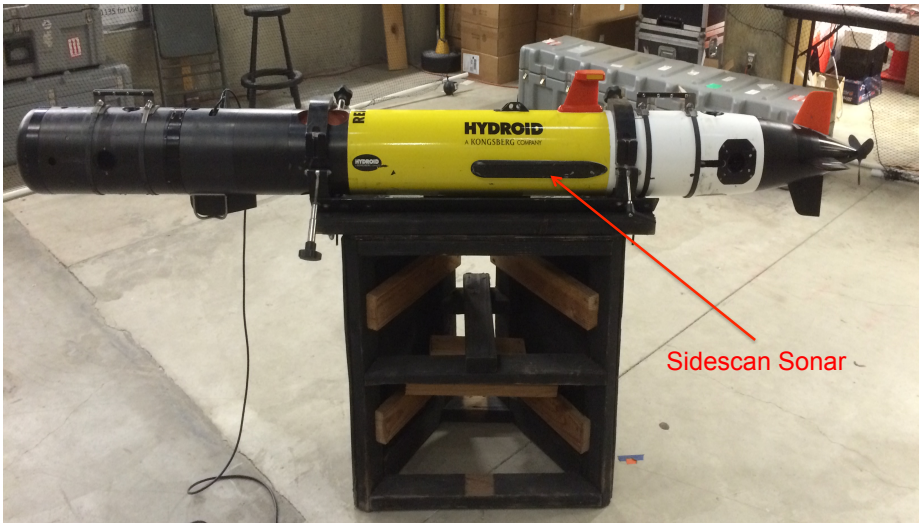
Exploration Vehicle (WIEVLE), which autonomously explores and maps the interior spaces of the target shipwreck. The WIEVLE architecture incorporates many of the best features of the vehicles discussed in the literature review, modified for the DRM of Chapter II. Specifically, WIEVLE incorporates the basic shape, autonomous mapping capability, and low snag features of DEPTHX. DEPTHX also inspired the concept of sensor arcs to eliminate the need for excess maneuvering to position sensors. WIEVLE incorporates some features shared by HAUV, U-CAT, and ACQUAS as well, including the capability to be launched from confined spaces, with or without the use of a delivery vehicle. WIEVLE incorporates some of the aspects of modularity of ACQUAS and the small size (approximately the size of a volleyball), reduced silt-disturbing propulsion and buoyancy control pistons of U-CAT. The vehicle architecture addresses the need for a small, lightweight, low-snag vehicle with silt-out resistant propulsion, autonomous localization and mapping capability for confined environments, data collection, and autonomous decision making, as identified in the capability gaps section of Chapter III. The software development aspects of the vehicle are not discussed, with the exception of a rudimentary logic map for interior mapping, localization, and entrance prioritization. Hardware aspects, however, are explored in greater detail.

1. Physical Architecture Elements

PA1: REMUS DV kit

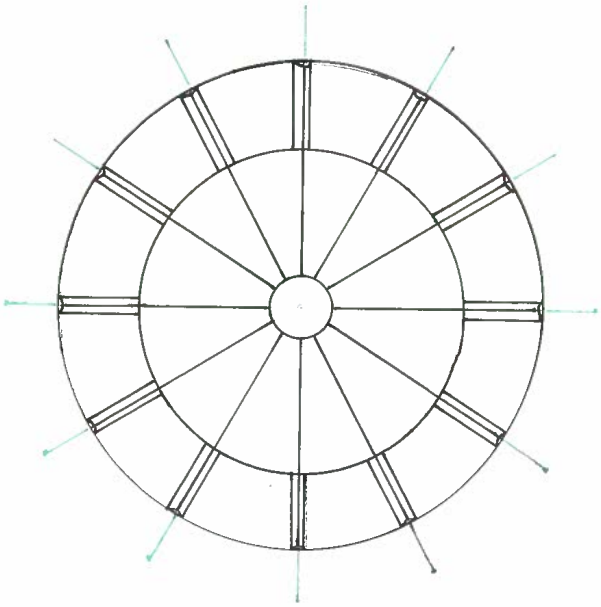
The DV kit attaches to the front of REMUS and consists of two primary subcomponents: the WIEVLE cage and the laser rangefinder array. The REMUS AUV is shown in Figure 31.

Figure 31. REMUS AUV Delivery Vehicle



The laser rangefinder array consists of a narrow, cylindrical band of rangefinders oriented outward from the REMUS central axis, giving the beams a wagon-spoke-like appearance, as shown in Figure 32.

Figure 32. Laser Rangefinder Array

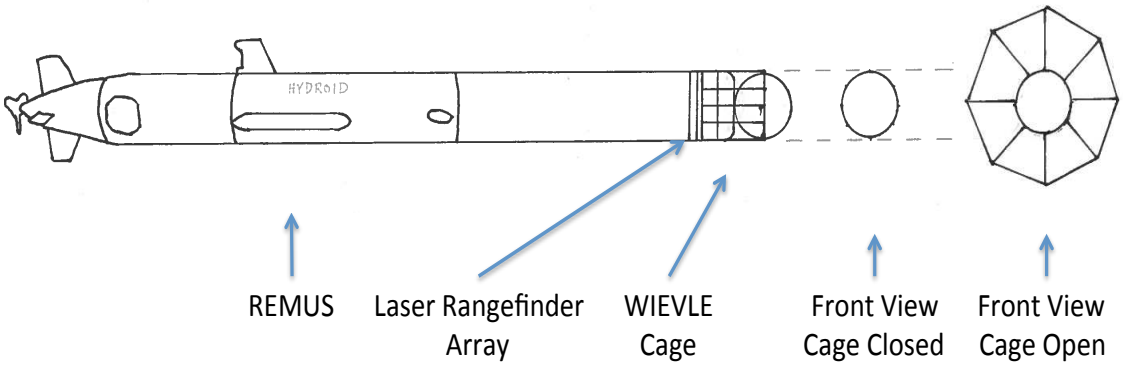


These rangefinders are used to determine when REMUS has sufficiently penetrated the breach in the TS hull to safely deploy WIEVLE. Since WIEVLE is

located forward of the rangefinder array, when a sufficient number of sectored beams intercept a nearby surface, the DV nose is properly positioned within the interior, and the DV may safely release WIEVLE (see Figure 43).

The WIEVLE cage is mounted forward of the rangefinder array on the DV kit. WIEVLE is carried from the HS to the TS within this expandable cage, as shown in Figure 33.

Figure 33. WIEVLE Cage



In the closed position, WIEVLE is secured within the cage with minimal snagging risk. In the expanded position, WIEVLE is allowed to jettison upon insertion into the TS hull. The cage remains in the expanded position at the end of the mission, as WIEVLE returns to REMUS, to aid the docking process. When WIEVLE is in position, the cage contracts to secure WIEVLE for transport back to the HS. A homing navigational beacon, called the origin beacon, is located at the center rear of the basket and provides the final waypoint for WIEVLE's return at the end of the mission (see Figure 44).

PA2: WIEVLE sensor sleeves

The sensors are mounted flush with WIEVLE's outer shell within movable sleeves in order to preserve the smoothness of the exterior surface. The sensor array includes two high-definition (HD) cameras for visual environmental recording with corresponding LEDs for illumination, and two LIDAR scanning sensors, as shown in Figure 34. The LEDs should be oriented such that the beams do not intersect near the camera lens in order to prevent unwanted illumination, known as "bloom-out," of particulate matter close to the lens.

Figure 34. WIEVLE Exterior—Side View

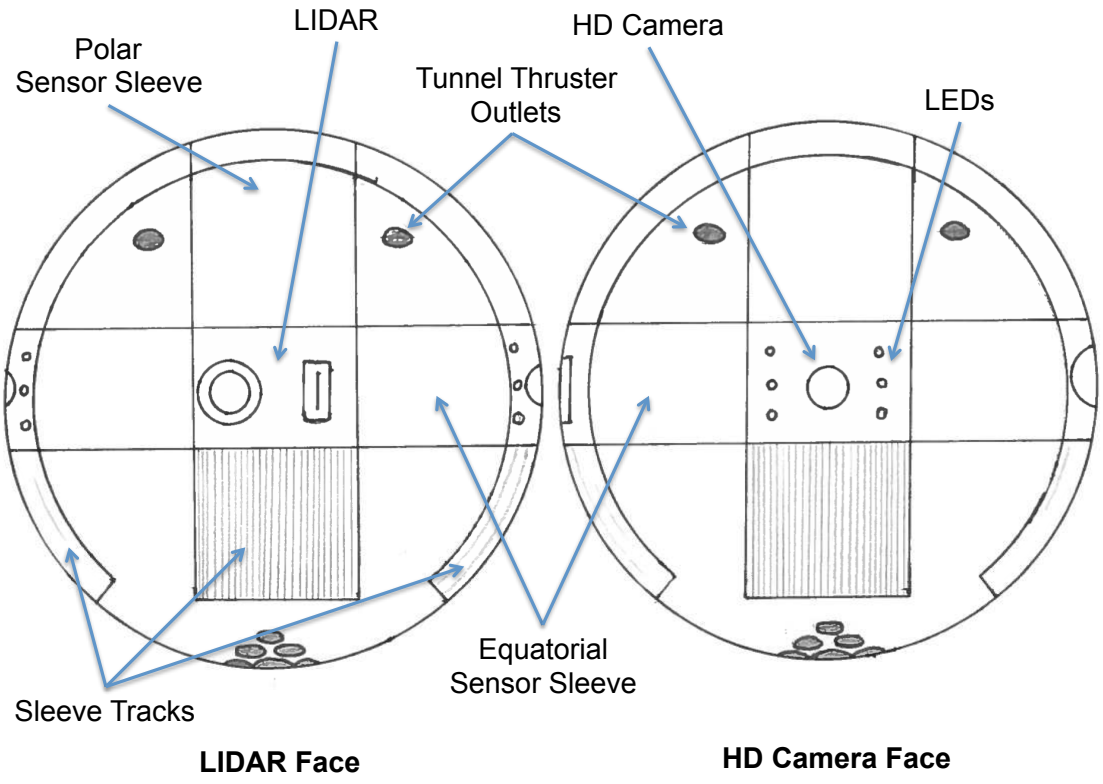
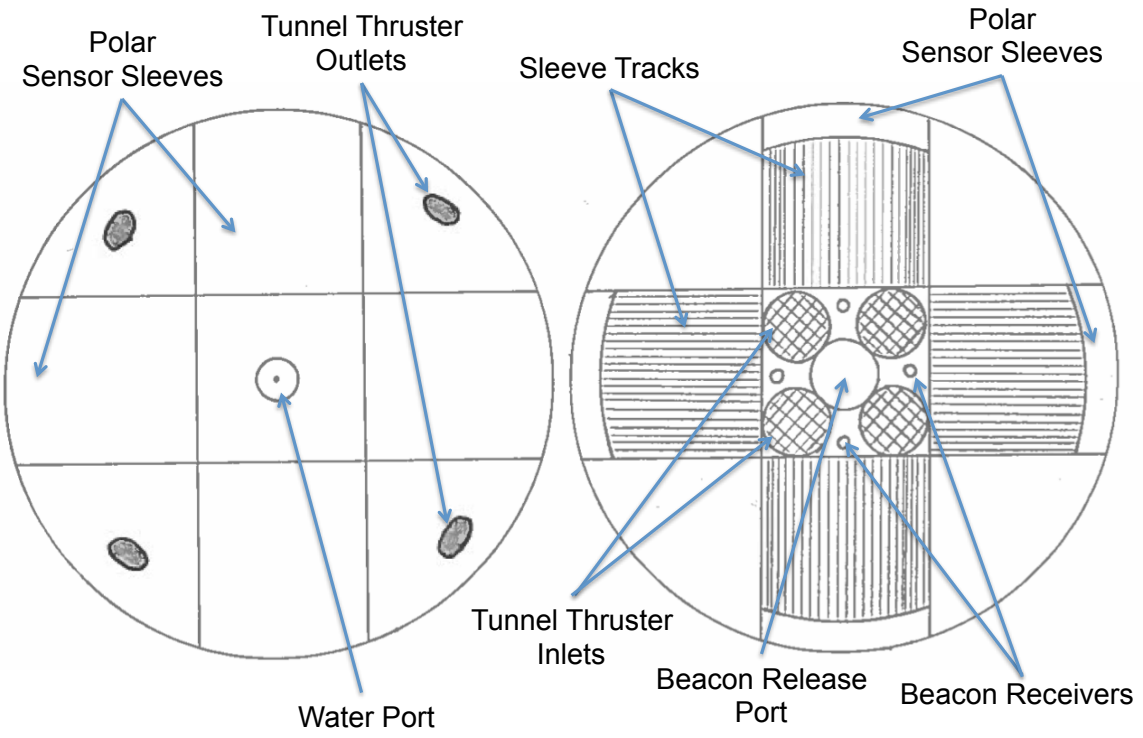
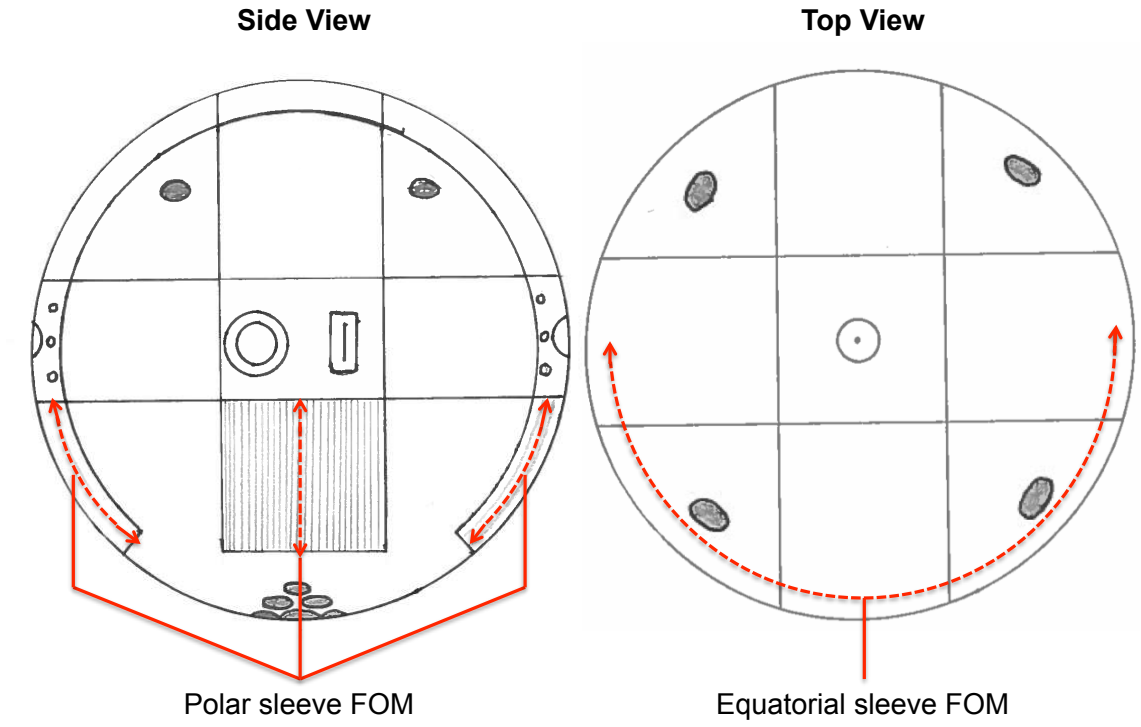


Figure 35. WIEVLE Exterior—Top and Bottom View



Three sleeves, two longitudinal arcs (polar sleeves) and one equatorial circle (equatorial sleeve), enable the four sensor sectors to rotate. The polar sleeves rotate about the geometric center in the vertical plane while the equatorial sleeve rotates up to 180 degrees about the geometric center in the horizontal plane, as shown in Figure 36.

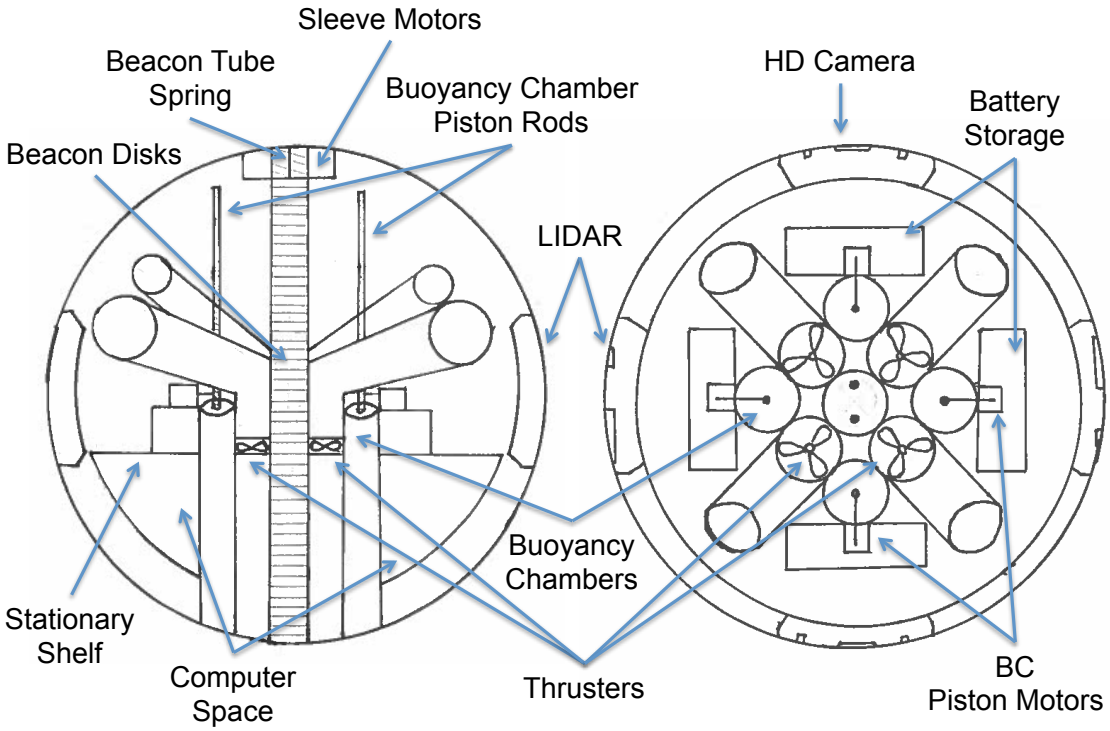
Figure 36. WIEVLE Sensor Sleeve Freedom of Movement



The sensor sleeves rotate on tracks via small electric motors in order to position the sensors during the scanning process. The sleeve's freedom of movement (FOM) is limited to prevent interfering with the tunnel thruster and buoyancy compensator tubes and ports at the bottom of the vehicle. The sensor sleeves lock and unlock the plates in which the sensors are mounted as necessary to allow the plates to be handed off from the equatorial sleeve to a polar sleeve, or vice versa, as necessary. Due to the relatively large field of view of the sensors (50 degrees for the ULS 100 LIDAR), a nearly complete scan of the environment can be achieved. The uncovered regions, two cones oriented along the vertical axis on the top and bottom of the vehicle, will be covered as the vehicle translates in any horizontal direction from the hovering position. A principal benefit of the use of rotating sleeves is the elimination of a great deal of maneuvering necessary for sensor coverage, and consequently, less disruption of silt.

Internally, the vehicle's modular components are positioned symmetrically in order to ensure a distribution of weight that maintains a center of gravity slightly lower than the geometric center, with equal off-axis weight distribution. The distribution of internal components illustrated in Figure 37.

Figure 37. WIEVLE Internal Architecture

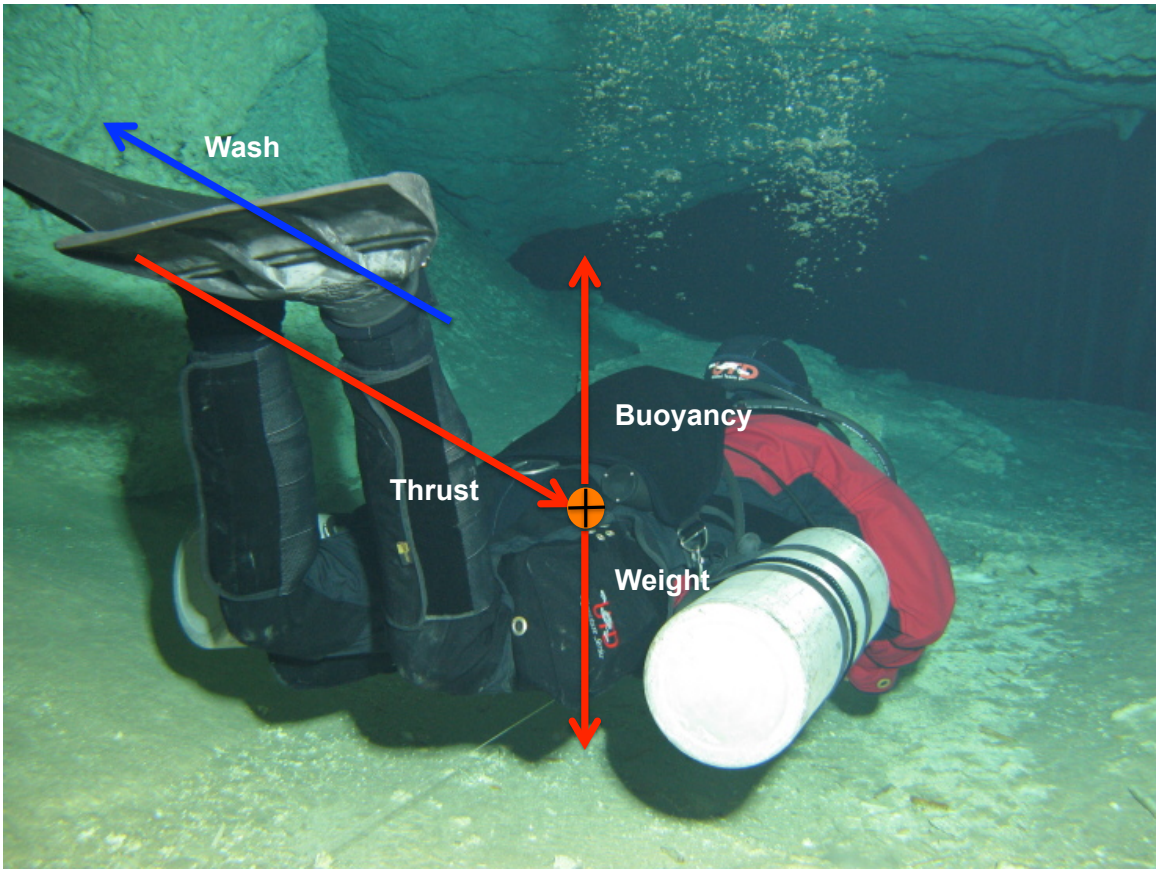


An equipment shelf, located below the geometric center, remains fixed to the vertical tubes, which house the thrusters, buoyancy compensator pistons, and beacons. The equipment shelf is an attachment point for battery storage, computer space and the motors, which drive the buoyancy compensator (BC) pistons. Note the clearance from the shelf to the sensor arrays necessary to allow for the sleeve's FOM. The functions of the thrusters, buoyancy compensators and beacon cylinder shown in the figure will be discussed in following sections.

PA3: WIEVLE flight control system

WIEVLE uses four angled tunnel thrusters to provide propulsion. The tunnel thrusters are located symmetrically about a central vertical shaft that contains the deployable network beacons. Internal thrusters minimize the risk of fouling the propellers on debris. The upward oriented water jets reduce silt-out conditions. Since sediment mostly collects on the floor of the structure, orienting the jets upward avoids the jet path impacting a majority of the silt. This technique is similar to a technical scuba diver's frog kick cycle, as shown in Figure 38.

Figure 38. Technical Diver Executing Proper Form

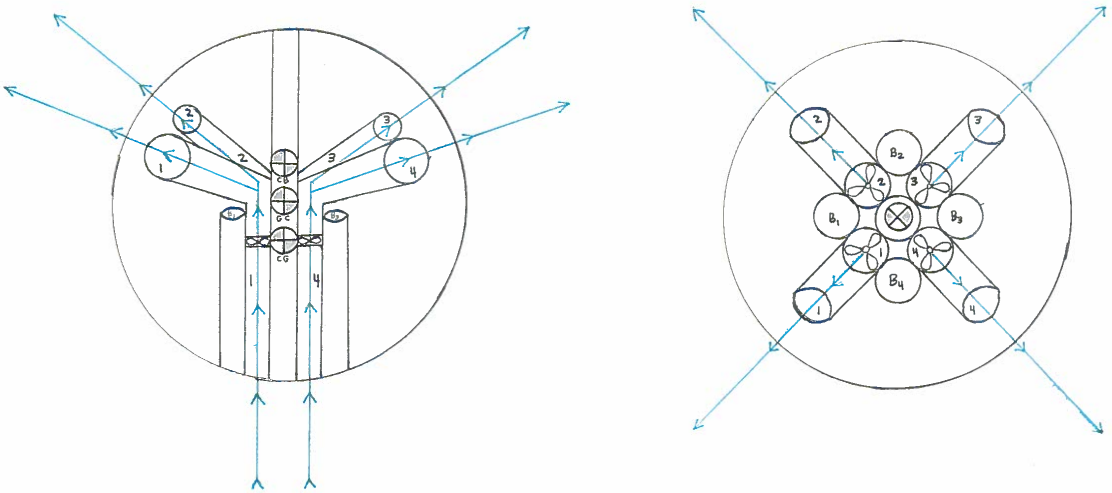


Adapted from: Unified Team Diving. 2015. "UT Side Mount Diving." Accessed Dec. 5. http://unifiedteamdiving.ning.com/group/utdsidemountdiving.

When a diver executes a frog kick, the knees are bent and the fins rotated in small, opposing circles. The horizontal thrust component slowly propels the

diver forward, while the corresponding fin wash is directed upward and aft of the diver, away from the floor sediments. WIEVLE's tunnel thrusters draw water through the four lower inlets. The inlets are guarded with screens to prevent ingesting propeller-fouling debris such as string or wire, and may be cleared of debris if necessary with a momentary reversal of thrust direction (see Figure 35). The flow path of water through the vehicle's internal structure is shown in Figure 39.

Figure 39. Water Flow Through WIEVLE Tunnel Thrusters

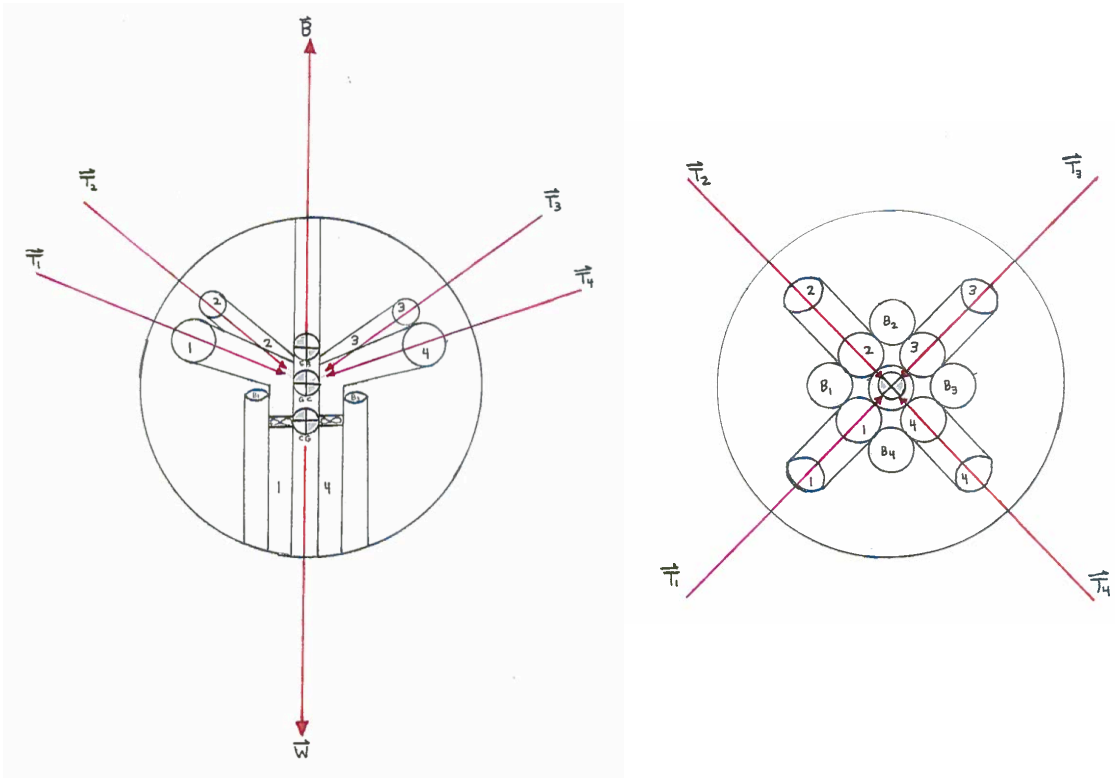


Front View Top View

Note the four tunnel thrusters, labeled 1–4, and the buoyancy chambers, labeled B1–B4. In a stationary hover, the four thrusters produce equal thrust, as necessary to offset the vehicle's buoyancy, while producing no net horizontal thrust. The vehicle's buoyancy is controllable by changing the volume of four airtight pistons located within the buoyancy chambers. To increase the buoyancy of a chamber, the compressed air cylinder piston expands downward, displacing the water out of the tunnel and replacing it with the expanding air. The

corresponding volume increase generates the buoyant force. Likewise, the piston retracts and compresses the air to decrease the buoyancy. The pistons may act collectively or individually to compensate for thrust as necessary. The center of gravity is located below the geometric center, and the center of buoyancy is located above the geometric center to maintain a self-righting attitude. The free body diagram for the hovering state is shown in Figure 40.

Figure 40. Free Body Diagram for WIEVLE in Hovering Mode



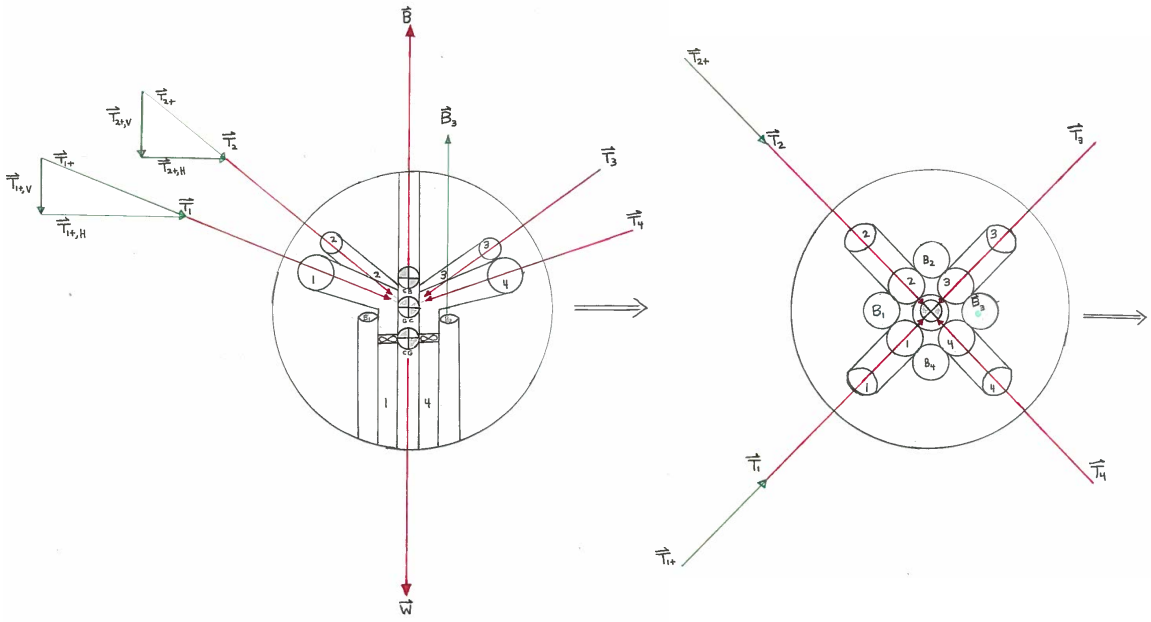
Front View

Top View

Note the thrust forces associated with each tunnel thruster, labeled T_1–T_4, act at the point of flow direction change, near the geometric center. The weight, W, acts at the center of gravity, and the net buoyancy, B, acts at the center of buoyancy. With the tunnel thrusters providing equal and sufficient force to offset the buoyancy, the vehicle hovers in static equilibrium. To move forward, the thrust from any two thrusters can be increased to produce a net horizontal

component of thrust that allows the vehicle to be propelled in any direction within the horizontal plane. The free body diagram for the forward flight state is shown in Figure 41.

Figure 41. Free Body Diagram for WIEVLE in Forward Flight



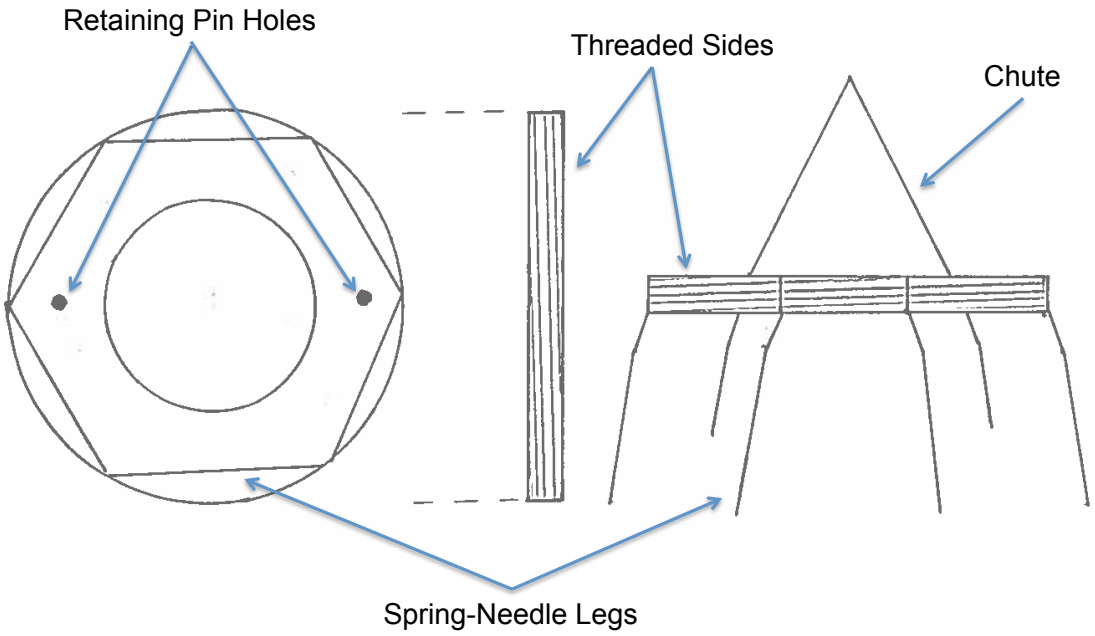
Front View Top View

Note the additional thrust component vectors, T_{1+} and T_{2+}, which produce a net positive horizontal thrust (to the right) allowing translation. To move forward without sinking, the vehicle's buoyancy is increased to offset the increase in the net vertical thrust that results from increasing the output of tunnel thrusters 1 and 2. The buoyancy chamber opposite thrusters 1 and 2 is activated for this task. The net buoyant force is increased sufficiently to prevent the vehicle from sinking. The clockwise moment about the center of gravity caused by the increased thrust is counteracted with a counterclockwise moment caused by the increased buoyancy from B_3. Adjustment of either total vehicle buoyancy or net vertical thrust allows the vehicle to translate in the vertical plane and regulate buoyancy throughout the mission, as the network beacons are dropped.

PA4: WIEVLE deployable network beacons

WIEVLE houses multiple navigational beacons within a sealed pressure cylinder along the vehicle's vertical axis. These individually identifiable beacons are deployed to establish the navigation network. The low profile, camouflaged beacons are disk-shaped and stack tightly within the cylinder to eliminate wasted space.

Figure 42. Deployable Beacon



The beacon cylinder contains a spring and a water port at the top. The spring maintains downward pressure on the watertight plunger, which presses down on the beacon stack to ensure a reliable feed at the bottom of the vehicle. The water port allows a small volume of water to enter the cylinder above the plunger, after each beacon deployment, to replace most of the weight lost and reduce the need for internal buoyancy compensation. As shown in Figure 42, the disks contain two small holes on opposite sides of the central axis. Two corresponding rods, secured at the top of the vehicle near the spring and water port, extend through these holes, preventing the disks from rotating. The disks

edges are threaded, allowing them to be screwed into a threaded sleeve, which fits snugly inside the beacon cylinder. The threaded sleeve is rotated inside the beacon cylinder by an actuator motor when a beacon dispense command is received from the onboard computer, and the lowest beacon is screwed out at the bottom of the tube. A thin metallic wafer separates each beacon to shield the lowest disk from the ambient water.

The disks are slightly heavier than water and sink upon release. As the beacon sinks, a small cone-shaped chute is pushed upward by initial water flow and acts as a drag chute to keep the disk vertically oriented (see Figure 42). The water activates the beacon by completing an electrical circuit, similar to a standard dive watch. Water-soluble epoxy secures six spring-needle legs in place along the top of the beacon during storage in the cylinder. When released, the epoxy quickly dissolves and the legs swing down into the landing position. The needle-sharp legs allow the beacon to land on various surfaces, which may be slanted or covered with a layer of silt or slime, and resist sliding or tumbling after contacting the surface, thus preserving the integrity of the map.

2. Functional Architecture Elements

FA1: REMUS AUV DV is launched from the HS

A submerged Virginia-class submarine launches a REMUS AUV (the delivery vehicle) from its dry dock.

FA2: REMUS searches for the TS

REMUS descends to the search pattern depth (approximately 20–30 m.) and commences its search of the sea floor for the target submarine using its side scan profiling sonar. This dual frequency (900 kHz and 1800 kHz) sonar propagates from each side of the vehicle in a fan with an average range of approximately 80 m. (see Figure 31).

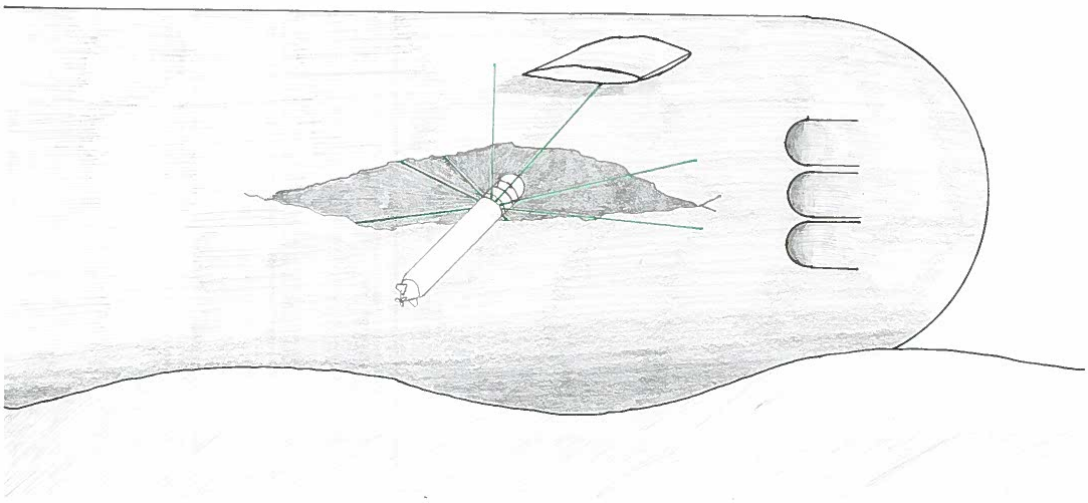
FA3: REMUS conducts a TS hull survey

Upon locating the target, REMUS transitions its flight path and begins conducting an external hull survey, looking for a breach in the hull, using its micro-bathymetry profiling sonar—a high-resolution, 2250 kHz sonar with a 10 m. maximum range—and, upon locating a potential breach, a dual-axis imaging sonar for even higher resolution.

FA4: REMUS deploys WIEVLE into the TS interior

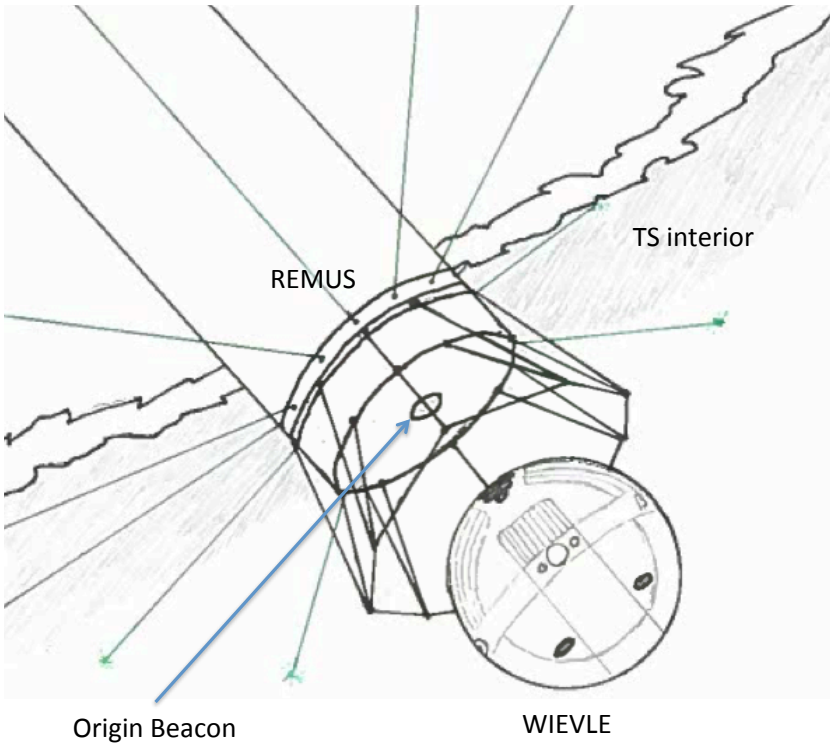
Upon discovering a suitable breach, REMUS hovers nose-forward into the hole, stabilizing itself relative to the hull. Using its laser rangefinder array, REMUS determines that it has sufficiently penetrated the TS hull to safely deploy WIEVLE. Figure 43 depicts the delivery of WIEVLE to the TS hull breach.

Figure 43. REMUS Inserts WIEVLE Through Target Submarine Hull



When these conditions are met, REMUS releases WIEVLE by opening the cage, and WIEVLE propels itself away from REMUS with a thrust burst. Figure 44 depicts the delivery of WIEVLE to the TS interior.

Figure 44. REMUS Deploys WIEVLE Into the Target Submarine Interior



Upon undocking, the origin beacon is activated in REMUS, which continues to hover in place at the entrance.

FA5: WIEVLE commences TS interior exploration

WIEVLE begins executing the interior exploration by scanning and translating through the interior. As the vehicle travels, it scans and records the wreck interior by systematically rotating the sensor sleeves.

FA6: WIEVLE localizes while building the 3D map

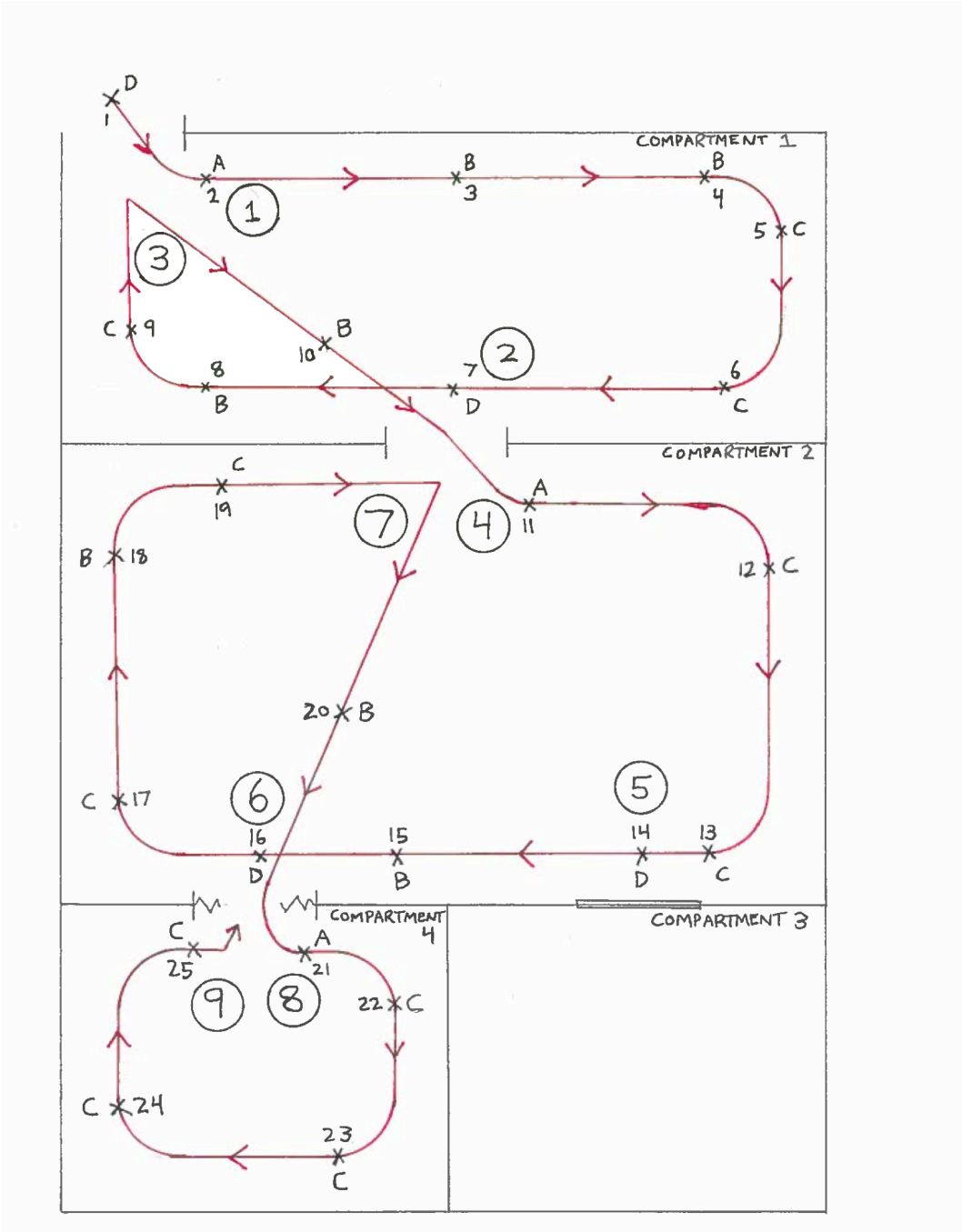
As WIEVLE begins its exploration, it initially records and monitors its relative vector to the origin beacon on REMUS. This beacon becomes the origin of the 3D map it will create by laying its beacon network, as well as the exit point of the escape path it will maintain throughout the mission. Upon translating the necessary distance interval, it releases the first deployable network beacon, which sinks to the floor. The beacons are deposited throughout the interior to create a network grid, as shown in Figure 45.

WIEVLE assigns an identifier for each beacon released at nominal distance intervals or specific events, such as the turning of a corner in the 3D flight path. The vehicle maps the interior using its LIDAR without the need for SLAM since geo-rectification of the map may be attained with the numbered beacons. Thus, the beacon disks both aid in the creation of the map and become a sort of “bread crumb trail” leading back to REMUS.

FA7: WIEVLE executes a complete, systematic search of the TS interior

WIEVLE assesses the map completion status of each compartment within the TS. The vehicle continues the scan until the compartment is fully mapped while simultaneously looking for an entrance to another compartment or a potential hatch to breach. Open, obstructed and closed entrances are noted on the map and prioritized in that order, with open entrances assigned priority over closed or obstructed entrances. The identification of an entrance, such as a hatch, window or door, is a target recognition problem that will not be addressed in this work. Upon completion of the mapping of a compartment, the vehicle continues the exploration by moving to the priority entrance or returning to the DV. In Figure 45, a four-compartment generic shipwreck space is represented.

Figure 45. WIEVLE Beacon Network



Each compartment has either an open, closed, or partially obstructed hatch. The vehicle begins the exploration in compartment 1 at the top of the figure. Each beacon release point is annotated on the diagram with a numbered

“x.” Each beacon is also labeled with a letter corresponding to the logic for the beacon release. “A” represents beacons released at the beginning of a new compartment search. “B” represents beacons released after translating a nominal distance along the wreck interior. “C” represents beacons released after turns greater than a nominal number of degrees. “D” represents beacons released to mark the location of an entrance. The large, circled numbers represent the following major events:

1. WIEVLE begins exploring compartment 1.
2. An unobstructed entrance is noted.
3. Compartment 1 scan is complete and WIEVLE decides to move to the priority entrance (at beacon 7).
4. WIEVLE begins exploring compartment 2.
5. A closed hatch entrance is noted.
6. An obstructed hatch entrance is noted.
7. Compartment 2 scan is complete and WIEVLE decides to move to the priority entrance (at beacon 16).
8. WIEVLE begins exploring compartment 4.
9. Compartment 4 scan is complete, no further exploration is possible (due to the closed hatch of compartment 3), thus, WIEVLE decides to end the mission and return to the DV. The updated escape path at Event 9 (beacon 25) is 16 – 20 – 7 – 2 – 1.

FA8: WIEVLE overcomes obstacles when necessary.

To overcome an obstacle, the vehicle must maneuver around it, move it, or destroy it. Maneuvering around the obstacle is the preferred method. To maneuver around the obstacle, the vehicle must first sense the obstacle and a potential path around the obstacle. The vehicle then alters course to navigate around the obstacle or through the gap. If the vehicle determines the obstacle cannot be avoided, but a suitable space exists beyond the obstacle, then it must decide to attempt to move the obstacle, destroy the obstacle, or abort the effort. If the vehicle aborts the effort, it may continue exploring another reprioritized

compartment or return to REMUS. If WIEVLE decides to move the object, it may attempt to push past it. The smooth design of the vehicle is helpful in this effort, yet the blunt nature of a sphere and the limited power of non-horizontally configured thrusters hinders this effort. One potential option for reducing the risk of damage to the sensors as the vehicle pushes past movable obstacles, such as dangling wires or insulation, is to rotate the sensors out of direct contact with the obstruction during the push through.

3. WIEVLE Architecture Map to General Functional Requirements

The physical architecture elements (PAEs) and functional architecture elements (FAEs) are mapped to the corresponding general functional requirements of the previous chapter in Table 10.

Table 10. Architecture Map to Functional Requirements

PAE	Requirements	FAE	Requirements
1	7, 34	1	1
2	9, 10, 11, 12	2	2, 3, 4
3	8, 9, 16, 17, 18, 30, 31, 32, 33	3	5, 6
4	13, 14, 15, 21, 23, 30	4	7, 8
		5	9
		6	11, 13, 14
		7	13, 14, 15, 19, 22, 24
		8	25, 26, 27, 28, 29

4. Future Versions

The WIEVLE architecture, as described in this chapter, encompasses one possible solution to most of the essential tasks identified for wreck interior exploration. Many changes will inevitably take place in future iterations throughout the preliminary design, detail design, and prototype testing phases. Looking forward, one may speculate options for future versions of the system. The ability to overcome challenging obstacles and collect targets of opportunity are two such potential versions.

The ability to overcome obstacles is satisfied in a very limited manner by the first version of the vehicle (WIEVLE 1.0). As mentioned in the functional architecture discussion, the vehicle's only course of action, given an autonomous decision to move (or move through) an obstacle is to push it in an attempt to slide past. No capability to destroy the obstacle exists. The drawbacks of this technique were also mentioned. In version 2.0, the vehicle might incorporate gripper arms to assist in the moving of light objects such as wires, monofilament and other relatively benign obstacles. Perhaps the arms could take the form of an arc that extend from the equatorial sensor sleeve, or coiled from within the vehicle. A simple gripper could be replaced or assisted by a cutting tool, perhaps in the form of sheers or a rotary cutting bit. Heavier obstacles, such as fallen pipes or closed metal hatches, present a much more formidable problem. The delivery of explosives to the obstacle, though possible, would likely silt-out the wreck and possibly destroy or entrap the vehicle. The use of thermal cutting devices might overcome some of these obstacles. Dragging gas lines through the wreck is unlikely to be successful, but non-gas underwater cutting methods, such as the use of a thermite pyrotechnic cutting tool, present a possibility. A flexible thermite rope may be fixed around an object in order to destroy or cut through it by heat without sending a silt-disturbing shock wave throughout the wreck.

Another consideration for a version 2.0 WIEVLE is the ability to retrieve targets of opportunity. If the vehicle's capacity for thrust and collective buoyancy were high enough, the vehicle may have the ability to lift small objects from areas within the wreck and bring them back. Besides the necessary lifting force and propulsive power, the vehicle would need sufficient controllability while loaded to maneuver along the escape path and back to the DV. Even if the vehicle returns with the object, however, the trip back to the HS through potentially high currents while carrying the load may prove either impossible or a recovery hazard for the HS. Perhaps WIEVLE's strongest contribution to the physical object collection effort would be to mark the location of a target of opportunity on the map and

collect sufficiently high-resolution video and mapping data to provide a positive identification for a future collection effort with another vehicle.

The use of other vehicles, in combination with WIEVLE, as part of a system-of-systems, is a potentially optimal approach for problems of such complexity as the full exploration and exploitation of an underwater shipwreck. Specialized vehicles, perhaps cooperating with one another, are, in the author's opinion, much more likely to be successful in the hostile and technologically challenging environment of shipwreck interiors. Adding "bells and whistles" to any vehicle design until it becomes a Swiss army knife will more likely result in the vehicle's inability to do anything well.

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VI. CONCLUSION

The objective of this thesis was to develop, using a systems engineering approach, a functional analysis, general requirements, key performance parameters, and high-level architectural tradeoff considerations leading to an architecture synthesis for an AUV capable of shipwreck interior exploration.

A. SUMMARY

Throughout this thesis, the research questions posed in the introductory chapter were addressed. In Chapter I, the first primary research question set the stage for the design reference mission: What type of challenging AUV mission might be of interest to the Department of the Navy? The exploration of shipwreck interiors by an AUV was presented as a challenging and important potential mission for a number of key stakeholders, including the Department of the Navy. The absence of an existing solution for this mission was described. A brief synopsis of the history of shipwreck exploration, the specific importance of shipwreck interior exploration, a background on UUVs and a discussion of AUVs set the stage for an enhanced understanding of the DRM of Chapter II.

The DRM described, in specific detail, the Soviet nuclear submarine *Komsomolets,* the background of her sinking, important characteristics of her construction and the environment in which she rests. A hypothetical reference mission was then offered, detailing a specific objective and describing potential intelligence collection targets. Following the DRM, the second primary research question was asked: What high-level alternatives exist for such a mission? Four high-level alternatives were then discussed in detail. The benefits and drawbacks of traditional human shipwreck penetration, human shipwreck penetration using atmospheric suits, ROV shipwreck penetration, and the covert raising of the submarine itself were all established. Following this, the decision to proceed with an AUV system solution to the mission was justified and the preliminary mission planning was begun. After laying out the key assumptions, the next important

research question was raised: What are the high-level essential tasks for the mission laid out in the DRM? The resulting nine tasks became the bedrock for the remaining research effort. The principal constraints were then discussed, outlining first the expected operating conditions during the submarine loading and transport phase, the submarine launch phase, the target exploration phase, and the recovery phase. Logistic considerations and time constraints were followed by a detailed assessment of expected environmental threats to the mission and the vehicle itself, to include entanglement, silt-out, strong and unpredictable currents, abrasion puncture and shock damage, temperature and pressure variations, toxic substances, corrosion, failure to collect the required data and compromising the secrecy of the mission due to signature at the target site.

In Chapter III, the problem space was developed, beginning with the answer to the fourth research question: What are some of the potential stakeholder's effective needs? The resulting needs analysis began by identifying the stakeholders and carefully considering the value each could receive from an AUV solution to the problem. The needs were refined into effective needs statements for each stakeholder. The chapter concluded with the answer to the next research question: What would the scope of such a mission look like? The purpose of the effort, division of future life cycle responsibilities among systems engineering, program management, and Defense Department personnel, and operational context—culminating in the creation of an operational concept graphic, context diagram and definitions, followed. Within the discussion of project scope, the next research question was answered: What are the relevant concerns and objectives? The identification of principal concerns began with a list of the characteristics of a perfect vehicle and a discussion of the key concerns of an actual AUV solution. The system objectives were then discussed, with a mention of the system capabilities outside the scope of the effort of this thesis.

The literature review, contained in the second half of Chapter III, provided detailed discussion of the architecture of some of the most relevant existing AUV

systems. The vehicle descriptions and methodologies for DEPTHX, HAUV, ARROWS (including U-CAT) and ACQUAS provided the answer to the critical research question: What are the characteristics of the architecture and methodology employed by existing AUVs for the exploration and mapping of other unexplored three-dimensional environments? Following this analysis, the advantages and disadvantages, with respect to wreck interior exploration, of each vehicle's architecture were generated in four tables. The analysis that followed answered the critical research question: What are the corresponding capability gaps? Five primary gaps were identified: 1) vehicle size, shape and weight, 2) vehicle propulsion and control capability, 3) vehicle localization and mapping capability, 4) vehicle data collection, storage and processing capability, and 5) vehicle autonomous decision-making capability.

Chapter IV detailed the general functional analysis and requirements generation that answers the research question: What are the functions and requirements of an effective AUV solution? The resulting functional decomposition resulted in 11 primary functions, with sub-functions up to two levels down decomposed from these. In keeping with standard systems engineering discipline, the functions were then mapped back to the effective needs. A requirements analysis then followed, resulting in the generation of 38 general requirements, which were then mapped to the high-level essential tasks. Non-functional requirements were then explored, examining the system attributes of modularity, autonomy, vulnerability, reliability, availability, maintainability, testability, adaptability, affordability, compatibility, interoperability, modifiability, portability, recoverability, reusability, and usability. This resulted in the generation of 39 non-functional requirements. All requirements were then mapped back to the original stakeholder needs, and seven key performance parameters were established.

Chapter V harvested the effort sown in the first four chapters by synthesizing one possible architectural solution to the DRM. The chapter began with an examination of five key architectural tradeoff considerations, thus

answering the final research question: What key tradeoffs should be considered in the architecture synthesis? After discussing the advantages and disadvantages of tethered and untethered vehicles, vehicle size, vehicle shape, propulsion method, and the use of LIDAR and sonar, a wreck interior exploration vehicle (WIEVLE) architecture was developed. The physical architecture elements were described first, followed by the functional architecture elements. The architectural elements were then mapped to the general functional requirements of Chapter IV. The chapter concluded with recommendations for possible future versions of the vehicle.

B. GENERAL RECOMMENDATIONS FOR FUTURE ARCHITECTURE DEVELOPMENT

Based on the analysis of existing systems and the problem space, the author recommends that future architectures include the following characteristics:

- small outer dimensions (approximately the size of a basketball)
- smooth, preferably round, solid outer surfaces with flush-mounted sensors
- minimum weight
- tunnel thrusters, or guarded propellers
- maximum sensor freedom of motion and field of view
- minimal required maneuvering for sensor positioning
- robust, reliable and precise mapping and localization capability
- robust and conservative autonomous decision making capability

C. AREAS FOR FUTURE RESEARCH

In addition to the future versions of WIEVLE discussed at the end of the previous chapter, much work remains in the development of autonomous underwater vehicles for exploring shipwreck interiors. Continuing with the development of WIEVLE is one possible avenue. A preliminary design, leading to a prototype, would undoubtedly bring significant change to the physical and

functional architectures in future iterations. Another avenue is the development of other, supporting AUVs, which might aid a vehicle like WIEVLE in the exploration effort as a part of a system-of-systems. Yet another fascinating area for future research leaves the realm of AUVs entirely—the development of a low-profile, highly-capable atmospheric suit, enabling human shipwreck penetration under atmospheric conditions. Perhaps the attractiveness of such a solution owes largely to man's inherent desire to go to extreme environments and see the mysteries first hand. Each of these avenues, if pursued in earnest, could potentially yield a trove of new and valuable discoveries.

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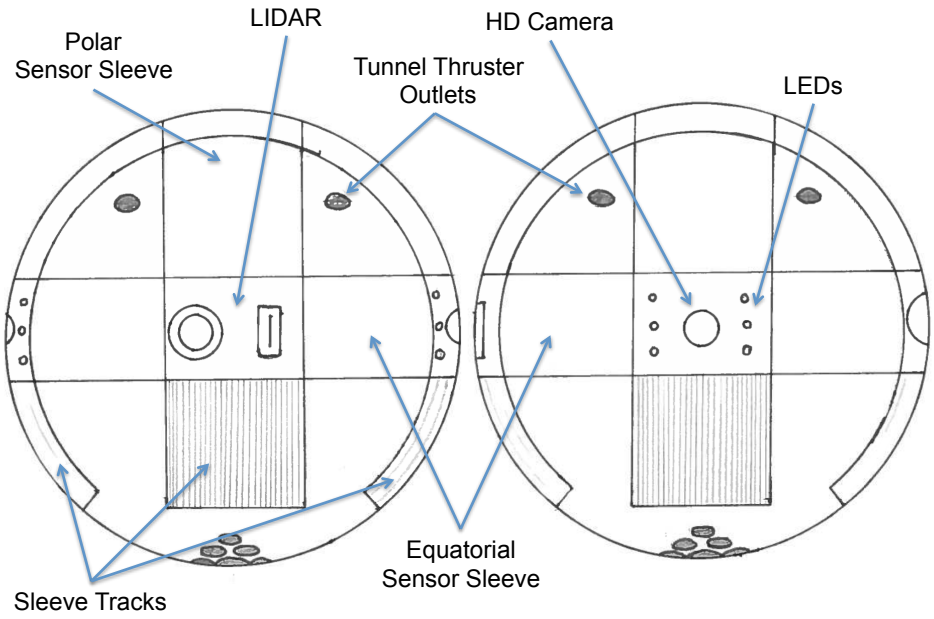
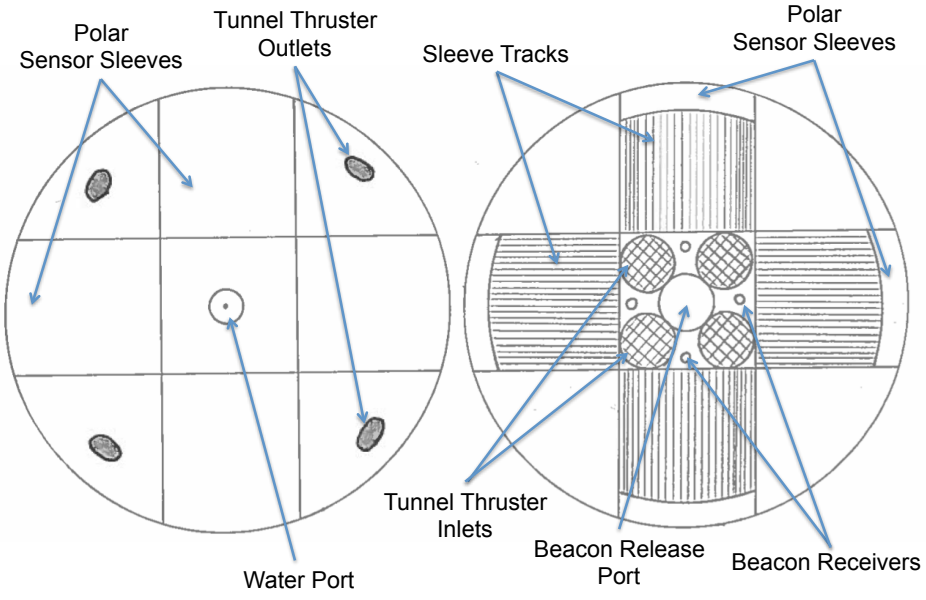
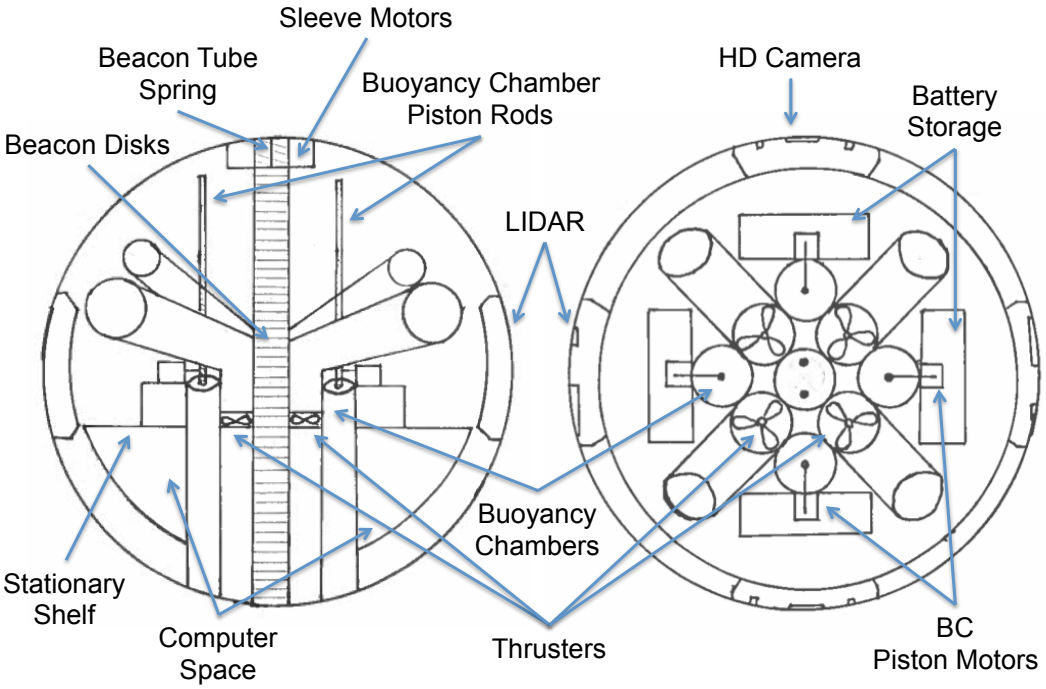
APPENDIX

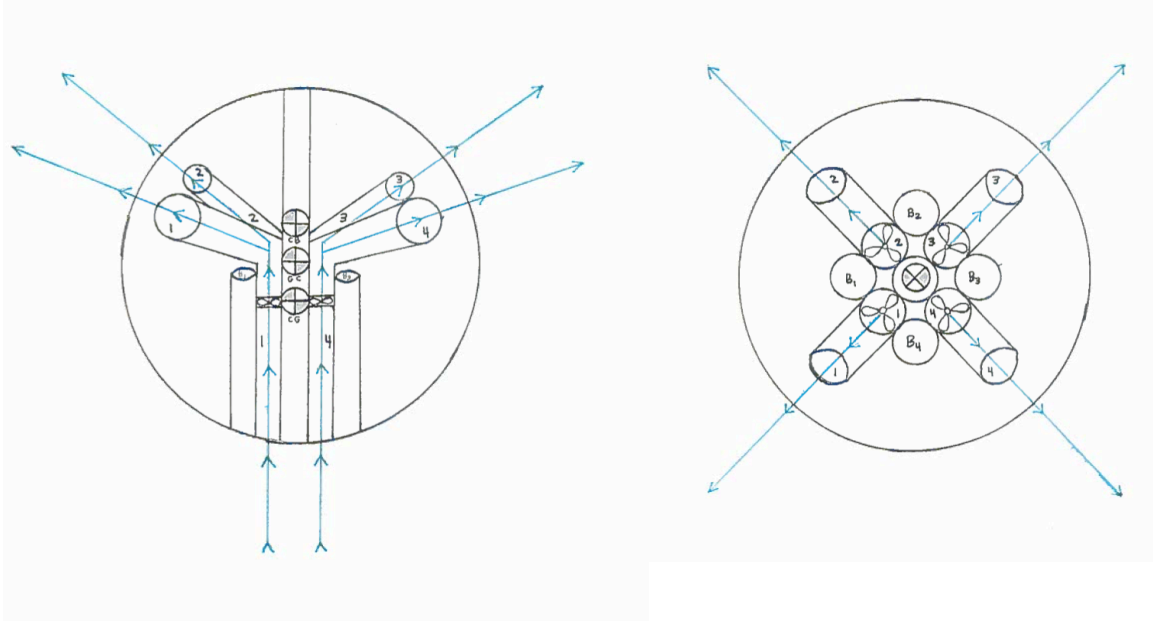


LIDAR Face **HD Camera Face**



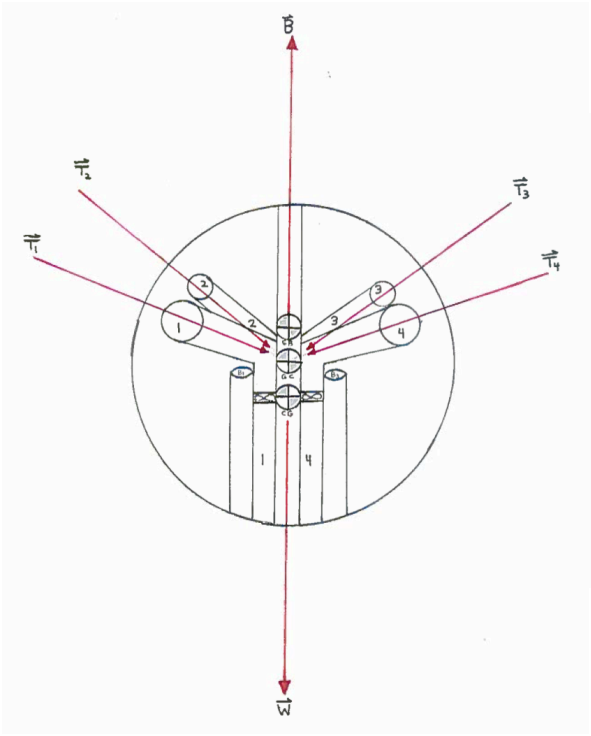
Top View **Bottom View**



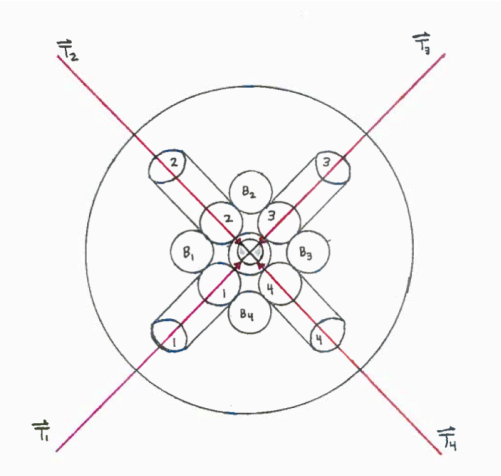


Front View

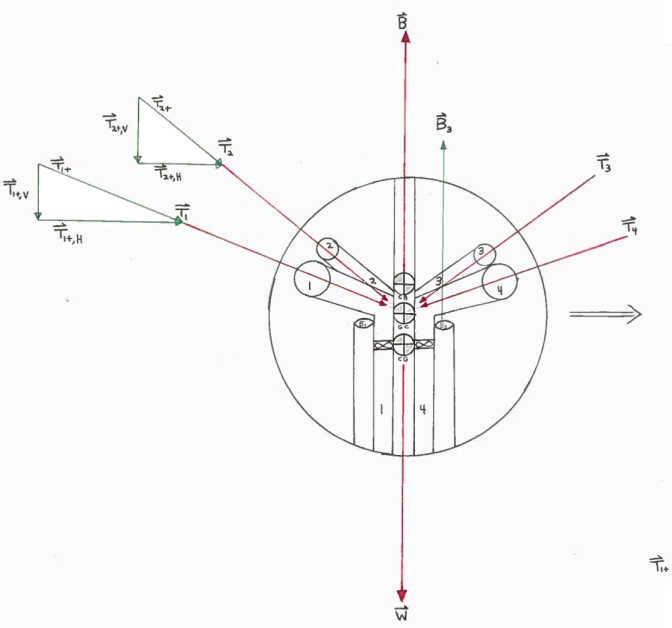
Top View



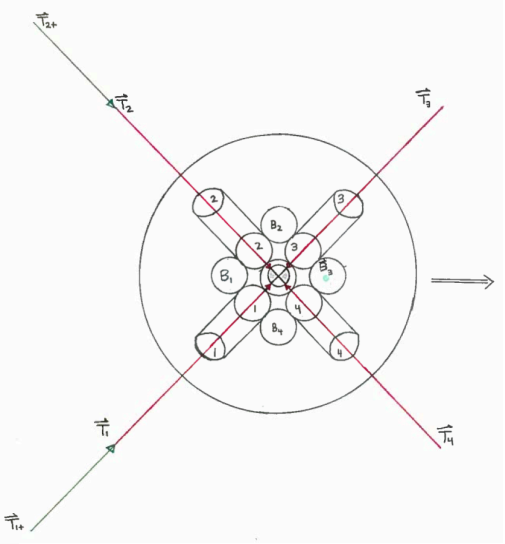
Front View



Top View



Front View



Top View

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