CUTLASS:

Coral Reef, Underwater Terrain, and Littoral Archaeological Site Surveyor

by

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Doctor of Philosophy

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ABSTRACT

Undersea scientific ocean exploration and research only began in earnest approximately 150 years ago. Much has been learned and discovered in that time, but there are also gaps in understanding of the ocean depths. One source of the knowledge gap is the relative lack of crewed exploration in some regions of the ocean. This work presents a vehicle that provides divers with longer time at deeper depths than is currently available in an unpressurized environment, reduces diver workload, and improves situational awareness. Working in collaboration with the scientific diver community, top-level requirements were defined, and a Concept of Operations was developed. This effort is followed up with a vehicle design which provides the capability for two divers to complete unpressurized dives to 200 meters, remain there for 20 minutes, and return to the surface within 12 hours. Additional functionality provided by the vehicle includes significant cargo capacity, voice and data communication with the surface, geolocation capabilities, and automated maneuvering and decompression management. Analysis of the hull shape and propulsion system is presented which demonstrates that the vehicle can reach its velocity and acceleration performance requirements. A virtual environment is then presented which has the potential to allow for end-to-end mission performance evaluation. Finally, the constraints on the life support system are discussed and source code for a simulation is presented. The final chapter of this work examines a hypothetical mission to 200 meters depth. The various phases of the mission are discussed as well as the potential consumption of both oxygen and electricity. Two life support gas mixtures are examined, and the resulting decompression profiles are presented. The final analysis

shows that it is possible to conduct dives to 200 meters, perform 20 minutes of work, and return to the surface within 12 hours using the CUTLASS vehicle that is presented.

DEDICATION

For Hope. Without her support this would never have been possible.

ACKNOWLEDGMENTS

I would like to thank Dr. Paul Scowen for his guidance and advice over the last several years of this effort. I would also like to thank each of the committee members for their willingness to participate in this journey. Special thanks to Basilio, Blaze, Johnathan, and Cooper for their contributions to this effort.

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CHAPTER 1

UNDERSTANDING AND IMPROVING OCEAN EXPLORATION

Oceans cover approximately 71% of the Earth's area (Eakins & Sharman, 2010) (NOAA, 2021). Given the importance of, and significant area covered by, water on this planet, one would think that the world's oceans would be well explored; sadly, this is not the case. In fact, "more than eighty percent of this vast, underwater realm remains unmapped, unobserved, and unexplored (NOAA, 2021)." Scientific exploration below the surface is a relatively new endeavor. The 1872 HMS Challenger expedition began the era of real undersea exploration; it lasted just over 1000 days, and when completed, the resulting report took 50 volumes and 23 years to publish (Challenger Society for Marine Science, 2022). Today's expeditions do not last nearly as long, nor take 23 years to publish the results, but they continuously push the boundaries of engineering and exploration. From Jacques Cousteau's Aqua-Lung to James Cameron's Deepsea Challenge, crewed exploration of the oceans has made significant advances, but there are still gaps and limitations in our knowledge. The work presented here will explain the exploratory needs, the challenges associated with exploration, how far ocean exploration has come, and what still needs to be done. A crewed exploration vehicle that addresses these knowledge gaps will be detailed, including a hypothetical excursion relying on this enabling technology.

Oceans of the World

Earth is unique within our solar system. Not only are we the only planet known to support life, but we are also the only planet known to have liquid water on the surface. This liquid water "is essential for the kind of delicate chemistry that makes life possible

(NASA, 2007)." In addition to providing the chemistry necessary for life as we know it, the oceans help regulate the temperature of the planet and drive the weather. There are five recognized oceans and several minor seas. Collectively, seawater covers about 363 million square kilometers (Eakins & Sharman, 2010). Each of the oceans and seas has different characteristics that make it unique in its challenges and discovery opportunities.

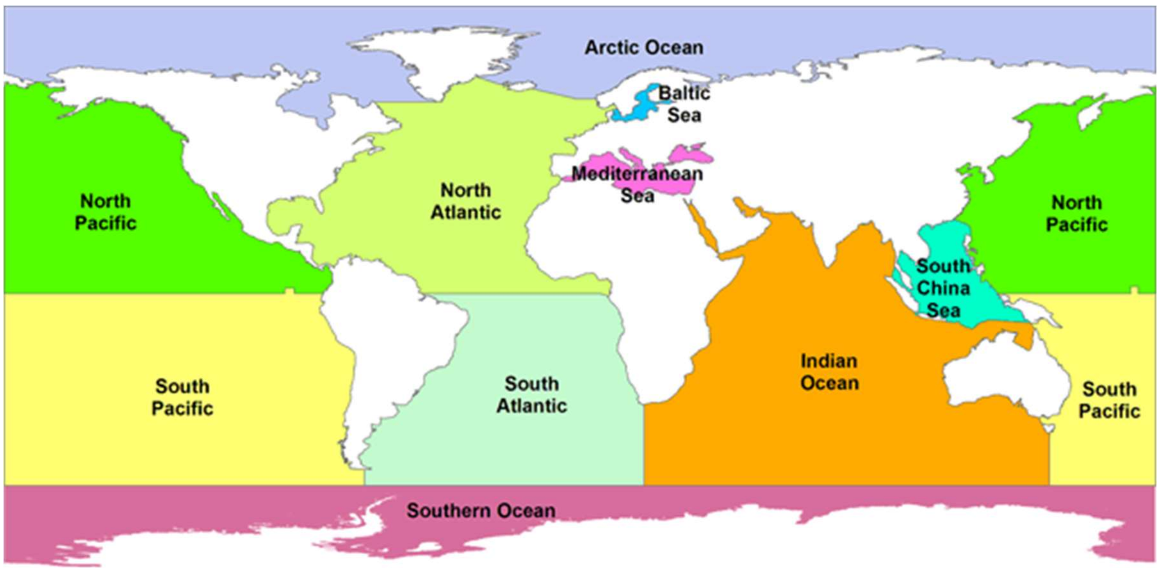

Figure 1: *Ocean Boundaries for Volume Calculations* – ETOPO1 Global Relief Model was used to calculate the volumes of the Earth's oceans and seas. The boundaries "include only major oceans and marginal seas and … the Southern Ocean south of 60°S (Eakins & Sharman, 2010)".

The Arctic Ocean is situated to the extreme north of the planet and contains about 4.3% of the ocean surface area (Eakins & Sharman, 2010). Due in large part to the climate and the accessibility of the region, the "Arctic Ocean is largely unexplored, especially those aspects not visible to the human eye from a surface ship or to a satellite sensor (Crane, Potter, & Hopcroft, 2005)." What exploration has occurred in the Arctic has generally been driven by gas and oil companies.

The Atlantic Ocean is comprised of the North Atlantic Region (which includes the Caribbean Sea), the South Atlantic Region, and the Baltic and Mediterranean Seas. The Atlantic Ocean is the second largest ocean by both area and volume and is bounded by Africa and Europe to the east, North and South America to the west, the Arctic Ocean to the north and the Southern Ocean to the south. (Eakins & Sharman, 2010) (Central Intelligence Agency, 2022). The Atlantic Ocean makes up approximately 23.5% of the surface area of the ocean and 23.3% of the total volume of ocean water on the planet (Eakins & Sharman, 2010). The Mediterranean Sea portion of the Atlantic Ocean region, while covering only 0.8% of the surface area of the planet, accounts for 7.5% of the global ocean biodiversity (Eakins & Sharman, 2010) (Danovaro, et al., 2010). This concentration of biodiversity, coupled with the ease of access from southern Europe and year-round mild climate, makes the Mediterranean Sea a particularly interesting target for undersea exploration. Likewise, the mild climate, number of coral reefs, and known and undiscovered shipwrecks make the Caribbean Sea another area of interest.

The Indian Ocean covers the area of ocean bounded by Africa to the west, Asia to the north, Australia to the east and the Southern Ocean to the south. It covers approximately 19.5% of ocean surface area making it the third largest ocean (Eakins & Sharman, 2010) (Central Intelligence Agency, 2022). The location of the Indian Ocean presents a different set of challenges as compared to the other oceans: “The deep Indian Ocean is far less studied than the depths of the other oceans, for economic reasons: it is ringed by underdeveloped countries (Hofmeyr & Lavery, 2020).” The biodiversity of the Indian Ocean is not well known; but what is well known is that the Indian Ocean contains 161,000 km2 of coral reef, second only to the Pacific Ocean (Keesing & Irvine, 2005).

The various coral reef populations within the Indian Ocean and the relative lack of general exploration of the region begs for attention.

The largest of the five oceans, the Pacific Ocean covers the area of the Earth between North and South America to the east, Asia and Australia to the west, and the Arctic Ocean and Southern Ocean to the north and south respectively (Central Intelligence Agency, 2022). Not only does the Pacific Ocean cover the largest area at 161,000,000 km^2, but it also contains twice the volume of the Atlantic Ocean at 660,000,000 km^3, almost 50% more area of coral reef than the Indian Ocean with 211,000 km^2, and more marine species than any of the other oceans (Eakins & Sharman, 2010) (Keesing & Irvine, 2005) (Secretariat of the Pacific Regional Environment Programme, 2017).

The Pacific Ocean also has the distinction of containing the deepest point on Earth. Known as Challenger Deep and located in the Mariana Trench, the deepest point on Earth measures 10,935 meters deep (National Oceanic and Atmospheric Administration, 2022). With the largest coral reefs, deepest point on the globe, more marine species than any other ocean, and largest area, the Pacific Ocean quickly becomes a primary target for undersea exploration efforts.

Figure 2: *Deepsea Challenger in the Challenger Deep* – This image was captured by autonomous cameras placed prior to the arrival of Deepsea Challenger. This marked the second time a crewed submersible had been at this depth, and the first-time images were captured of the vehicle.

The Southern Ocean is located between 60 degrees south latitude and Antarctica. The Southern Ocean accounts for 5.4% of total ocean volume (Eakins & Sharman, 2010). As with the Arctic Ocean at the north pole, the Southern Ocean can be covered with ice and has many of the same challenges to exploration as the Arctic Ocean. Because of the climate and accessibility limitations, the Southern Ocean is not a particularly enticing target for undersea exploration.

Considering climate, accessibility, and the occurrence of marine life, the regions of the oceans located in temperate waters and near the coast become the obvious choices for exploration. Considering those criteria, it is also important to understand how depth influences exploration.

Ocean Layers

Oceanographers recognize five distinct zones from the surface down to the greatest depths: Epipelagic Zone, Mesopelagic Zone, Bathypelagic Zone, Abyssopelagic Zone, and Hadal Zone.

The Epipelagic Zone, also called the sunlight zone, extends from the surface down to 200 meters, and is characterized by the easy penetration of light and abundant ocean life (National Oceanic and Atmospheric Administration, 2021). Half of this range (to 100 meters) is easily accessible for exploration by either conventional scuba or commercial rebreather equipment (Scuba Schools International, 2012) (European Committee for Standardization, 2013). The other half of this region is generally out of reach except with robotics or single-atmosphere submersibles. Depths of 100-200 meters depth are almost exclusively the realm of robots since "scientific research utilizing deep-sea submersibles has primarily focused on habitats at depths well in excess of 500 ft / 150 m (Pyle, 1996)."

Of particular interest in this zone are the continental shelves. The shelves are defined as "a zone adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths (Harris, Macmillan-Lawler, Rupp, & Baker, 2014)." Although only accounting for less than 9% of the ocean surface area, the shelves contain all marine plant growth and are some of the most productive areas of the ocean (Roberts, Aguilar, Warrenchuk, Hudson, & Hirshfield, 2010) (Woods Hole Oceanographic Institute, 2022).

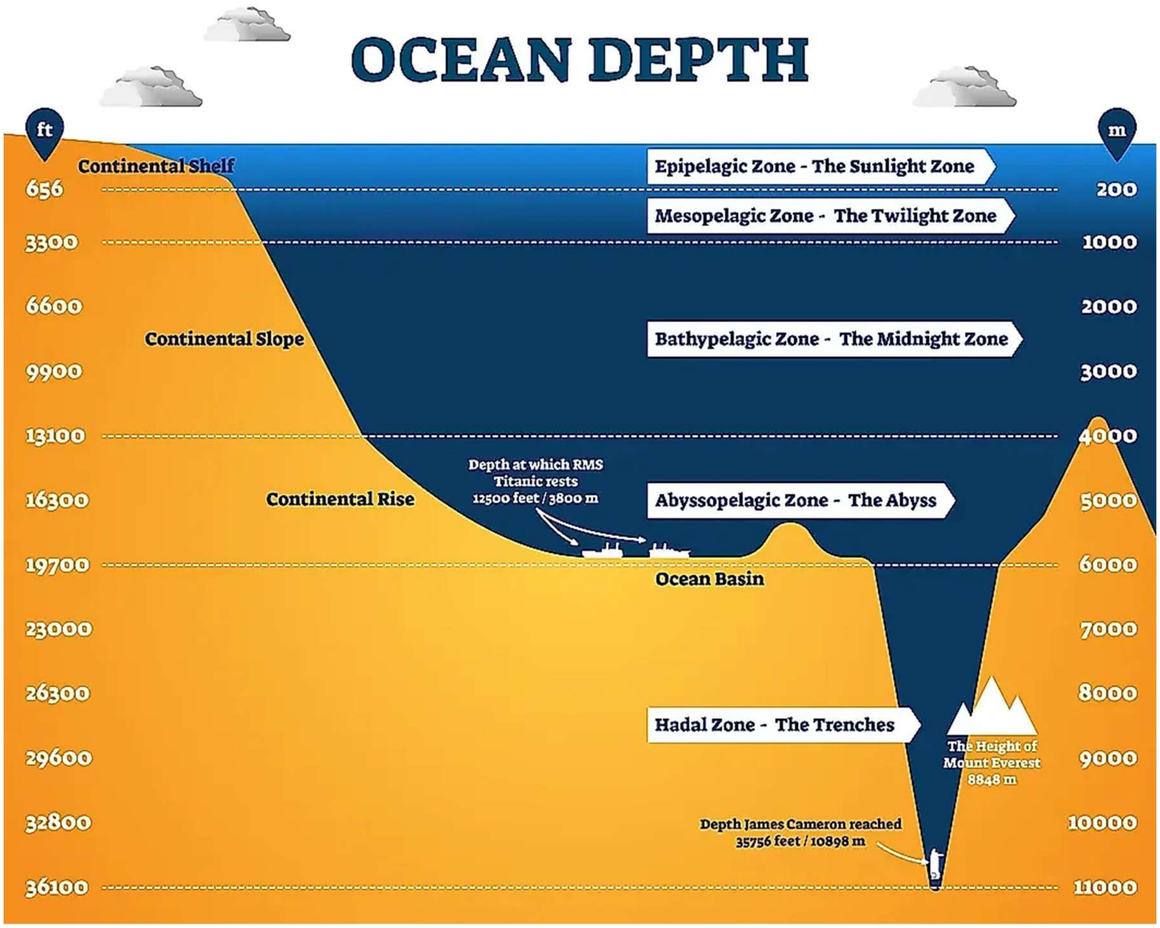

Figure 3: *Ocean Depth Zones* – Both the Epipelagic and Mesopelagic Zones are accessible to divers, although access to the Mesopelagic Zone would likely require saturation dive techniques outside the scope of this work. The deepest three zones will remain the domains of well-engineered, pressurized submersibles.

The Mesopelagic Zone, commonly referred to as the “Twilight Zone,” begins around 200 meters and extends downward to 1000 meters. An almost complete absence of light characterizes this zone. Photosynthesis does not occur below 200 meters, and light cannot penetrate even the clearest water below 1000 meters (National Oceanic and Atmospheric Administration, 2021). The exact depths of this region vary because it begins at the depth where photosynthesis ends (Nelson, 2013), so there is overlap with the bottom of the Epipelagic Zone. This zone is poorly explored because, “for a long time, researchers have considered this place too deep for traditional scuba diving and too shallow to justify exploring with expensive submersibles (Simon, 2016)."

The remaining three zones, the Bathypelagic Zone, the Abyssopelagic Zone, and the Hadal Zone are all characterized by no sunlight, extreme pressure, and constant cold. Considering the depths where life is most abundant, and opportunities for new exploration exist, the space between 100 meters and 200 meters is the focus of this effort.

Exploration Technology

The technology used in ocean exploration has come along a great deal since the days of the HMS Challenger. The technology needed to explore the region between 100 meters and 200 meters will be the culmination of technological advancements dating back to the earliest days of crewed ocean exploration.

The Bathysphere was a crewed submersible invented in the late 1920's. The Bathysphere was a simple enough concept: a sphere designed to resist the pressure of the ocean depths with windows for observing the sea life outside. In 1930, Otis Barton and William Beebe completed the first prototype and completed uncrewed testing (Lemelson-MIT, 2022). Onboard life support included pressurized oxygen tanks that provided two liters of oxygen per minute, a container of soda lime to absorb CO_2 and another container containing calcium chloride to absorb excess moisture in the air (Beebe, 1934).

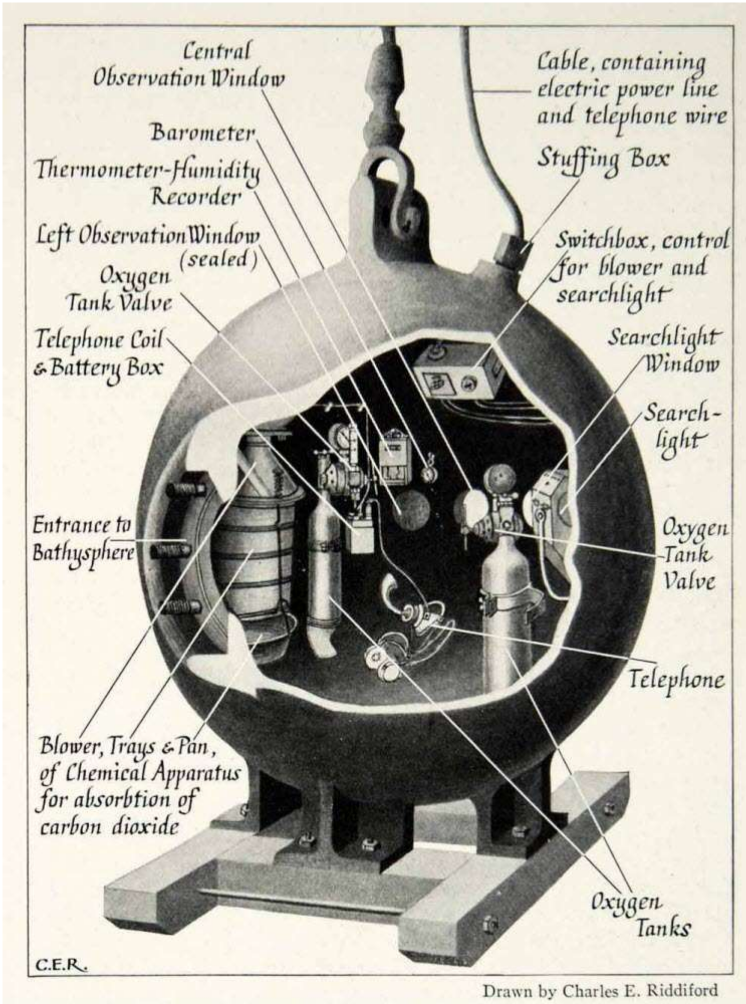

Figure 4: *Bathysphere* – Much of the technology and design methodology developed for the Bathysphere persists today including the spherical pressure vessel, the conical windows, and the closed-circuit life support system.

The Bathysphere completed 35 dives, including one to 923 meters, in 1934, a record that would stand until 1949 (History of Diving Museum, 2022) (Patowary, 2020). While the Bathysphere had no independent mobility and limited visibility through its 3-inch windows, the concept showed that crewed exploration of the ocean depths was possible.

Perhaps no one person has done more to expand the understanding of the world beneath the waves than Jacques Yves Cousteau. Cousteau was born in France in 1910 and joined the French Navy in 1933. He served as a gunnery officer and later as part of the French Resistance during World War II, which earned him the Legion of Honour (The Editors of the Encyclopedia Britannica, 2021). Cousteau was so fascinated by the undersea world, he co-invented the on-demand scuba regulator with Emile Gagnan in 1943 by modifying a fuel regulator (Cousteau Society, 2022) (Hartigan, 2021).

After the invention of the "Aqua-Lung", Cousteau worked with the French Navy conducting research dives. In 1947, one of his divers succumbed to nitrogen narcosis at around 120 meters depth and became the first person to die using the Aqua-Lung (Ecott, 2001). Cousteau took scientific leave from the Navy in 1951 and officially left the Navy in 1956 with a rank of Captain.

Figure 5: *Jacques Cousteau* – Inventor of the on-demand scuba regulator and several other undersea research tools and techniques, Cousteau blazed a trail for others to follow.

During his leave of absence from the Navy, Cousteau began his work on undersea documentaries and was able to secure the use of a boat with the backing of British philanthropist Thomas Loel Guinness. Because this was early after the invention of the on-demand scuba regulator, Cousteau and his team were the first to dive in many places around the world (Gronfeldt, 2015). From 1950 until his death in 1997, Cousteau authored or co-authored 43 books, produced dozens of documentaries, enjoyed 8 seasons of "The Undersea World of Jacques Cousteau", won three academy awards, and was presented with the U.S. Presidential Medal of Freedom. Prior to Cousteau, most people had no idea what the world under the sea looked like; after Cousteau, they wanted to see it for themselves.

While Cousteau was interested in developing the techniques and equipment necessary to allow humans to exist as part of the ocean environment, others were working on the technology necessary to allow for exploration of the deepest parts of the ocean. In 1953, the bathyscaphe Trieste was constructed and launched in Italy. It was operated for a few years by the French Navy until the United States Navy acquired it in 1958. Trieste consisted of a steel sphere where the crew of two were housed attached to a series of ballast tanks.

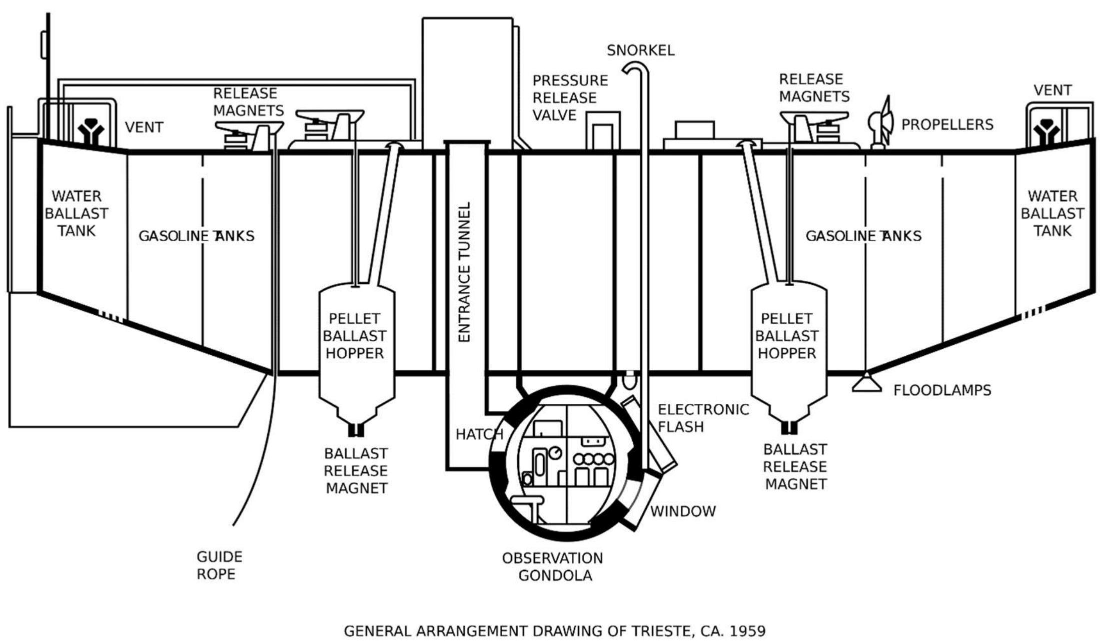

Figure 6: *Trieste* – Even though Trieste is not very hydrodynamic, it was inherently stable; by placing the gasoline filled ballast tanks above the observation gondola, the center of buoyancy was above the center of gravity.

The thickness of the walls of the sphere necessary to resist crushing at 11,000 meters made the vehicle negatively buoyant. As a result, the ballast tanks were filled with gasoline which is lighter than water and non-compressible; additionally, releasable iron pellets were installed so that the vehicle would be negatively buoyant on descent and positively buoyant on ascent. The vehicle also contained a closed-circuit rebreather life support system like the one on the Barton and Beebe Bathysphere.

The Deep Submergence Vehicle Alvin (1964) was designed primarily because the Office of Naval Research had determined that a smaller, more maneuverable vehicle than Trieste was needed to support future research and exploration activities (Humphris, German, & Hickey, 2014). Like the Bathysphere and Trieste, Alvin was designed with a spherical control room to support the research team and there were viewports out of the control sphere and closed-circuit video cameras for steering. Alvin is capable of diving to 4500 meters depth and supporting three divers for ten-hour missions (Parsons, 2021), and in 1986 Alvin famously explored the Titanic and deployed a remotely operated vehicle, or ROV, to explore the interior.

Current State of Exploration

There are three broad categories of subsea exploration techniques today: crewed exploration, uncrewed exploration, and remote sensing. Crewed exploration can be further divided into pressurized and unpressurized exploration.

Unpressurized crewed exploration is mainly focused on coral reef imaging. For example, the XL Catlin Seaview Survey has been conducting expeditions to image coral reefs since 2012. Their efforts have resulted in image collection of 150 km of reefs in Australia, 390 km of reefs in the Caribbean, 221 km of reefs in Southeast Asia, and hundreds of thousands of geo-referenced coral reef images (XL Catlin Seaview Survey, 2022). Coral reefs are critical to the ocean ecosystem and readily accessible to divers. Most of the world's coral reefs are shallow enough to explore using standard scuba equipment.

There is currently a race between three of the world's billionaires to lead commercial space travel; similarly, there appears to be competition between two other billionaires in the realm of ocean exploration (Than, 2012) (Five Deeps Expedition, 2022). In 2012 James Cameron, Hollywood director and producer of films such as Avatar and Titanic, piloted a purpose-built vehicle to the bottom of Challenger Deep, becoming the third person in history to do so. As with other crewed submersibles able to reach great depths, Cameron's vehicle, Deepsea Challenger, consisted of a spherical control capsule with small windows and contained the life support and control systems. Like Trieste, it had disposable ballast to allow for positive buoyancy during ascent. Unlike Trieste, the Deepsea Challenger was designed for optimal descent and ascent speeds and was able to reach the bottom in just over two and a half hours and ascend in 70 minutes (Than, 2012). Also, unlike Trieste, Cameron was able to spend several hours exploring the depths, as compared to the 20 minutes spent by Trieste, before returning to the surface (Muller & Penberthy, 2012). In addition to the exploration vehicle, several automatic cameras were deployed to the bottom to collect video of Cameron's vehicle for use in a documentary film. The vehicle was transferred to Woods Hole Oceanographic Institution is 2013.

The Five Deeps Expedition was an ambitious project launched by equity fund manager Victor Vescovo with the goal to reach the deepest point in each of the five oceans. The vehicle, called the Limiting Factor, supports two operators for 16-hour missions, with 96 hours of emergency life support, to depths of 11,000 meters (Five Deeps Expedition, 2022). As with the Deepsea Challenger, the Limiting Factor was designed to optimize the vehicles ascent and descent speed as opposed to focusing on forward speed.

Uncrewed ocean exploration is conducted using both remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV). One recent expedition conducted by NOAA utilized a remotely operated vehicle called Deep Discoverer that conducted dives on the New England and Corner Rise Seamounts. This expedition used the Deep Discoverer to map the seafloor at depths between 250 and 4,000 meters (National Oceanic and Atmospheric Administration, 2021). Utilization of a ROV allowed researchers to conduct exploration and mapping missions without the expense of a pressurized crewed submersible and without risk to divers in the water. NOAA has been conducting several expeditions in the North Atlantic recently using both ROV's and AUV's to great effect.

One of the latest technologies to be utilized in undersea exploration is remote sensing. The applications include coral reef monitoring, ocean temperature mapping, and detecting previously unknown undersea mountains and ridges by examining how the waves pass over such objects. Remote sensing allows for collecting information on a scale that would be impossible for other forms of exploration.

Summary and Conclusions

There is an incredible amount of unexplored seafloor with most of it reachable only with well-engineered, single-atmosphere submersibles or remotely operated vehicles. The ocean regions best suited to efforts to expand crewed exploration are the areas near the coast with depths ranging from 100 to 200 meters. Reaching these depths in an unpressurized vehicle, and providing meaningful time on the bottom, would fill an obvious gap in current undersea exploration capabilities.

CHAPTER 2

DEVELOPING REQUIREMENTS WITH COLLABORATION OF THE USER COMMUNITY

The first step of any engineering project is understanding the needs of the user community and establishing requirements that the project must meet. The CUTLASS project began as a remotely operated vehicle and then evolved into a crewed exploration vehicle. After the decision was made to pivot towards a crewed vehicle, it was necessary to understand what the needs of the user community would be. To support that understanding, a survey was developed and disseminated to various undersea research organizations. Finally, with the user needs understood, the top-level functional requirements and Concept of Operations were created.

Project Motivation

Remote sensing allows for researchers to determine how much area a coral reef covers and allows them to determine the health of coral reef populations. What remote sensing does not allow is the understanding of what is happening to the reef at the local level. The CUTLASS project began in 2015 with the hypothesis that much of the discussion about coral reef health at a local level was anecdotal and the research community could benefit from a better method of data collection and analysis.

Dr. Eric Hochberg, from the Bermuda Institute of Ocean Sciences, was contacted in February of 2016 to better understand how coral reef research is conducted. Dr. Hochberg was also the principal investigator for NASA's Coral Reef Airborne Laboratory project that utilized "airborne instrumentation and remote sensing approaches to identify reef composition and model primary production from an ecosystem perspective (Bermuda Institute of Ocean Sciences, 2022)." During those conversations, Dr. Hochberg described the typical methodology of conducting a coral reef survey which included:

- loading the gear onto a boat
- traveling to the survey site
- diving onto the coral reef and deploying transect tapes
- return to the surface to off gas and change scuba tanks
- dive back onto the site and collect images
- return to the surface to off gas and change scuba tanks
- dive back onto the site, finish image collection as needed and remove transect tapes
- return to the surface to off gas and change scuba tanks
- move to a new site, or return to the pier as time permitted

Dr. Hochberg explained that his team could expect to complete approximately 400 m^2 of coral reef survey over the course of three days of diving. The inefficiency of data collection at the local level, as compared to the massive amounts of area that were to be collected during the CORAL project allowed for the hypothesis that utilizing a ROV to conduct coral reef site surveys was a worthwhile pursuit. Not only could a ROV collect data faster than divers, but the ROV could do so without exposing people to the hazards that are included in scuba diving.

Origins

ROV's were rather expensive pieces of equipment when the project began. Most ROV's were in the hundreds of thousands of dollars range and were large enough that they were not very portable. At the beginning of the project, the vehicle that was the most suitable for conducting the type of coral reef survey that we were interested in was the Teledyne Seabotix LBV200-4. This system consisted of three primary components: the vehicle itself, the controller, and the tether. The vehicle weighed about 11 kg, the controller was slightly heavier due to the built-in power transformer, and the 350-meter tether was even heavier than that. The vehicle was rated to 200 meters depth, had some autonomous functionality, and provided primary video back to the controller (Teledyne SeaBotix, 2022). There were other similar platforms available at the time that all had the same basic system level design. In terms of data collection capability, none of the commercially available solutions were designed for high quality image collection or collection of other data points in conjunction with the images. Also, the cheapest available Teledyne product at the time came with a cost of about $35,000.

Figure 7: *Teledyne SeaBotix LBV200-4* – The Teledyne SeaBotix LBV200-4 was used as inspiration for the first version of the, now abandoned, CUTLASS ROV.

The chief goal of the original CUTLASS project was to provide a solution that would allow for coral reef site surveys to be conducted at an affordable cost with integrated, not federated, image and data collection capabilities. To support that, a vehicle was designed, and components sourced to support a build budget of $10,000; one-third of the cost of a Teledyne SeaBotix solution.

At the system level, the CUTLASS ROV included a surface control station, a tether, and a vehicle. Unlike the commercially available products, the CUTLASS ROV included onboard power as opposed to surface supplied power. While this added weight to the vehicle, it also allowed for future expansion to include untethered operations.

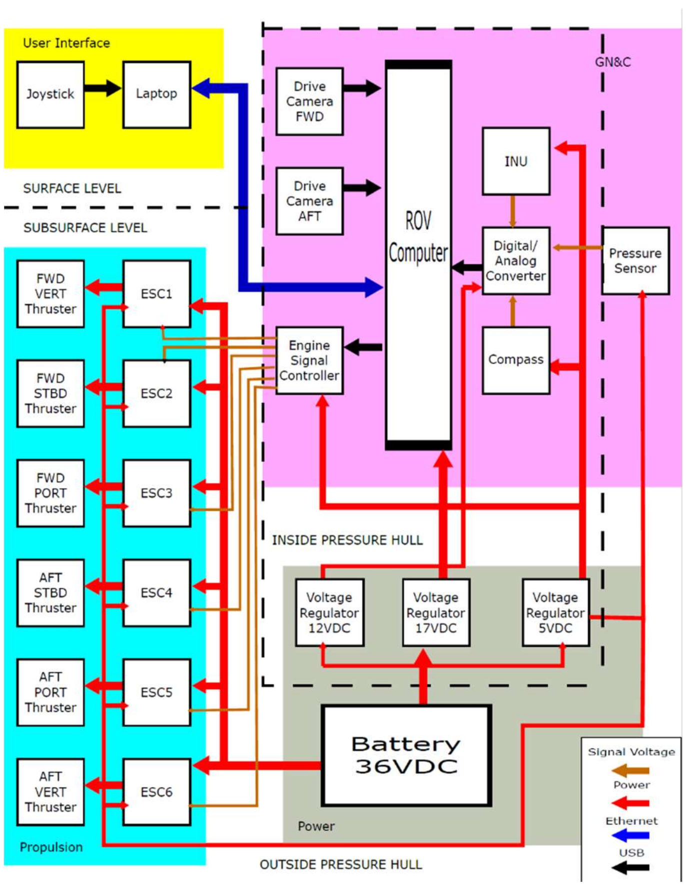

Figure 8: *CUTLASS ROV System Block Diagram* – The system block diagram for the original ROV CUTLASS project. The ROV was abandoned in favor a crewed submersible.

Ultimately, a prototype CUTLASS vehicle was constructed for the $10,000 budget; however, competition in the commercial ROV market has driven costs down to less than half of that amount, rendering the CUTLASS ROV non-competitive and unable to meet one of the key goals of providing an affordable solution to underwater site survey.

Pivot to Crewed Exploration

With the lower cost commercially available ROV's entering the market, a new goal was needed. New thinking about how to shift the project to design something that was unique and filled a gap in the ocean exploration mission space was needed. Crewed exploration using conventional scuba methods is generally limited to about 40 meters; pressurized deep-sea submersibles are generally utilized well below 150 meters; the area between is largely unexplored (Pyle, 1996) and is essentially the realm of autonomous and remotely operated vehicles. Identification of this gap in crewed exploration capability was interesting and it was decided that more information was required to determine what functionality the scientific diver community would desire in a vehicle that would support crewed exploration down to 200 meters.

User Community Survey

At the end of 2019 a survey was constructed and sent to the community of scientific divers. The entire survey is available in Appendix A. The goals of the survey were to better understand which aspects of diving were taking most of the attention of the divers and what they would like to see in a diver assistance platform. This line of questioning was designed to elicit the types of responses necessary to allow for the beginning of the engineering process.

Survey Questions

The survey began with basic demographic data collection including the number of dives each diver had completed, what certifications they carried, and what their area of research focused on. The number of dives ranged from 750 to well over 3000 with an average of 1600 dives reported. Eighty percent of the divers reported some form of instructor certification and 40 percent reported as carrying cave diver certifications. Twenty percent of the respondents reported certification to operate a closed-circuit rebreather. Most of the respondents reported biology as their primary area of research with geology coming in second.

The next set of questions were broken into four main categories: navigation, depth control, technical, and equipment. Respondents were asked to respond to each question on a scale of one to five where one carried a value of strongly disagree to the statement and five carried a value of strongly agree to the statement. The text of each statement or question is italicized.

Navigation:

1. *The ability to accurately navigate is crucial.* This question was created to determine the value of accurate navigation data and positional information. Averaging the responses yielded a value of 4.6, so this was determined to be crucial.
2. *I often navigate without any external reference.* This question allowed insight into what kinds of navigational environments the users generally worked in. Only twenty percent of respondents reported regularly working in environments without external references to aid in navigation. Undersea

navigation can be challenging without references due to drift and differences in the speed each diver swims at. Like anything else, this is a skill that gets better with experience.

3. *I often misjudge distance during navigation*. Possibly because most respondents did not report navigation without reference as a norm, this question scored heavily toward the disagree side of the spectrum with an averaged response of 2.2.
4. *I can usually find my way back to my starting point during dives.* Almost all respondents answered this question with a “strongly agree” value.
5. *Accurate navigation takes a great deal of my focus*. Sixty percent of respondents rated this as “agree” or “strongly agree”.

It was concluded that accurate navigation takes a good deal of the diver’s attention and is a crucial part of the dive based on the responses received.

Depth Control:

1. *The ability to maintain accurate depth is crucial*. As with the first navigation question, the purpose of this question was to understand the working environment. Are divers focused on maintaining an accurate depth or are they more concerned with other issues? It was assumed that the divers who reported regularly performing technical dives that required decompression stops would consider this a more valuable skill than divers that were generally diving within the boundaries of no decompression. That was generally realized with eighty percent of respondents reporting either “agree” or “strongly agree” to the statement.

2. *I have no problems maintaining an accurate depth*. Unsurprisingly this statement garnered an average response of 4.8. This is one of the primary skills of scuba diving.
3. *My actual dive profile generally matches my planned profile*. The purpose of this question was to try and understand the rate at which the respondents were making ad hoc changes during dives and diverging from the plan. The revelation that almost all divers were very good at sticking to the preplanned dive profile was unexpected.
4. *I check my depth gauge frequently to ensure that I do not exceed my planned depth*. As with other questions, this one garnered an "agree" or "strongly agree" from each respondent. It was worded to better gauge the workload associated with accurately controlling depth.
5. *I would prefer to be able to focus more on my work and less on my depth*. This question received a rather neutral response. It is possible that most respondents saw this as part of the job and not something that was a hindrance to the more important aspects of their work.

Technical:

1. *I often dive deep enough or long enough to require decompression stops*. Most dives that take place occur within the no-decompression limits established by the US Navy dive tables (U.S. Navy, 2016). The question was posed to see how many of the respondents had a need of support outside the no-decompression limits. Unexpectedly, 80% of respondents regularly participate in dives that exceed the no-decompression limits.

2. *Completing prescribed decompression stops is crucial to safe technical diving*. This question was answered with a unanimous “strongly agree”.
3. *My primary dive equipment for long dives is a rebreather*. In accordance with guidance from the Navy which states, “Open-circuit SCUBA dives are normally planned as no-decompression dives” (U.S. Navy, 2016), the expectation was that more of the users would respond that they used closed-circuit systems (rebreathers). The same percentage of respondents (80%) that regularly participated in dives requiring decompression stops also reported that their deep dives were conducted on open-circuit systems. This appeared to be a potential opportunity for improvement.
4. *I prefer to use a drysuit*. One of the problems with deep diving (or diving in general) is the rate at which body heat is lost. As the depths get greater, the temperature of the surrounding water drops, which in turn affects the physical performance of the diver. The average value of the question worked out to 3.8 with only 20% of respondents reporting that they do not use drysuits on a regular basis. It is speculated that those respondents do not participate in deep dives, or generally dive in warmer waters.
5. *I often use a computer to manage my dive profile, ascent rate, deco stops and safety stop*. Unsurprisingly this question resulted in a unanimous “strongly agree” rating. Dive computers have become ubiquitous in the diving community and the days of diving without them seem to be limited to early divers who have yet to invest in one.

Equipment:

1. *I often carry extra tanks on dives*. This question averaged out to a neutral response with 40% of respondents reporting that they regularly carried extra tanks, 40% sometimes did, and 20% never dove with extra tanks.
2. *I often carry multiple cameras and lights on dives*. The response to this question was like the previous one with 40% reporting carrying extra lighting and camera equipment regularly, 40% reporting sometimes, and 20% seldom carrying cameras and lights.
3. *My dives typically require survey equipment*. This appeared to be a common need with 100% of respondents reporting either "agree" or "strongly agree" with this statement.
4. *My dives typically require heavy scientific equipment*. This statement appeared to also result in a common need with only 20% of respondents reporting that they "strongly disagree" with the statement. The remaining 80% responded with neutral or above responses.
5. *My dives result in numerous biological/geological samples being collected*. 40% of respondents affirmed this statement with the remaining 60% reporting this as either "strongly disagree" or "disagree". It is certainly possible that a wider dispersion of the survey into other communities (such as commercial exploration) might result in a stronger affirmation.

The remaining questions were more open ended and required written responses. When asked about which aspects of a dive required most of their attention, responses included statements such as equipment handling, descent control, navigation, monitoring depth and time, and decompression. When asked about which aspects of a typical dive were most challenging, responses were less varied with visibility, cold, and time restrictions being the most common responses. An almost universal response when asked how they reduce the workload on a dive was to increase the number of divers to spread the workload amongst more people.

The final question of note for understanding the needs and desires of the respondents was to ask for a list of features they would like to see incorporated into a diver assistance platform. Those responses included such desires as built-in lights, the ability to transport equipment to and from the surface, highly accurate location data, a line of communication with the surface, and the ability to locate previously deployed equipment easily.

Compilation of Results

The results of the survey were used to identify areas where the divers felt current equipment and processes were lacking and then use cases where a diver assistance platform (either crewed or uncrewed, remotely operated, or autonomous) could be beneficial.

Identified Challenges

The challenges associated with research diving were well articulated by the respondents to the survey. The four main issues that needed to be addressed included:

- more time to do work
- a method to combat the cold that is experienced while diving
- a need for better location information
- communications with the surface

To allow the divers more time on the bottom, one would have to address the issues of decompression diving. As previously indicated, the U.S. Navy recommends against using open-circuit scuba for decompression dives, so a closed-circuit solution would be required. Options for closed-circuit diving solutions include off-the-shelf rebreathers or building a rebreather solution into the platform.

There are currently three methods for combatting the cold while diving: wetsuits, drysuits, and suit heaters. Of these solutions, the most effective method is the employment of a suit heater. The current equipment designed to provide heat to divers is large, cumbersome, and designed to stay on the surface.

Identified Use Cases

One of the artifacts of Systems Engineering is the use case diagram in Figure 9. The operational use cases identified included: conducting site survey operations, transportation of equipment, enhancement of diver safety, and communications with the surface. The vehicle has three tasks that it will perform in this diagram, the surface team has two tasks, and the diver has the remaining four. Except for the "Communicate" use case, each diver use case has a dependency on one or more other use cases, this is illustrated by the dashed arrow <<use>> line running from the diver use cases to the vehicle use cases.

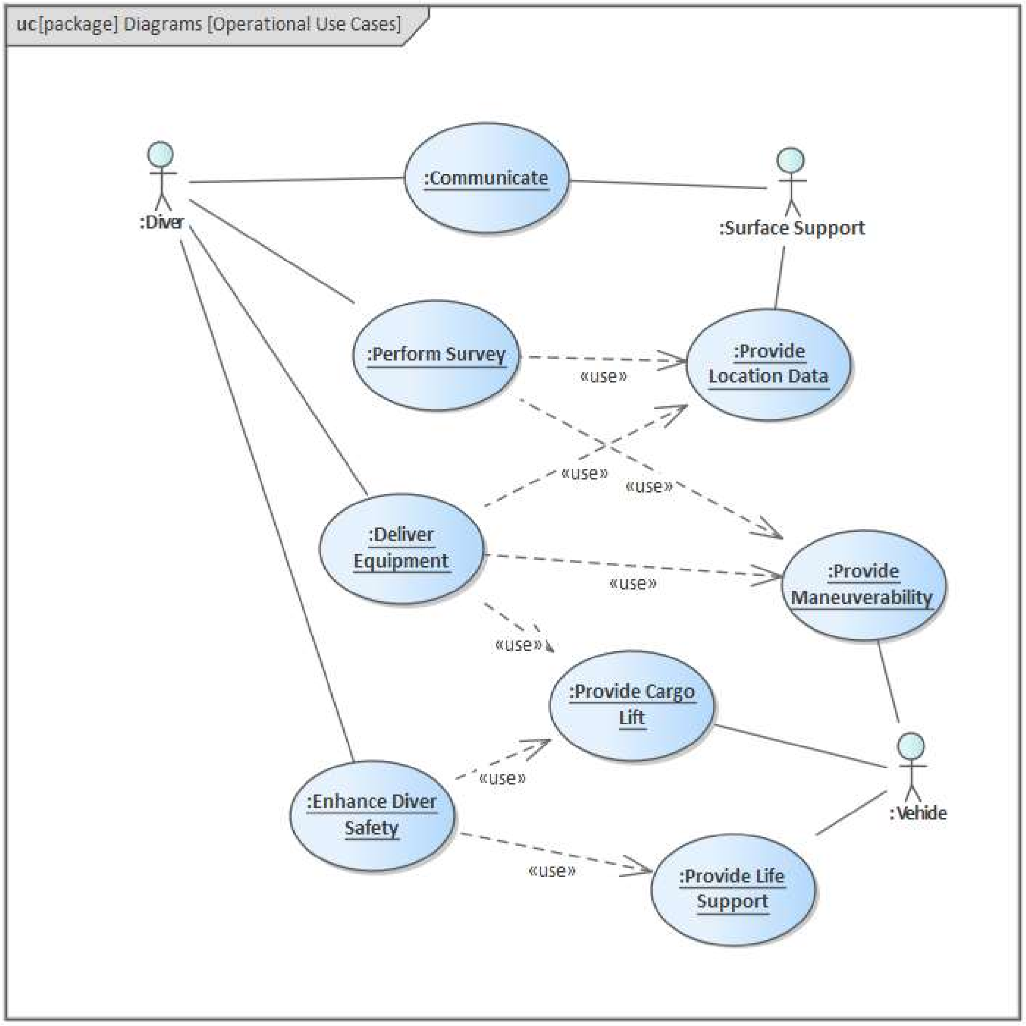

Figure 9: *Operational Use Case Diagram* – The diver interacts with the surface via the "Communicate" use case, while interaction with the vehicle requires interaction between various use cases.

Communication with the Surface. The first use case to be discussed is the provision of a path of communication with the surface. The survey results identified this as a high value desire with both enhancements to safety as well as the potential reduction in diver workload. By providing voice and data communication pathways, the surface support team can monitor the divers, the performance of the vehicle, the location of the vehicle, the progress of the mission, and provide any information the dive team may need during the execution of the mission.

Perform Site Surveys. One of the primary missions of this project is to conduct site surveys more quickly and accurately. Whether those surveys are biological, geological, or archaeological in nature is irrelevant to the methodology currently employed. A typical initial, non-decompression dive, site survey today requires a team of two divers to dive onto a site and deploy a grid of lines onto a site with careful consideration taken to ensure that the gridlines are accurately spaced. Within the time constraints of both the non-decompression limits and the capacity of the air tanks, this generally results in grid covering approximately 100 m^2. The dive team must then return to the surface for off-gassing and replenishment of their dive tanks. Subsequent dives on the site are then conducted with each resulting grid square being documented with images, notes, and additional measurements. Depending on the thoroughness of the survey and the desired information needed to be collected, this data collection phase will take 1 to N additional dives with the corequisite surface interval for off-gassing and replenishment (note that surface intervals get longer throughout a day of multiple dives) (U.S. Navy, 2016). The final dive on a particular site is used to collect the gridlines.

Conducting site surveys with the help of a platform with high-accuracy location data and multiple cameras built into it allows users to collect images of the site with known (within a margin of error) locations and distances to the target. Subsequently, the images can be processed after the dive and targets identified that require more scrutiny. Where the traditional method of conducting a site survey will yield approximately 400 m^2 over three days of dive operations, conducting surveys using an imaging platform with accurate location data can yield results an order of magnitude greater or more (Hochberg, 2016).

Provide Equipment and Sample Transportation. Another use case identified from the diver survey was the need, or at least the desire, to provide material handling capabilities. Manual transfer of equipment to and from the sea floor currently can require multiple divers operating lift bags as well as the possible inclusion of a winch operated by the surface crew. Moving equipment can be a dangerous activity as the possibility of losing control, either during ascent or descent, is always there. By providing a platform capable of moving several hundred kilograms worth of cargo, the hazards are greatly reduced.

Enhance Diver Safety. Perhaps the greatest opportunity presented by the creation of a diver assistance platform is the opportunity to enhance diver safety. If a platform is capable of moving equipment to and from the seafloor at a controlled rate, that same platform is capable of moving divers to and from the seafloor as well. Any platform capable of communicating with the surface can also allow for the dive team to communicate with the surface. And by increasing the size of the platform, we can add life support options to aid the divers and improve their productivity.

Functional Requirements

Seven functional requirements, available in Appendix B, were identified from the diver surveys and use case development. Those requirements included:

- The program shall provide support for crewed mission depths down to 200 meters.
- The program shall provide support for crewed mission durations of 12 hours.

- The program shall provide the ability for divers to survey underwater sites with accuracies of 1 meter/100 meters of depth.
- The program shall develop a system architecture that supports deployment from a small sized research vessel.
- The program shall provide the capability to move 300 kg from the surface to the sea floor or from the sea floor to the surface.
- All life support systems shall follow regulation BS EN-14143: Respiratory equipment — Self-contained re-breathing diving apparatus.
- The program shall develop a system architecture that is operable in sea state 3 or less and under 4 knots (2m/s) current speed.

Concept of Operations

Capturing the top-level requirements led to the development of a Concept of Operations (ConOps). This simple graphical illustration conveys the five phases of operations that were defined and allows the systems engineer to begin the process of designing a system around these operational concepts.

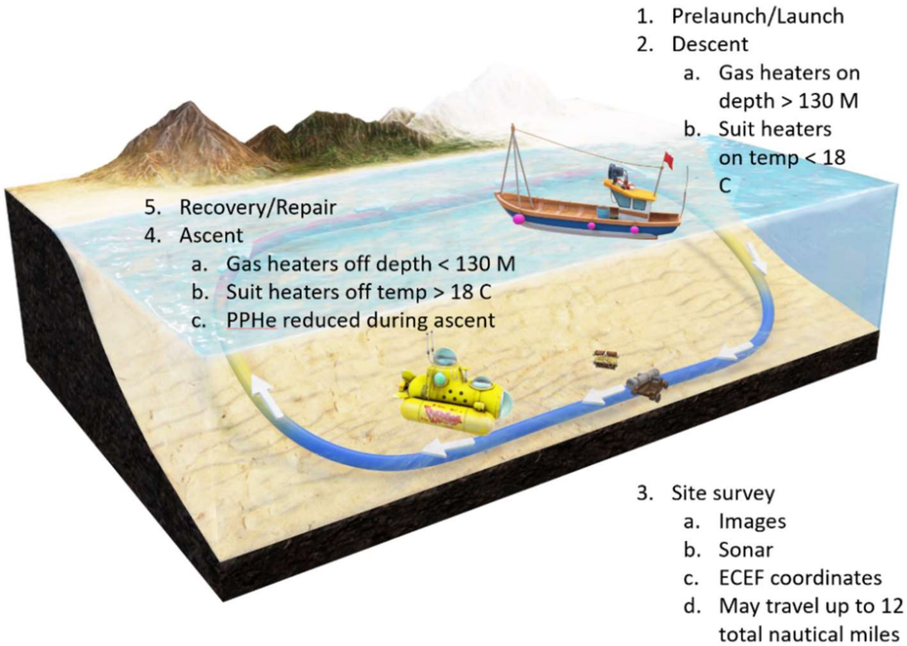

Figure 10: *CUTLASS Concept of Operations* – The Concept of Operations describes the various activities that can be expected in a typical mission. In this case, the sequential phase of operations is captured from vehicle launch to recovery.

Prelaunch/Launch Phase

During the prelaunch phase of operations systems that can be checked out prior to insertion into the water are verified to be operational. Additional checks while in the water can be performed while still secured to either a tender or pier.

Descent Phase

The descent phase of operations is a transit period between the surface and the target depth. Continuous operational checks are conducted. There are specific depth triggered events that will occur.

Site Survey Phase

Entry into this operational phase occurs when the vehicle reaches its target destination. This can include conducting of site surveys, delivery or retrieval of cargo, or any other needed tasking.

Ascent Phase

The ascent phase includes all required decompression stops.

Recovery/Repair Phase

The final operational phase begins when the vehicle surfaces and is secured to either a tender or pier. Work to checkout, repair, and replace any damaged equipment or expended materials is completed during this phase of operations.

Summary and Conclusions

Better understanding the needs and desires of the scientific diver program helped facilitate the evolution of the CUTLASS program from an uncrewed ROV to a crewed exploration system. The Coral Reef, Underwater Terrain, and Littoral Site Survey program was conceptualized to meet the needs of the scientific diver community that arose out of the survey and other discussions with various potential users. The program will provide the capability to transfer equipment to and from the surface, provide onboard life support systems to allow for long duration dives, provide automatic decompression stops to enhance diver safety, and provide a method to transfer GPS coordinates from the surface to allow for more accurate surveys.

CHAPTER 3

DESIGNING A SOLUTION

Design and development of a viable system that meets the top-level requirements and Concept of Operations is the whole purpose of Systems Engineering. This chapter will discuss the process that was followed to breakdown the system into subsystems and capture the requirements that each subsystem must meet. The Concept of Operations will be refined into operational phases. During the discussion of each subsystem, block definition diagrams will be presented that detail the primary components of each subsystem and how they are interrelated.

Systems Engineering

Once the ConOps was created, the engineering process could begin. The traditional method of Systems Engineering begins with the development of requirements and continues with functional decomposition and allocation of functions to the various subsystems (Friedenthal, Moore, & Steiner, 2015). That basic process was followed for this project as well.

High Level Requirements

First, five tiers of requirements were defined and are available for review within Appendix B. Tier 1 was defined as program level requirements. This level of requirements included such things as maximum supported mission depth, how long the mission duration would be, and how accurate the surveys needed to be. In total there were seven Tier 1 requirements defined.

Tier 2 captured the system level requirements. The system level requirements directly supported the decision to break the system into three components: Diver Support

Equipment, Surface Support Equipment, and the CUTLASS vehicle itself. Eight Tier 2 requirements were defined capturing everything from system architecture to reliability.

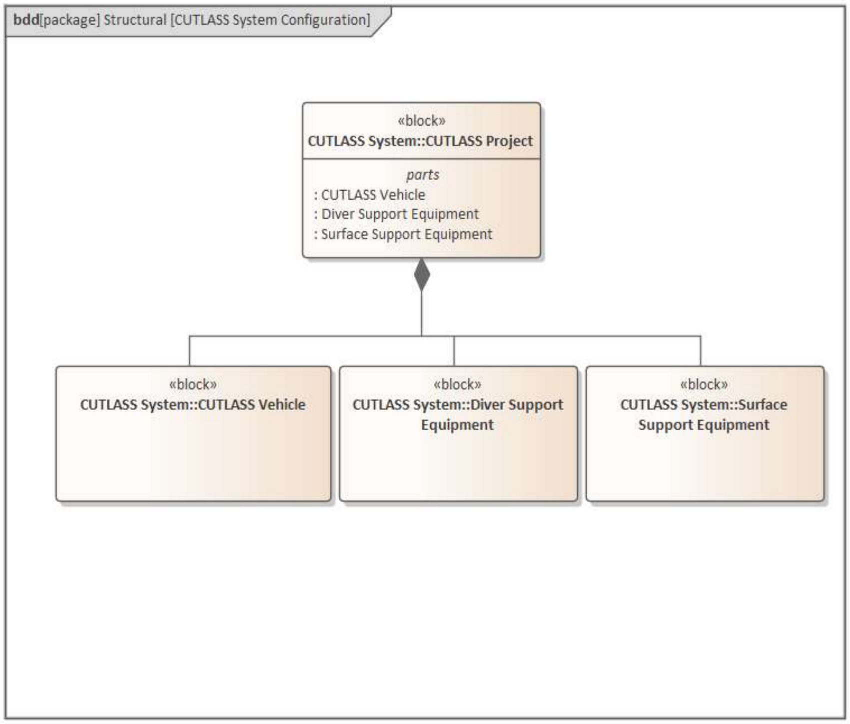

Figure 11: *CUTLASS System Block Definition Diagram* – The CUTLASS project was broken into three components: the vehicle, the diver support equipment, and the surface support equipment.

Tier 3 requirements cover the platform level. In this case there would be three distinct sets of Tier 3 requirements covering Diver Support Equipment, Surface Support Equipment, and the CUTLASS vehicle. This project is focused on the CUTLASS vehicle so those were the only requirements defined. There are 40 CUTLASS performance and constraint requirements.

Tier 4 defines the requirements for each of the subsystems within the CUTLASS vehicle and Tier 5 defines the requirements for components within those subsystems. Tier

4 remained undefined until after the subsystems were defined and the Tier 5 requirements are still undefined as they are outside the scope of this project.

Functional Decomposition

The first step to effectively designing a vehicle which meets the top-level requirements was to create an activity flow diagram based on the ConOps. Each node in this diagram was further decomposed into activity diagrams with the activities allocated to the three components of the CUTLASS system. The activity diagrams are contained in Appendix C.

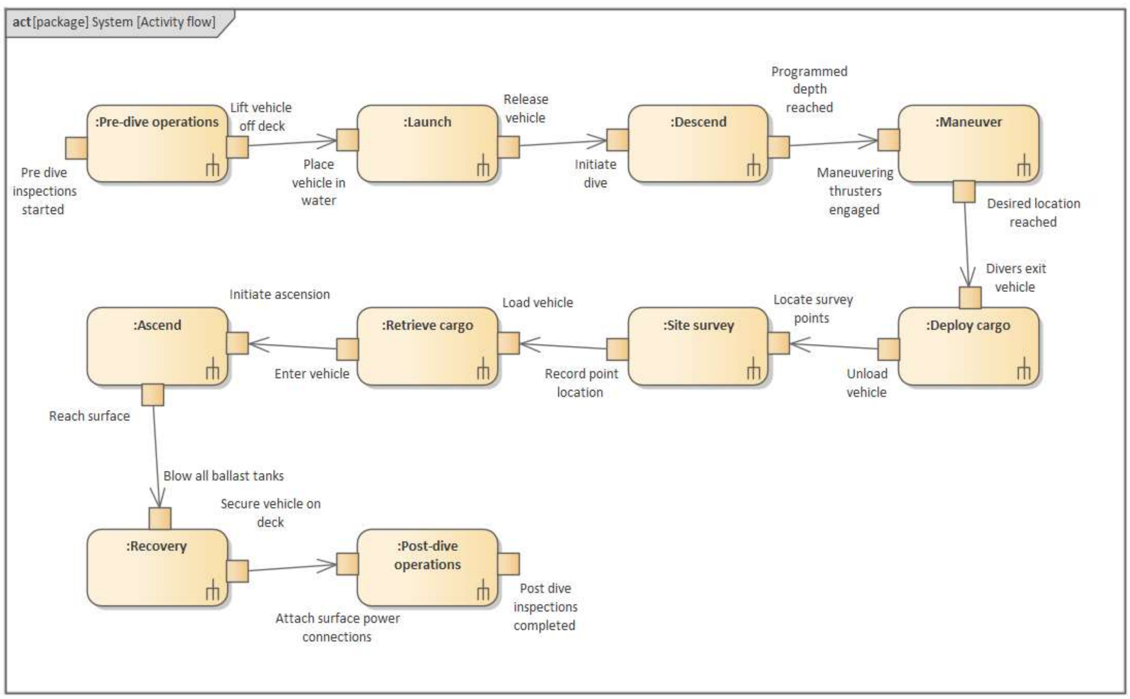

Figure 12: *Activity Flow Diagram* – This diagram describes the activities associated with a standard operational mission. This diagram also shows the generally sequential nature of the activities. It is possible that activities after launch and prior to recovery are executed in a different order with the possibility that activities are repeated.

CUTLASS System Overview

The CUTLASS system consists of three major components:

- Diver Support Equipment
- Surface Support Equipment
- CUTLASS Vehicle

Diver Support Equipment

The diver support equipment includes components such as the dive suit, dive helmet, diver worn life support systems (backup closed-circuit rebreather), and other redundant equipment such as a diver worn dive computer. The diver support equipment is outside the scope of this current effort.

Surface Support Equipment

The surface support equipment includes components such as the surface transportation system, the repair component supply chain, the vehicle data download and storage equipment, the GPS coordinate transfer equipment, the vehicle communication equipment, and the electrical charging equipment. As with the diver support equipment, the surface support equipment is outside the scope of this effort.

CUTLASS Vehicle

The focus of this design effort is the CUTLASS vehicle. The CUTLASS vehicle is an open cockpit submarine with onboard life support systems that is designed to support underwater site survey, equipment delivery and retrieval, as well as sample retrieval. The platform is capable of continuous operation with speeds up to 4 knots and can provide life support for two divers to conduct dive operations to 200 meters depth with a total mission time, including decompression, of 12 hours.

Upon completion of the CUTLASS system level functional decomposition into activities, the activities allocated to the CUTLASS vehicle were further decomposed. The exercise resulted in the creation of nine vehicle subsystems with each having various activities allocated to them in support of the system level functional activity. The vehicle activity diagrams are available in the appendix. The vehicle subsystems are:

- hull
- propulsion
- power management and distribution
- buoyancy control
- life support
- guidance, navigation, and control
- communications
- user interface
- thermal management

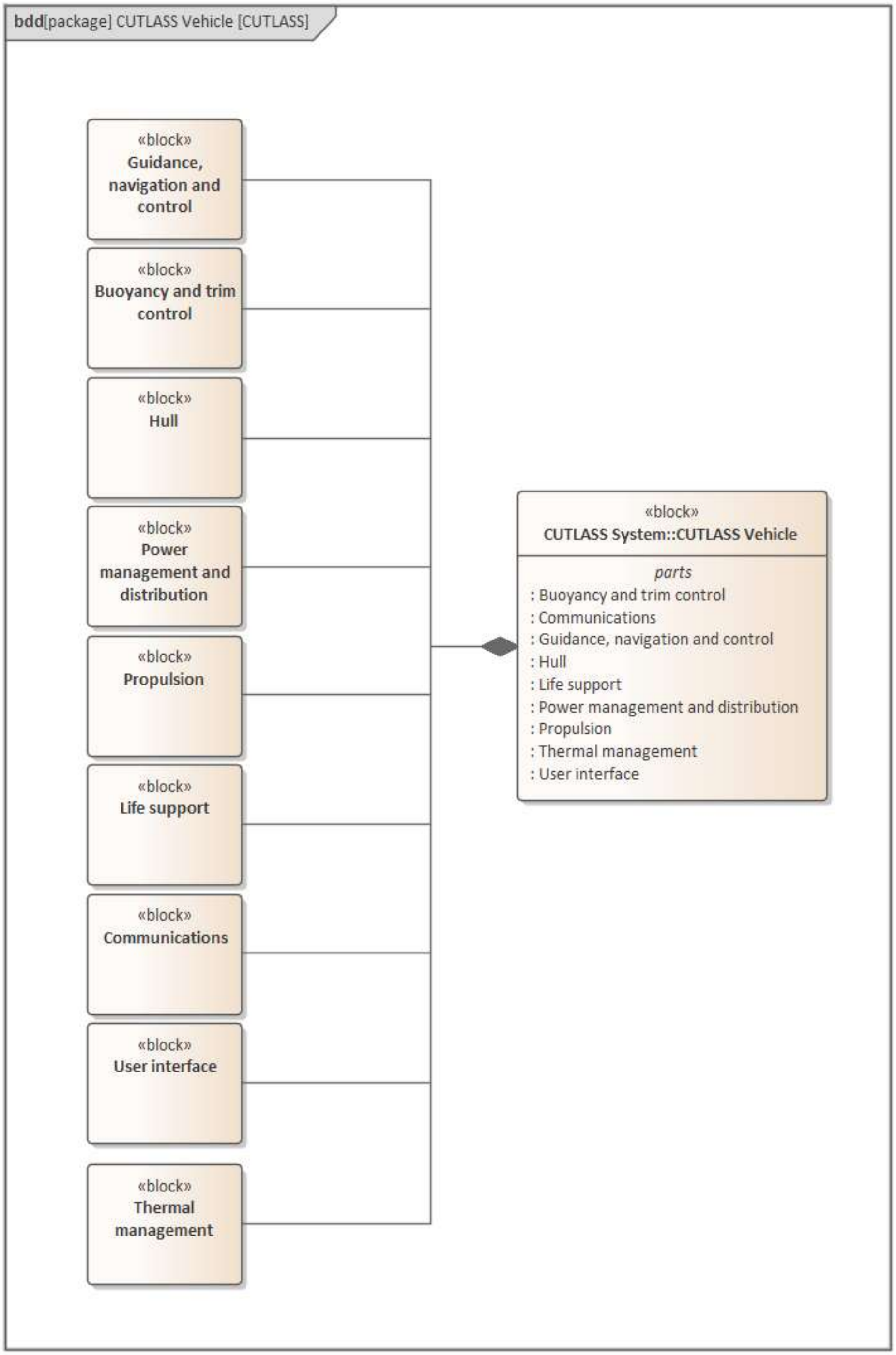

Figure 13: *CUTLASS Vehicle System Block Definition Diagram* – This diagram illustrates the various subsystems that were identified as necessary to the creation of the CUTLASS vehicle.

CUTLASS Vehicle Subsystems

The requirements for the vehicle subsystems are the Tier 4 requirements and are available for review in Appendix B.

Hull

The vehicle hull acts as the mounting point for all vehicle subsystems and provides a watertight, pressure resistant barrier to protect those subsystem components from the environment. Additionally, the hull provides an operator's station that is protected from the force of the water while the vehicle is in motion.

Design. The initial design for the hull included side-by-side seating for the operators, an open cargo bay in the rear, and two buoyancy tubes attached as outriggers to the primary hull (Figure 14). Requirement HULL4 required provisions for two crew members but did not specify a seating configuration; over the next few iterations the seating was switched to a tandem configuration to reduce drag (Figure 15). The open cargo bay at the rear of the vehicle was added to help meet requirement P5. It was ultimately replaced with an enclosable cargo bay and external cargo attachment points to also help reduce drag. The placement of the ballast tubes was chosen to help keep the center of buoyancy above the center of gravity (Figure 19) (Chakraborty, 2021). The size and placement of the ballast tubes were driven by requirements CUTLASS5, CUTLASS16, and CUTLASS29. The changes made to the hull design (see Figure 15) were done to reduce drag as much as possible while maintaining compliance with the requirements.

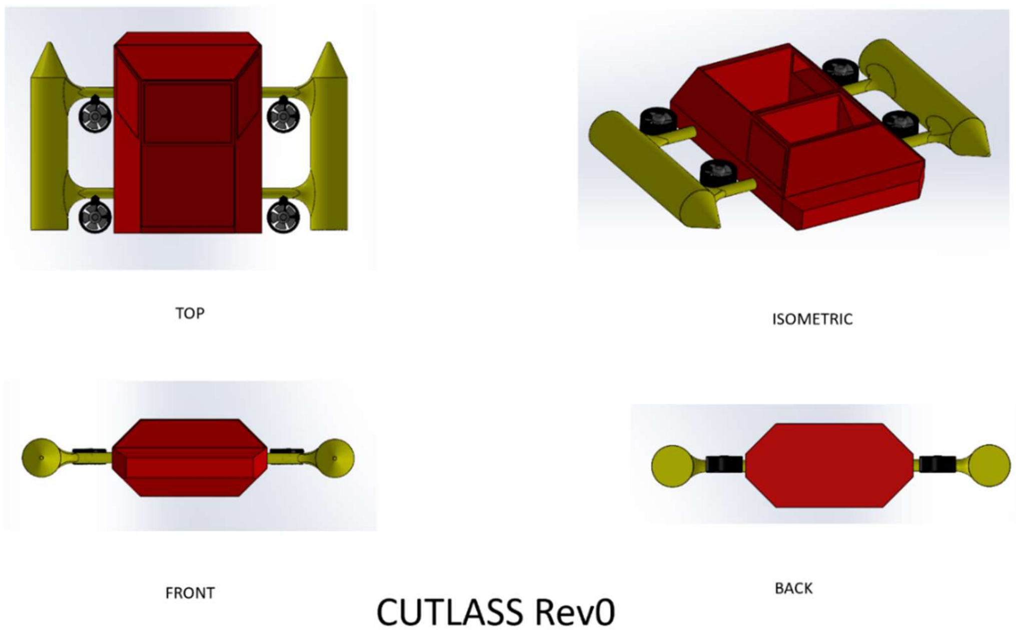

Figure 14: *CUTLASS REV0* – REV0 was an early, rudimentary effort to begin understanding what hull shape was necessary to reach the desired drag profile.

Figure 15: *CUTLASS MK1R3* – MK1R3 represents the latest configuration of the hull which provided the necessary drag coefficient to allow propulsion and power to meet their operational requirements.

Propulsion

The CUTLASS propulsion system is designed to provide power to maneuver the vehicle. The propulsion system controls the speed of each of the vehicle thrusters and as a result controls motion in the forward, backward, up, and down directions as well as rotations about the yaw, pitch, and roll axes.

Design. The propulsion system also went through several iterations during the development process. The original configuration consisted of four thrusters that were capable of rotating about the horizontal axis 270 degrees (Figure 14). These thrusters were to provide for all vehicle motion in compliance with CUTLASS15. As the design matured, it was determined that the four-thruster layout was insufficient to provide the power needed to meet the performance required by CUTLASS9, CUTLASS11, and CUTLASS18. The latest iteration of the vehicle includes four rigid mounted vertical thrusters to control vertical motion as well as rotations in the pitch and roll axes, and four articulatable horizontally mounted thrusters to provide forward, backward, and rotations about the yaw axis.

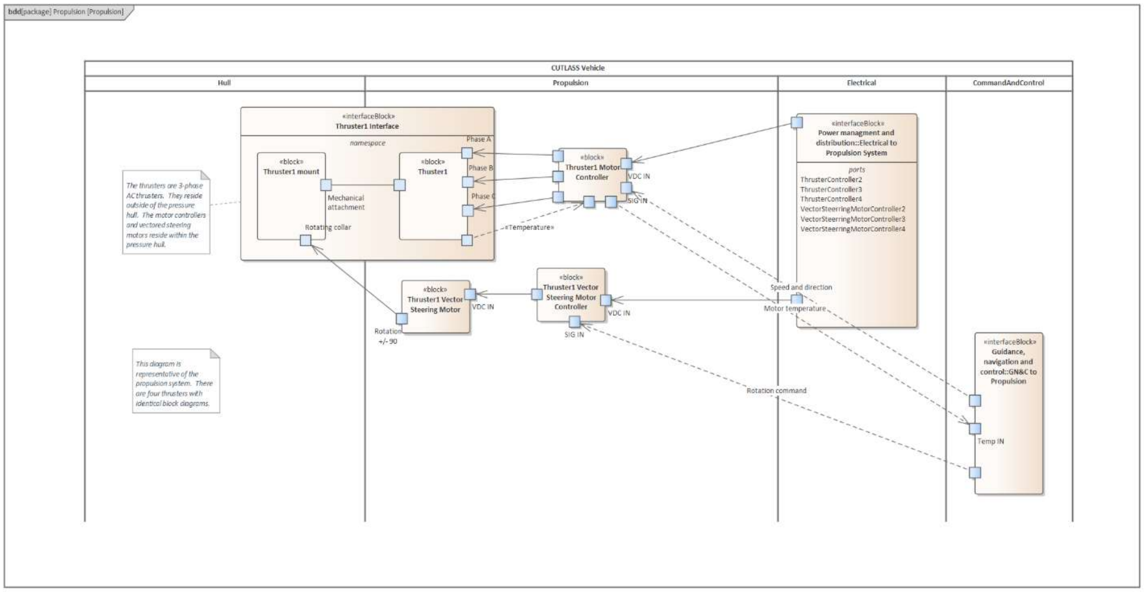

Figure 16: *Propulsion System Block Definition Diagram* – This diagram represents one thruster within the system and not the total number that are required.

Components. The propulsion system consists of eight Copenhagen Subsea VXL AC thrusters with motor controllers. The manufacturer reports a maximum depth of 3000-meters (Copenhagen Subsea, 2022). The thruster assembly is 3D printed from a glass/nylon composite material (the geometry of the blades is proprietary). The assembly itself is printed as a single piece which eliminates the interface between the blades and the housing as a point of flexibility. These thrusters are available with a symmetric housing which provides equal thrust in both the forward and reverse directions, meeting requirement PROP5. As will be shown later, these thrusters also provide the necessary force while meeting the power consumption requirements in PROP2 to reach the required 4 knots of speed.

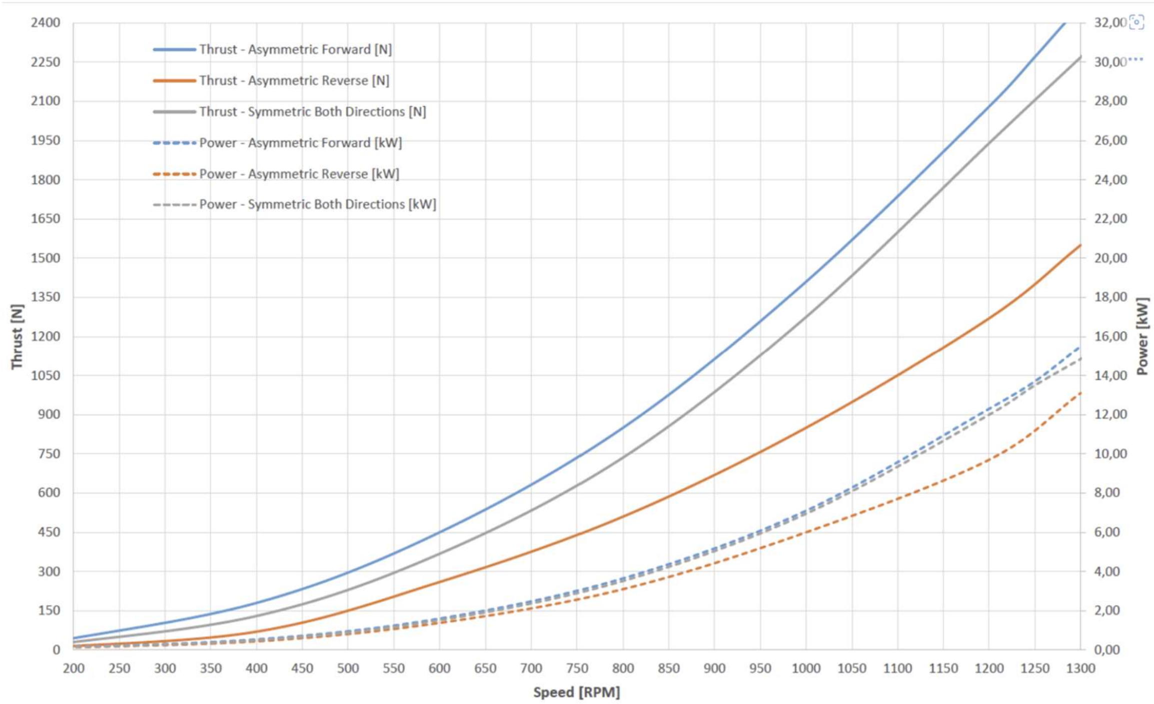

Figure 17: *Copenhagen Subsea VXL Power Curve* – Setting the four drive thrusters to 2 kWh each yields a symmetric thrust of approximately 500 N from each thruster, or 2000 N total available thrust in both the forward and reverse directions. The same values would apply in the vertical directions as well.

Power Management and Distribution

The purpose of the power management and distribution subsystem is to handle the input of 240 VAC power, conversion to 400 VDC for storage, and distribution of both high and low voltage DC power. In addition to these basic functions, the power management and distribution system also provides overload protection with circuit breakers. Given the fact that the power systems are sealed within the pressure hull of CUTLASS, all breakers and relays must be remotely operated.

To meet the 12-hour mission duration requirement (P2) as well as the 24-hour life support duration requirement (CUTLASS33), the battery pack is segregated into a 45-kWh pack for life support and a 60-kWh pack for propulsion and other mission functions.

Design. The CUTLASS power management and distribution subsystem includes:

- battery charger
- charge controller
- DC-DC converter
- low voltage distribution buss
- high voltage distribution buss
- life support system backup battery
- digital relay controller

The basic design of the power system mimics the current design of electric automobiles. This choice was made to maximize the ability to leverage off-the-shelf components. This design directly complies with requirements PMD3 and PMD4.

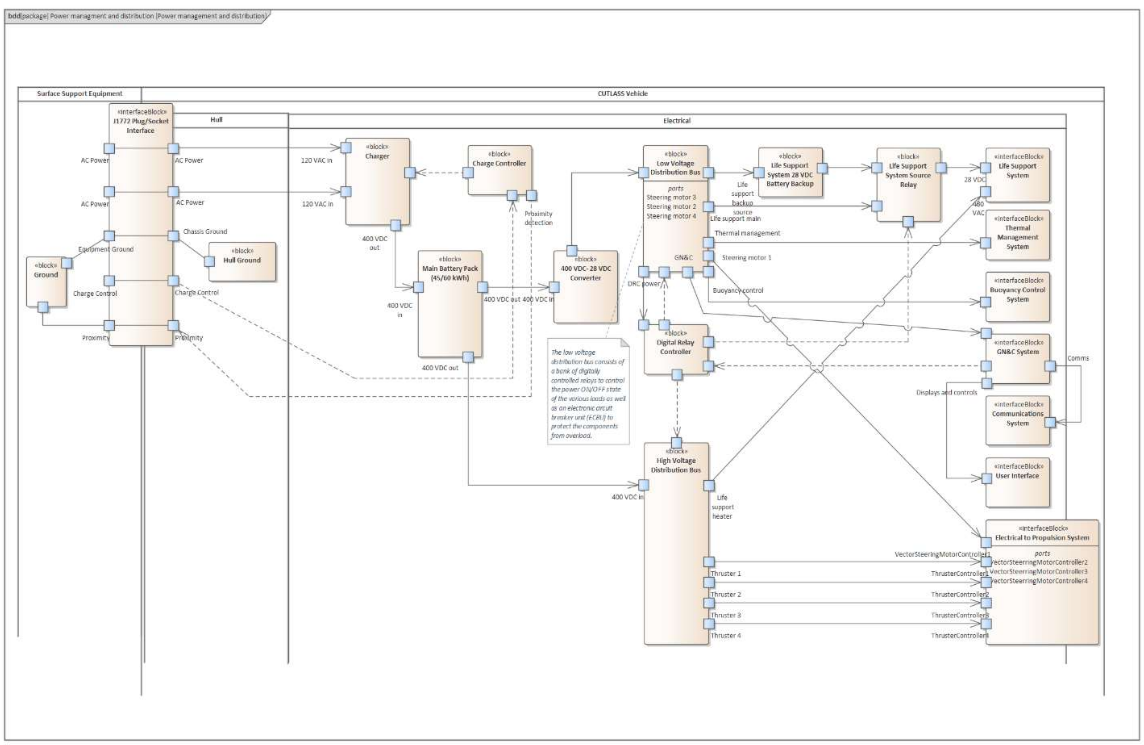

Figure 18: *Power Management and Distribution System Block Definition Diagram* – This diagram illustrates the components necessary to charge the battery and provide power to the various subsystems. The high voltage distribution buss provides power to

the thrusters and heater while the low voltage distribution system provides power to the various computers, pumps, and relays needed to operate the vehicle.

Components. The primary component of the electrical system is the battery pack. A 15-kWh battery pack from SolarEdge was selected to serve as the base of the electrical system (SolarEdge, 2020). Linking three battery packs together in parallel will provide us with a 400 vdc battery pack with 45-kWh for life support and linking the remaining four battery packs together in parallel will provide a 400 vdc battery pack with 60-kWh for primary system operations. As will be shown later, the 105-kWh capacity will be more than enough for the anticipated usage of the vehicle.

The advantage of having seven battery packs (as opposed to one monolithic block) is that they can be distributed throughout the vessel to assist with the weight and balance of the vehicle. Each battery pack weighs 130 kg and occupies a little more than a tenth of a cubic meter of space. This allows us to distribute the 910 kg as needed.
Each of the remaining components are sourced from electric vehicle (EV) suppliers, apart from the remote circuit breaker unit. These components are readily available and very common which simultaneously reduces both cost and risk. The remote circuit breaker unit is another common component found in aircraft and meets requirement PMD6.

Buoyancy and Trim Control

CUTLASS has adjustable buoyancy to support the variable payload requirement. Without any payload, and with ballast tanks flooded, CUTLASS is designed to be neutrally buoyant in seawater and slightly negatively buoyant in freshwater. The CUTLASS buoyancy control system can lift 350 kilograms of payload while maintaining a stable horizontal plane.

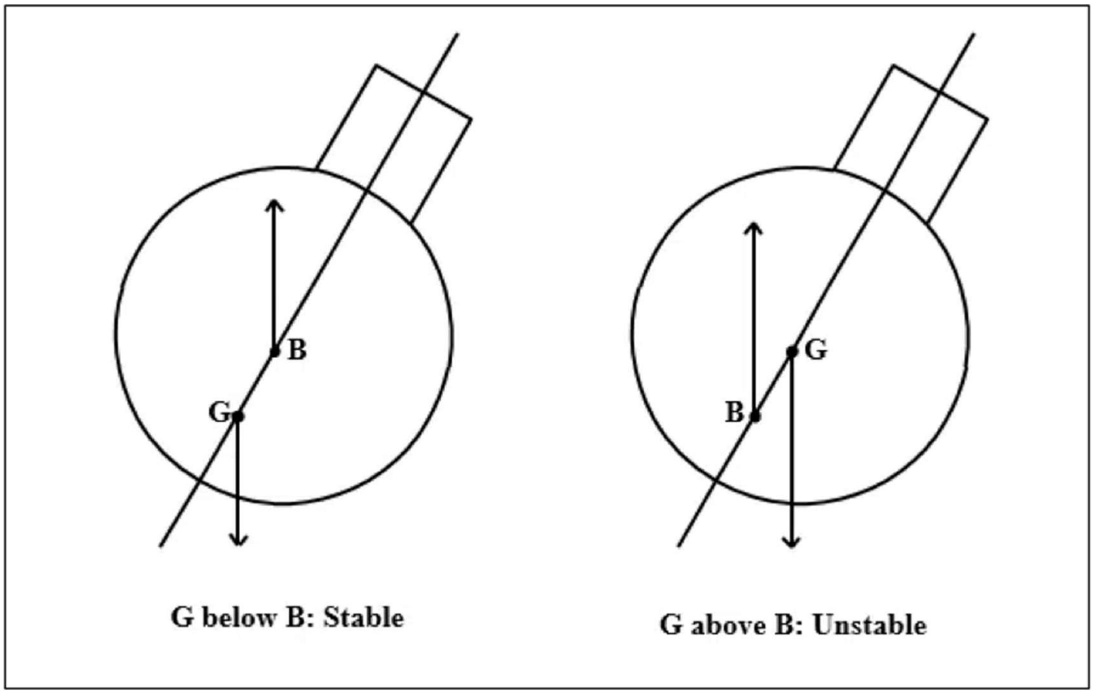

Figure 19: *Center of Gravity vs Center of Buoyancy* – The stability of a submerged body is dependent on the center of buoyancy being above the center of gravity.

Design. The buoyancy controls consist of four ballast tanks: two on the port side and two on the starboard side. These tanks can go from empty to full by opening flood valves and then back to empty using compressed gas to vacate the water ballast. This design allows larger adjustments to the center of buoyancy than would be possible with just one lateral tank on each side of the vehicle and the trim controls. This also helps meet CUTLASS16 and CUTLASS29.

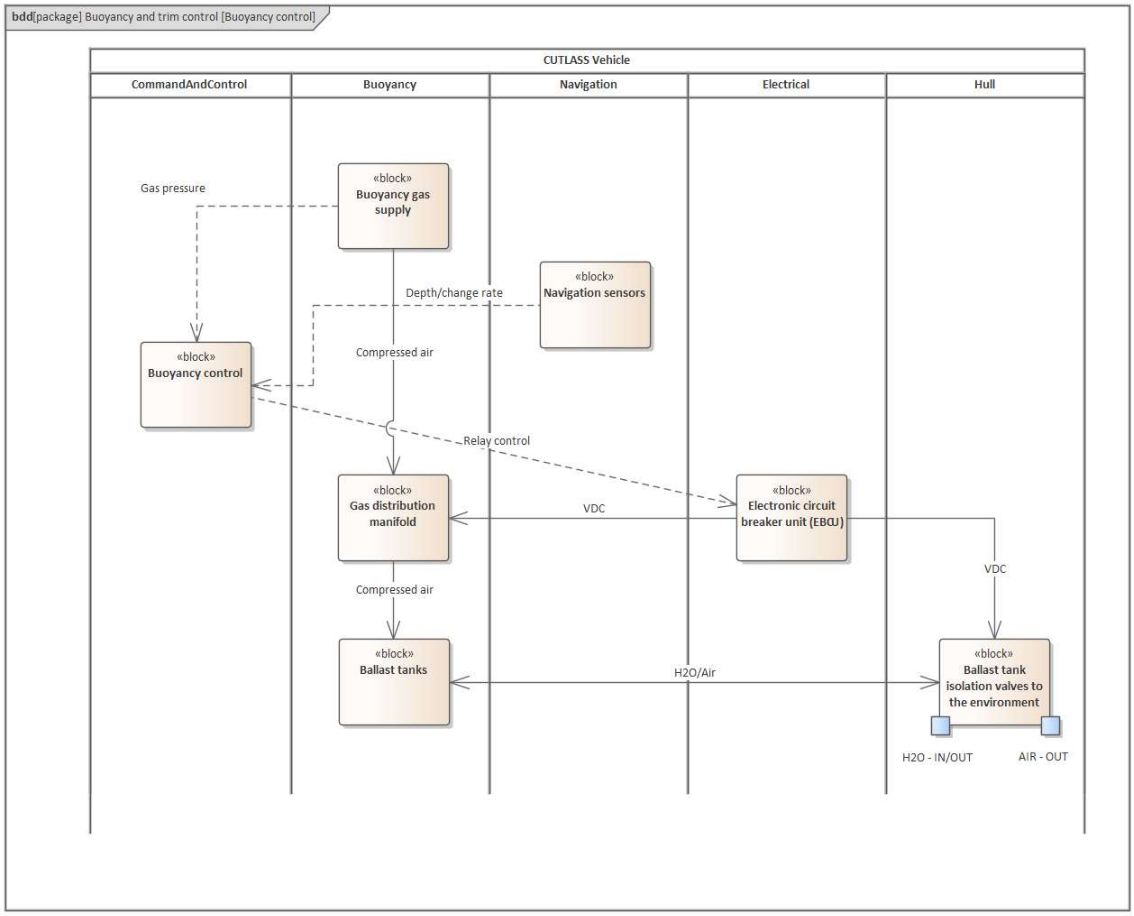

Figure 20: *Buoyancy Control System Block Definition Diagram* – This diagram illustrates the various components necessary for buoyancy control. Vehicle buoyancy is controlled by either flooding the ballast tanks with water or vacating the water by filling the tanks with compressed air. With four controllable tanks, there is the ability to provide large trim adjustments than what would be available through the trim controls alone.

Similarly, the trim controls also consist of four tanks: two mounted fore and aft along the physical centerline of the vehicle and two mounted port and starboard at the center of gravity. In three-dimensional space, each of these tanks are mounted above the center of gravity to maintain vehicle stability as illustrated in Figure 19. These systems are sealed, with ballast being transferred between the two sets of tanks.

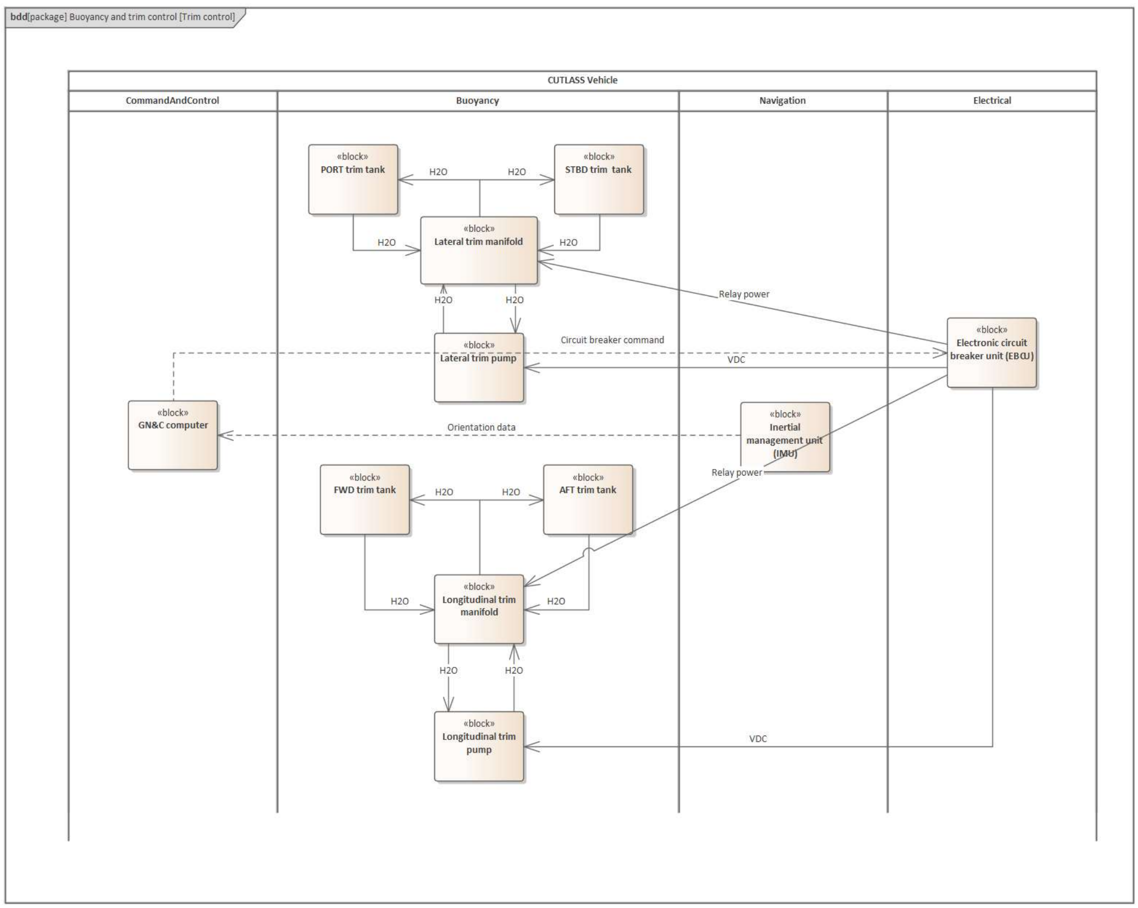

Figure 21: *Trim Control System Block Definition Diagram* – This diagram illustrates the components necessary for trim control of the vehicle. Smaller than the four primary ballast tanks, these tanks are designed to provide finer adjustments to the center of gravity. Water in a closed system is shifted fore and aft or port and starboard along the vehicle centerlines.

Life Support

The life support system consists of two separate subsystems: the closed-circuit rebreather for providing breathing gases and the water heater for providing warmth to the dive team. Design of the warm water supply system is not very interesting and will not be presented, but the design of the closed-circuit rebreather is.

Design. The primary component of the life support system is the onboard rebreather. The concept of the rebreather has been around since at least the 1930's when Otis Barton and William Beebe incorporated onboard life support equipment into the Bathysphere. That system included pressurized oxygen tanks that provided two liters of oxygen per minute, a container of soda lime to absorb CO_2 and another container containing calcium chloride to absorb excess moisture in the air (Beebe, 1934). What makes this design different is that this system can function either as a conventional rebreather, or it will have the ability to make dynamic changes to the diluent gas mixture during the ascent phase of operations if so desired by the dive team. There are some theories which suggest switching from helium rich to a nitrogen rich gas as depths get more shallow helps reduce the decompression time (Andreu, 2017). This work supports those claims and will show that not only is decompression time reduced, but decreasing helium in favor of nitrogen is required to meet the performance specifications.

Just as in a commercially available rebreather, gas is exhaled and pushed through a CO_2 scrubber. Then the gas is analyzed for oxygen, helium, nitrogen, and carbon monoxide concentrations. If the diver is on the ascent phase and has programmed a dynamic diluent adjustment, nitrogen will be injected into the system. Finally, the amount of oxygen required to maintain the desired partial pressure will be injected into the system and supplied to the diver.

Due to requirements P1 and P2, a rebreather is the only reasonable way to provide the life support gases necessary. As will be shown in Chapter 4, the amount of open-circuit gas that would be required to support a mission to 200 meters is not reasonable even for a dedicated dive vehicle.

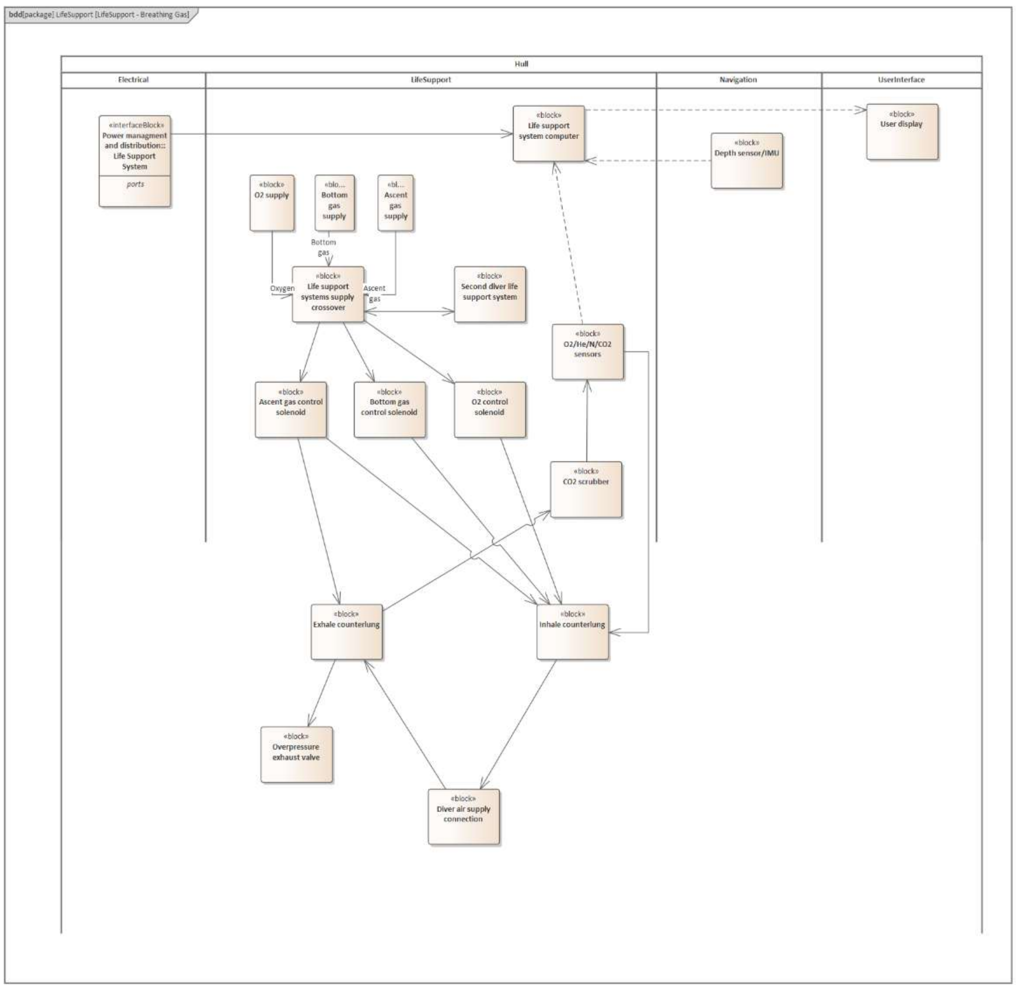

Figure 22: *Life Support Closed-circuit Rebreather System Block Definition Diagram* – This diagram represents the components necessary to construct a closed-circuit rebreather. As described above, this design supports the idea of dynamic diluent gas adjustments such that the helium content required for the descent and operational phase of a dive can be completely replaced by nitrogen during the ascent phase of the dive.

Guidance, Navigation, and Control

The guidance, navigation, and control (GN&C) subsystem consists of the various computers and communication buses required for the other vehicle subsystems to function.

Design. As with the power distribution system of the CUTLASS vehicle, the GN&C subsystem aims to leverage the auto industry in terms of available components. Most automobiles use components that work on a Controller Area Network (CAN) bus. The design illustrated in Figure 23 shows the distributed architecture of the system. Rather than have two redundant computers that drive the vehicle, this design allows for smaller redundant computers that are only responsible for their respective subsystems. Life support is managed locally, as is navigation, and propulsion. The primary computer only provides an interface between the surface, the operators, and the vehicle.

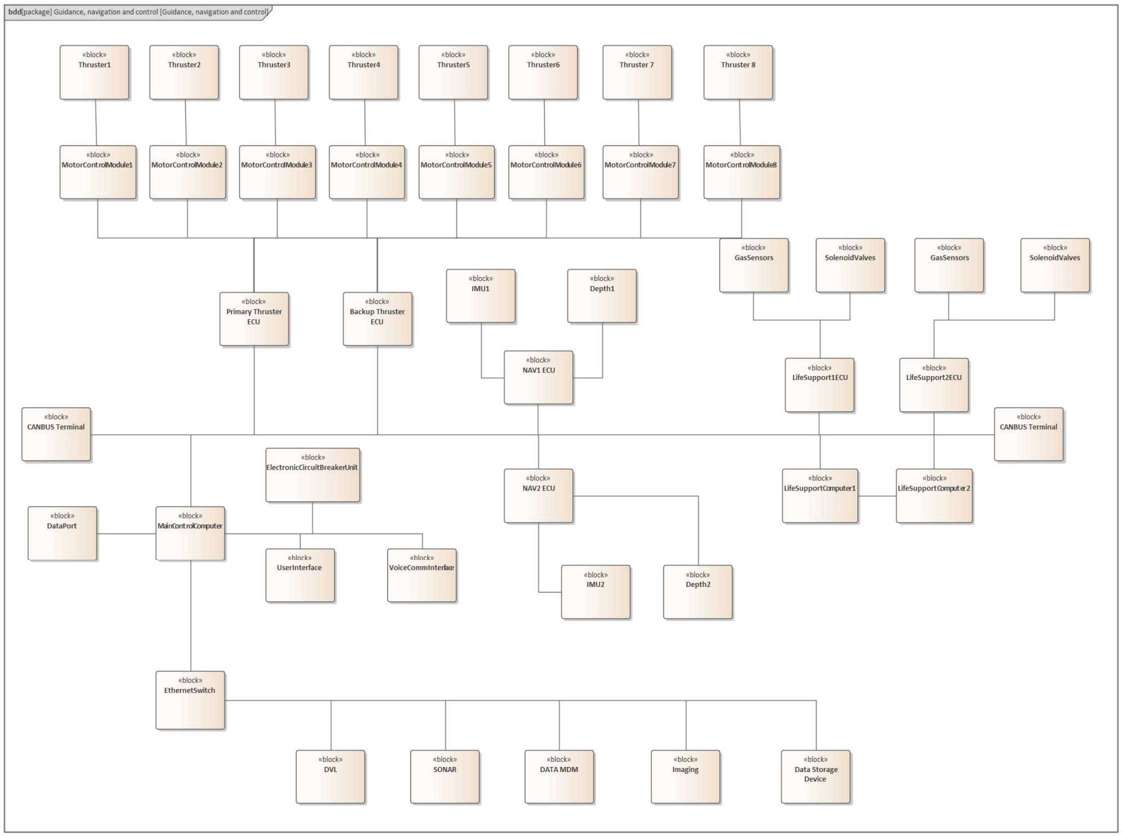

Figure 23: *Guidance, Navigation, and Control System Block Definition Diagram* – The GN&C system block diagram represents some of the various computers and computer-controlled components within the CUTLASS vehicle. As can be seen, this design follows a distributed redundant architecture as opposed to a central controller.

Summary and Conclusions

Using standard systems engineering practices and methods, an architecture was created which supports the operational functionality identified by the ConOps. Then, through further functional decomposition of those activities a systems architecture was created for the vehicle component of the CUTLASS system.

Each of the CUTLASS vehicle subsystems were designed using block definition diagrams. The utilization of block definition diagrams allows for system design without needing to identify specific components early in the process. These diagrams allowed for a detailed understanding of how the various subsystems discussed here would meet their functional requirements. Requirements define what a system must do, block definition diagrams define how it will be done.

CHAPTER 4

ANALYZING THE DESIGN

With the completion of the functional decomposition and initial allocation of requirements and functionality to various subsystems, it was now possible to analyze the proposed solution for performance characteristics. This chapter will detail the development of the "digital twin" and will include the analysis of the vehicle model for acceleration and top speed. Additionally, this chapter will present a model that allows analysis of the physiological effects of a deep dive given changes to diluent gasses and variable rates of descent.

Model-Based Systems Engineering

Rather than utilizing a document-based systems engineering process, where system design documentation consists primarily of textual documents and spreadsheets, a model-based systems engineering (MBSE) approach was utilized. MBSE is defined as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases" (International Council on Systems Engineering (INCOSE), 2007) and more closely resembles the approach that other engineering disciplines have used for decades (Friedenthal, Moore, & Steiner, 2015).

Methodology

Defining the MBSE methodology to be used is a mandatory prerequisite to a successful MBSE project. MBSE methodology can be defined as a "collection of related processes, methods, and tools used to support the discipline of systems engineering in a “model-based” or “model-driven” context (Estefan, 2008). What follows will be a more detailed explanation of the processes, methods, and tools used during the CUTLASS design process.

Process. As discussed in the preceding chapter of this work, a standard Systems Engineering process was followed including:

- needs analysis and development of a Concept of Operations
- requirements definition
- logical architecture definition
- physical architecture definition
- evaluation of proposed solutions
- development of a verification and validation plan

This process follows the standard Systems Engineering Vee model (Figure 24) with the design process terminating at the implementation phase. As will be shown later, CUTLASS utilized the concept of a “digital twin” (Figure 26) in the development process to conduct verification and validation of the design.

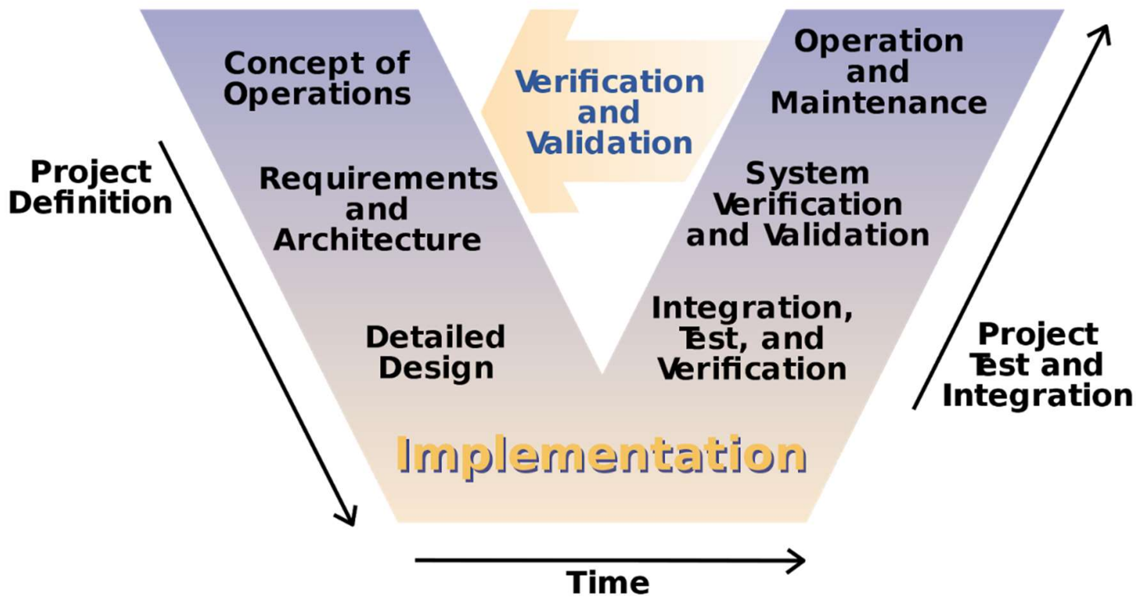

Figure 24: *Systems Engineering Vee Model* – The standard Systems Engineering process is illustrated here. The CUTLASS project is currently in the detailed design phase.

Method. Where the process defines "what" is to be accomplished, the method defines the "how" (Estefan, 2008). In this case, the "how" started with the top-level model organization utilizing the so-called "four pillars of SysML" (Friedenthal, Moore, & Steiner, 2015). As each tier was constructed, the requirements for each tier were defined, activity diagrams were constructed to understand the necessary functionality at that tier, and subsystems were created to allocate functionality. When the subsystems were created, they were each immediately imbued with their own "four-pillars" packages as is shown in Figure 25. The advantage to this approach is that each subsystem or component becomes its own separate model. This allows for individual developers to construct and integrate stand-alone models instead of each developer working within the same packages and potentially stepping on each other when merging models together. Figure 25 only shows the Tier 1 and Tier 2 levels of the model, but it should be clear that each subsystem of the CUTLASS vehicle would branch out from the CUTLASS Vehicle Structures package, and each would contain a requirements, structures, behaviors, and parametrics package.

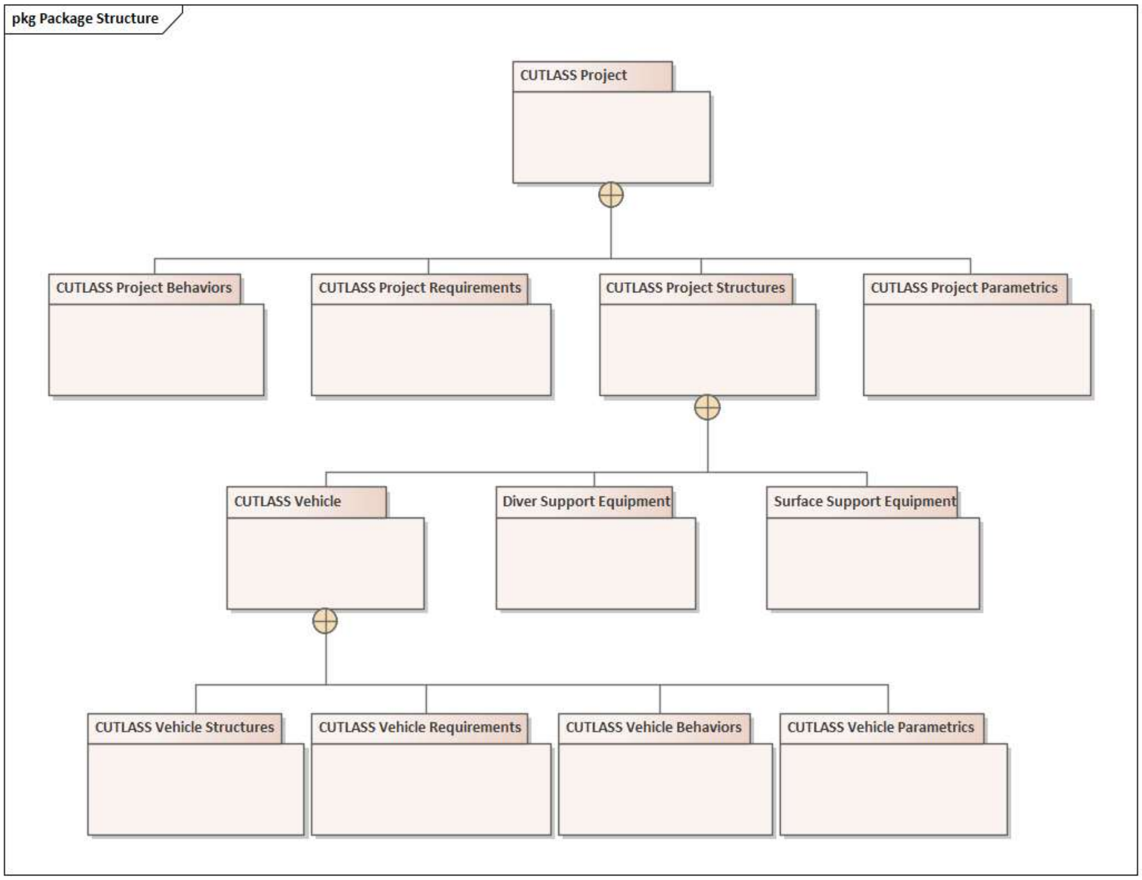

Figure 25: *CUTLASS Project Package Diagram* – Each tier is connected to the preceding tier via the 'structures' folder. This allows for each level or component within the model to be a stand-alone model with links and references to sibling or parent components.

Tools. The third piece of a MBSE methodology is the toolset. The tools that were selected to aide in the model management and development process included:

- Sparx Enterprise Architect
- Lieber Lieber Lemon Tree
- Git Configuration Management

There are many SysML modeling tools available for use. The four that were considered for use on this project included Cameo Systems Modeler (formerly known as Magic Draw) (Dassault Systemes, 2022), Enterprise Architect (Sparx Systems, 2022), Rational Rhapsody (IBM, 2022), and Papyrus (The Eclipse Foundation, 2022). Each tool has various pros and cons associated with it. Papyrus is open source, and therefore carries no cost, but is also only a modeling tool. Rhapsody and Cameo are incredibly capable and can be used to generate source code for construction of system simulations but carry a considerably steep learning curve and are expensive tools to purchase; they also prefer to be housed within a live database and managed by a database management tool. By contrast, Sparx Enterprise Architect provides capable modeling tools, simple execution of activity and sequence diagrams, and is compatible with Lieber Lieber Lemon Tree and Git.

Lieber Lieber Lemon Tree is a visual based model merging tool. Prior experience with model merging included work with both Rhapsody and Cameo. Each of those tools, in the experience of the author, would allow merging of models but only at a textually descriptive level. There was no support for seeing how individual diagrams would appear prior to the completion of a merge. This often resulted in incorrect merges, missing components, and broken models. Lemon Tree helps prevent those issues. Lemon Tree is best described as Beyond Compare (Scooter Software, 2022) for models. Lemon Tree renders the local model, the remote model, and the merged model into individual windows and allows the user to examine how inclusion or exclusion of various colliding components will impact the finished product prior to completion of the merge. This greatly reduces the opportunity for incorrect merges thus better facilitating multiple model developers.

The final piece of the toolset is a configuration management system. Both Sparx Enterprise Architect and Papyrus are compatible with Git, while Rational Rhapsody is fully integrated with Rational ClearCase (IBM, 2022) and Cameo requires a live database. Git is an open-source configuration management tool that is supported by many online repository hosting services including Github, Gitlab, Bitbucket, and can even be hosted on a Google Drive account.

The author of this work had previous experience with each of these modeling tools in a professional capacity and ultimately decided that the ease of use of Sparx Enterprise Architect, as well as the compatibility with Lemon Tree and Git, made Enterprise Architect the most attractive option.

Digital Twin

Given the nature of the project, it was decided that a digital twin would be created and used throughout the development process. A digital twin is defined as "a virtual model designed to accurately reflect a physical object" (IBM, 2022). The digital twin of the CUTLASS vehicle was made up of a virtual representation of the vehicle hull, a software simulation of the various subsystems, and a virtual environment within which the vehicle could be tested. The Boeing MBE Diamond Model (Figure 26) best illustrates the relation of the digital twin with the physical system. Each step in the lower, physical portion of the diamond model has a corresponding activity in the upper, virtual portion. The value of a digital twin is directly proportional to the fidelity of the digital twin. Low fidelity models can be used to rapidly examine some of the physical and functional properties of a system, medium fidelity models will expand the properties and provide more granular data, and high-fidelity models can represent a system with such detail that the datasets generated by the simulation accurately predict the datasets generated by the physical system after construction of the first prototype. The fidelity of the system can be assessed by the quality of these three elements (GSE Solutions, 2017):

- technology
- engineering rigor
- experience

The technology element refers to the quality of the model. A model that operates on a simple rules-based system where:

$$SystemState = f(x_1, x_2, ..x_n) \tag{1}$$

and x represents various other states, cannot accurately capture scenarios outside of the finite number of states explicitly defined. Because of this shortcoming, the CUTLASS simulation was built using an object-oriented approach. Embedding the functionality into an object and defining that functionality in terms of equations used to drive real-world objects allows for a higher fidelity model.

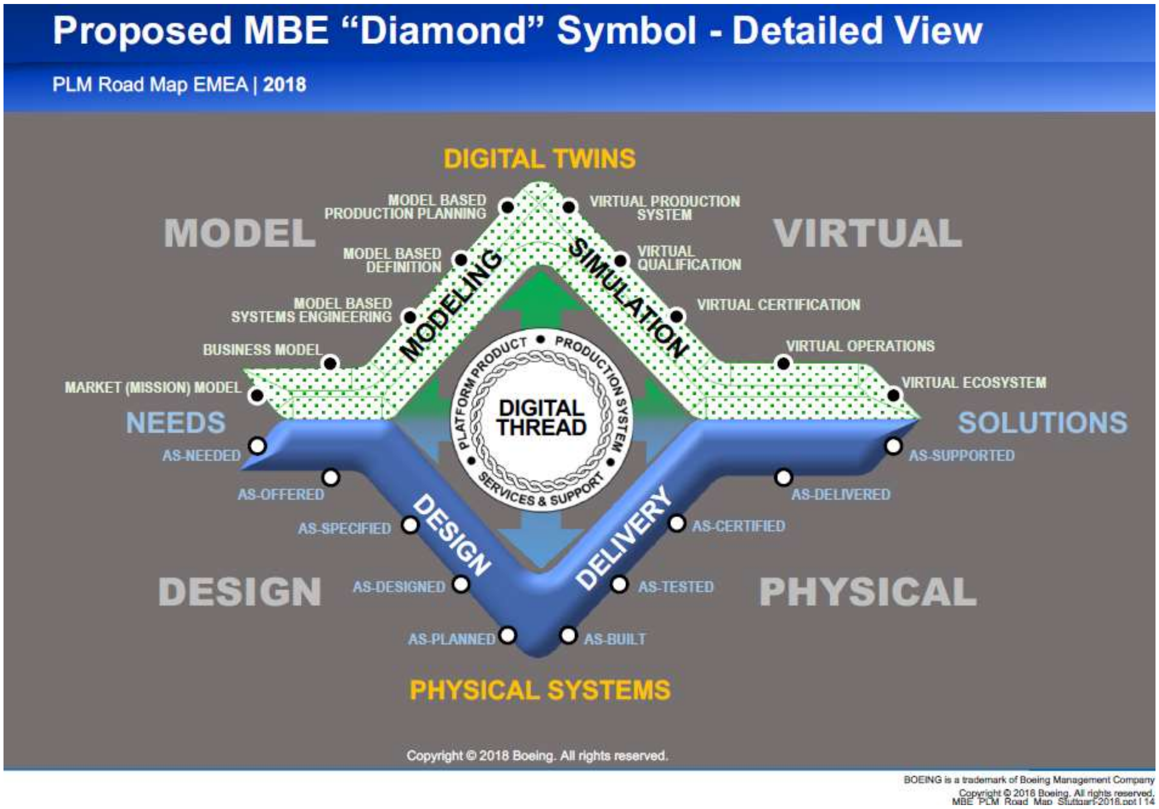

Figure 26: *Boeing MBE Diamond Model Detailing the Concept of the 'Digital Twin'* – The bottom half of the diamond model mirrors the standard Systems Engineering Vee in Figure 24. The top half of the diamond model represents a similar process applied to a completely virtual representation of the system.

Engineering rigor describes the level of detail that is modeled. More subsystems and more components that are modeled results in a model that is capable of more accurate simulation. A simple analogous example would be that of computer graphics. As can be seen in Figure 27, the greater the granularity the higher the quality of the model.

Figure 27: *Example of how Increased Granularity Improves the Quality of a Model –* This example is to show how finer granularity improves fidelity. With the 8-bit graphics, the character is only rudimentarily modeled; but, with the 64-bit graphics, the character begins to take on three-dimensional qualities.

The final component of fidelity is the experience of the engineers modeling the system (GSE Solutions, 2017). As the amount of experience of the model developers increases, one should naturally expect that the accuracy of the simulation would increase as well. Alternatively, presenting the functional simulation to subject matter experts for evaluation would prove equally as effective in improving the quality of the model.

Computer Aided Design

There were two tools that were utilized for development of the physical model of the CUTLASS vehicle: SiemensNX (Siemens, 2022) and Solidworks (Dassault Systemes, 2022). Each of these tools is similar and provides the user with the ability to create 2D and 3D models of systems and components. This initial development effort was restricted to the external shape of the hull, correct sizing of the cockpit, and the placement of the thrusters.

The workflow for hull model development can best be described as following the waterfall model. System requirements were presented to the mechanical engineer, the mechanical engineer developed additional requirements that were then presented to the modeling team, the modeling team then made the requested modifications to the model. After the new model was created, it was analyzed for compliance with the requirements. The process would then be repeated until the model met the requirements or it was determined that the requirements could not be met as written and they would be reevaluated and modified.

There have been a total of seven iterations of the hull design. As was previously discussed, the first iteration of the hull design (Figure 14) is very different from the current iteration of the hull design (Figure 15).

Physical Analysis

There were several metrics that needed to be calculated to verify the ability to meet the functional requirements. The coefficient of drag was calculated by conducting fluid analysis of the hull using Siemens NX software. Buoyancy force was calculated, as was velocity and acceleration.

Coefficient of Drag

A wind tunnel simulation was created, and the fluid density and viscosity were set to 1,027 kg/m^3 and 0.0014 Ns/m^2 to most closely mimic seawater. Each revision of the vehicle was analyzed with a forward velocity of approximately 2 m/s. These simulations allowed the coefficient of drag for each of the MK1 revisions (Table 1) to be determined.

These results were not unexpected since, when a body is fully submerged, the coefficient of drag is a function of the length of the vehicle (Granville, 1976).

$$C_D = f\left(R_L, \frac{L}{L_1}, \frac{L}{L_2}, \ldots, \frac{L}{L_n}\right) \tag{2}$$

Where R_L is Reynolds number as defined in (3), U_∞ is the speed of the fluid, and υ is the kinematic velocity of water.

$$R_L = \frac{U_\infty}{\upsilon} \tag{3}$$

Thus

$$C_D = f\left(\frac{U_\infty}{\upsilon}, \frac{L}{L_1}, \frac{L}{L_2}, \ldots, \frac{L}{L_n}\right) \tag{4}$$

The coefficient of drag is necessary to calculate both the maximum vehicle velocity as well as the vehicle acceleration rate.

Velocity

The velocity of the vehicle needed to be calculated to evaluate compliance with requirement CUTLASS18. This requirement states that "the CUTLASS platform shall have a horizontal speed of at least 2 m/sec". The vehicle's maximum velocity is a relatively straight-forward extension of Newton's Second Law of Motion (Newton, 2002) and can be mathematically defined as (5).

$$F_{net} = F_{thrust} - F_{drag} = ma \tag{5}$$

Setting equation (5) equal to zero yields

$$F_{thrust} = F_{drag} \tag{6}$$

When the force of thrust is equal to the force of drag the vehicle will no longer be accelerating and will be at its maximum velocity. The drag force of the water acting against the vehicle can be defined as

$$F_{drag} = \frac{1}{2}\rho C_D A \upsilon_t^2 \tag{7}$$

where ρ is the density of seawater, C_D is the drag coefficient, A is the surface area presented to the fluid flow, and υ is the velocity of the vehicle. Then, solving for velocity yields

$$\nu = \sqrt{\frac{2F}{\rho C_D A}} \tag{8}$$

The value of the applied force for normal cruising speed is determined by the amount of force that can be provided by the thrusters while remaining within the constraints defined by requirement PROP2; the value of the applied force for maximum speed is determined by the maximum thrust capacity of the thrusters. With four primary drive thrusters configured symmetrically, the chart in Figure 17 provides the necessary information to calculate those values.

As can be seen, each version of the MK1 hull design provides the maximum speed required but REV3 provides both the fastest maximum speed as well as the fastest cruising speed.

Acceleration

The rate of acceleration is important to the safety and performance of the vehicle. With a slow acceleration rate, the vehicle would have trouble maintaining its position and could collide with other objects. To better understand the performance of the vehicle, it was necessary to calculate the amount of time required to meet the maximum velocity. Beginning with (5) and rewriting as a differential equation resulted in

$$F_{thrus} \; - \frac{1}{2} \rho C_D A v_t^2 = m \left(\frac{dv}{dt} \right) \tag{9}$$

Then apply the separation of variables technique

$$\int_0^t \frac{1}{m} dt = \int_0^{v_t} \frac{1}{F_{thrust} - \frac{1}{2}\rho C_D A v_t^2} dv \tag{10}$$

Application of partial fractions

$$\int_0^t \frac{1}{m} dt = \int_0^{v_t} \frac{1}{-\left(\sqrt{F_{thr}} + v\sqrt{\frac{1}{2}\rho C_D A}\right)\left(\sqrt{F_{thrust}} - v\sqrt{\frac{1}{2}\rho C_D A}\right)} dv \tag{11}$$

Integrate

$$\frac{t}{m}|_0^t = \frac{1}{2\sqrt{F_{thrust}}\sqrt{\frac{1}{2}\rho C_D A}} \ln\left|\frac{\sqrt{F_{thrust}} + v\sqrt{\frac{1}{2}\rho C_D A}}{\sqrt{F_{thrus}} - v\sqrt{\frac{1}{2}\rho C_D A}}\right| |_0^{v_t} \ (where\ v \neq \pm 1) \tag{12}$$

Because $F_{thrust} = \frac{1}{2}\rho C_D A$ it is necessary to evaluate the expression in parts.

Thus

$$t = \frac{m}{2\sqrt{F_{thrust}}\sqrt{\frac{1}{2}\rho C_D A}}\left[\ln\left|\frac{\sqrt{F_{thrust}} + v\sqrt{\frac{1}{2}\rho C_D A}}{\sqrt{F_{thrust}} - v\sqrt{\frac{1}{2}\rho C_D A}}\right| |_0^1 + \ln\left|\frac{\sqrt{F_{thrust}} + v\sqrt{\frac{1}{2}\rho C_D A}}{\sqrt{F_{thrust}} - v\sqrt{\frac{1}{2}\rho C_D A}}\right| |_1^{v_t}\right] \tag{13}$$

Which finally simplifies to

$$t = \frac{m}{2\sqrt{F_{thrust}}\sqrt{\frac{1}{2}\rho C_D A}} \ln\left|\frac{\sqrt{F_{thrust}} + v_t\sqrt{\frac{1}{2}\rho C_D A}}{\sqrt{F_{thrust}} - v_t\sqrt{\frac{1}{2}\rho C_D A}}\right| \tag{14}$$

Due to the symmetric nature of the drive thrusters, the same amount of time needed to reach maximum velocity would also be required to stop the vehicle. As shown in Table 1, the heavier vehicle moving at a higher rate of speed takes more time to stop; this result was expected.

Buoyancy Force

Given the volume of the vehicle, it was possible to calculate the force of buoyancy using (15).

$$F_B = m * a = V_{vehic} * \rho_{seawater} * g \qquad (15)$$

Since the rate of ascent is not dependent on the mass of the vehicle and is only dependent on the mass of the water displaced, it was possible to calculate that MK1REV3 (Figure 15) would ascend at 2.71 m/s with ballast tanks emptied and no power applied. Conversely, it is not possible to calculate the projected maximum unpowered descent rate because that rate is dependent on the mass of the vehicle which is currently unknown.

Table 1: *CUTLASS MK1REVX Data* – Unpowered ascent is not calculated for the first three revisions because the top view of the surface area was not calculated.

	MK1REV0	MK1REV1	MK1REV2	MK1REV3
Front surface area (m^2)	4.06	5.11	5.45	5.43
Vehicle length (mm)	2940	4000	4000	5172
Displaced mass (kg)	4303	3913	5073	6265
Buoyancy force (N)	42,214	38,385	49,770	61,457
Coeff of Drag	0.707	0.846	0.443	0.342
Cruising velocity @8 kW power (m/s)	1.16	0.95	1.27	1.44
Maximum velocity (m/s)	2.47	2.01	2.69	3.07
Maximum acceleration (m/s^2)	2.09	2.30	1.77	1.43
Time to reach maximum velocity (s)	5.01	3.08	5.41	8.52
Required stopping distance at maximum velocity (m)	12.37	6.19	14.55	26.16
Maximum unpowered ascent rate (m/s)	N/A	N/A	N/A	2.71

Functional Analysis

There are two computer simulations being developed to support the functional analysis of CUTLASS. The first simulation is a functional representation of the CUTLASS vehicle designed to evaluate the performance of the vehicle in an integrated model and the second simulation is written specifically for understanding the tissue loading of the divers during dives. Ultimately the second model will become part of the integrated model.

Vehicle Systems Simulation

The integrated vehicle simulation was built within the UWSim framework which provides a virtual representation of the ocean environment and allows for the integration and testing of vehicle models in a dynamic environment (Prats, Perez, Fernandez, & Sanz). The initial efforts on the CUTLASS project included integration of the hull model into the underwater environment (Figure 28), integration with a joystick to allow for easier manual control, and a simple autopilot capable of executing a preplanned set of waypoints.

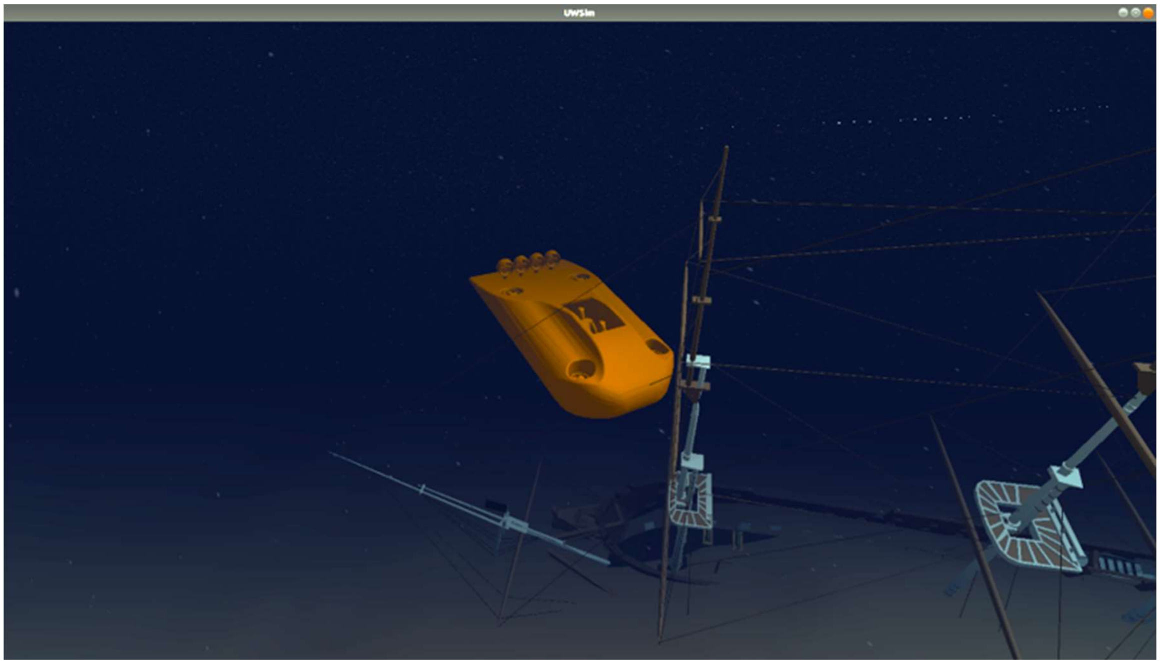

Figure 28: *CUTLASS MK1REV3 Inside the UWSim Shipwreck Scene* – The screen grab depicts the CUTLASS model within the UWSim virtual environment. The UWSim allows the developer to modify the model file to change depths of the floor, sea surface state, and currents.

UWSim provides two underwater environments for use: one with and one without the physics model of the water engaged. Early model development efforts were focused on integration into the non-dynamic environment. The non-dynamic environment still allowed for some testing, such as power consumption and life support, without the overhead that came with integrating into the dynamic environment. As development of CUTLASS continues, the dynamic simulation will be utilized for testing of the propulsion system and control laws.

Life Support Simulation

The life support system is the most critical system on the vehicle. Because this vehicle is designed to be open to the environment, the issues associated with deep diving come into effect. In a pressurized vehicle, the divers are exposed to 1 atm of pressure; in

CUTLASS, the divers can be exposed to as much as 20 atm of pressure. Exposure to that amount of pressure requires a life support system that is engineered to provide life support at those depths.

Dalton's Law of Partial Pressure. The first concept that needs to be understood when discussing the life support system in a high-pressure environment is partial pressures. Dalton's Law of Partial Pressure states

$$P_{total} = \sum_{i=1}^{n} P_i \tag{16}$$

In other words, the total pressure of a gas mixture is equal to the pressures of each component of that mixture. In the case of air at sea level, air is composed of approximately 0.79 atm nitrogen and 0.21 atm oxygen. Pressure increases at a rate of 1 atm every 10 meters as a diver descends so that at 200 meters, assuming the ratio of nitrogen and oxygen remained constant, the partial pressure of nitrogen at 200 meters becomes 15.8 atm and the partial pressure of oxygen at 200 meters becomes 4.2 atm. Understanding the physiological effects of different gases at higher partial pressures is key to designing a functional life support system.

Nitrogen Narcosis. Nitrogen narcosis is a feeling of euphoria that begins at 4 atm partial pressure of nitrogen and culminates with unconsciousness at 10 atm partial pressure (U.S. Navy, 2016). This effect can be mitigated by changing the diluent gas from nitrogen to helium. Helium is considerably more expensive and conducts heat more easily which results in the need to provide breathing gas heaters in colder water.

Oxygen Toxicity. Oxygen toxicity includes both pulmonary oxygen toxicity and central nervous system oxygen toxicity which can set in above 0.5 atm and 1.3 atm, respectively (U.S. Navy, 2016). In addition to consideration of the partial pressures of the breathing gases, the gradual accumulation of gas in the various body tissues needs to be considered.

Decompression Sickness. Henry's Law states that the amount of gas absorbed in a liquid is directly proportional to the partial pressure of the gas compared to the liquid.

$$P \propto X \tag{17}$$

As a diver increases depth, the amount of gas stored within the various tissues of the body also increases. Assuming 1 liter of gas is stored in the body at sea level, by the time the diver reaches 200 meters they will have approximately 20 liters of gas in their tissues. Decompression sickness occurs when excess diluent gas that has been absorbed in the body is rapidly released (U.S. Navy, 2016). Because of this, it is necessary to understand how the body absorbs and releases gas so that safe dive profiles can be planned and executed.

Bühlmann Algorithm. Beginning in the 1950's, Dr. Albert Bühlmann began studying the physiological effects on inert gases and tissue saturation. This research led to the publication of the Bühlmann algorithm used for calculating tissue saturation and desaturation rates. Bühlmann's work became the basis for many dive tables and dive computers (Chapman, 2022). Bühlmann segregated the human body into 16 tissue types, or compartments with varying rates of saturation. To understand the effects on the dive team at 200 meters, a simulation was constructed using the Bühlmann algorithm.

$$P_x = P_0 + \left(P_{gas} - P_0\right)\left(1 - 2^{-\frac{t}{hl_x}}\right) \tag{18}$$

Where P_x is the pressure of the current compartment after exposure, P_0 is the pressure of the compartment prior to exposure, P_{gas} is the pressure of the inert gas being breathed, t is the exposure time in minutes, and hl_x is the half-time of the current compartment in minutes.

In addition to the formula for calculating the saturation pressure, Bühlmann provides an algorithm to calculate the minimum pressure, thus depth, that a compartment can be reduced to before the formation of bubbles in the tissues.

$$P_{min} = b(P_x - a) \tag{19}$$

Where a and b are constants that are related to hl_x (Terrades Andreu, 2017).

$$a = 2hl_x^{-\frac{1}{3}} \tag{20}$$

$$b = 1.005 - hl_x^{-\frac{1}{2}} \tag{21}$$

Table 2: *The Half-time Values Associated with Bühlmann's ZH-L16A Algorithm* – The necessary constants for using the Bühlmann algorithm.

Cpt	Nitrogen half-time (min)	Nitrogen 'a' value	Nitrogen 'b' value	Helium half-time (min)	Helium 'a' value	Helium 'b' value
1	4.0	1.2599	0.5050	1.5	1.7435	0.1911
2	8.0	1.0000	0.6514	3.0	1.3838	0.4295
3	12.5	0.8618	0.7222	4.7	1.1925	0.5446
4	18.5	0.7562	0.7725	7.0	1.0465	0.6265
5	27.0	0.6667	0.8125	10.2	0.9226	0.6917
6	38.3	0.5933	0.8434	14.5	0.8211	0.7420
7	54.3	0.5282	0.8693	20.5	0.7309	0.7841
8	77.0	0.4701	0.8910	29.1	0.6506	0.8195
9	109.0	0.4187	0.9092	41.1	0.5794	0.8491
10	146.0	0.3798	0.9222	55.1	0.5256	0.8703
11	187.0	0.3497	0.9319	70.6	0.4840	0.8860
12	239.0	0.3223	0.9403	90.2	0.4460	0.8997
13	305.0	0.2971	0.9477	115.1	0.4112	0.9118
14	390.0	0.2737	0.9544	147.2	0.3788	0.9226
15	498.0	0.2523	0.9602	187.9	0.3492	0.9321
16	635.0	0.2327	0.9653	239.6	0.3220	0.9404

Source Code. To execute the Bühlmann algorithm a console application program was written. This program allowed the user to enter a target depth and a descent rate. Modifications to the source code allow for analysis using either an open circuit system with a constant percentage of oxygen, or a closed-circuit system where the percentage of oxygen was decreased to maintain a constant partial pressure of oxygen.

```
/*
 * Buhlmann.h
 *
 *  Created on: Aug 10, 2021
 *      Author: kirkb
 */

#ifndef INFRASTRUCTURE_BUHLMANN_H_
#define INFRASTRUCTURE_BUHLMANN_H_

#include <chrono>
#include "DataLogger.h"
```

```
class Buhlmann {
public:
	Buhlmann();
	virtual ~Buhlmann();
	void Init(DataLogger* logger);
	double CalculateDecoStopDepth(double currentDepth, double pgN2,
double pgHE2);

private:
	DataLogger* dataLoggerPtr_;
	bool m_commenceDiveFlag;
	int m_printCounter;
	std::chrono::steady_clock::time_point m_previousTime;
	double m_pcN2[16];
	double m_pcHE2[16];
	double m_pbN2[16];
	double m_pbHE2[16];
double const m_htN2[16] = {4.0, 8.0, 12.5, 18.5, 27.0, 38.3, 54.3,
77.0,
109.0, 146.0, 187.0, 239.0, 305.0, 390.0, 498.0, 635.0};
double const m_N2a[16] = {1.2599, 1.0000, 0.8618, 0.7562, 0.6667,
0.5933, 0.5282, 0.4701, 0.4187, 0.3798, 0.3497, 0.3223, 0.2971, 0.2737,
0.2523, 0.2327};
double const m_N2b[16]  = {0.5050, 0.6514, 0.7222, 0.7725, 0.8125,
0.8434, 0.8693, 0.8910, 0.9092, 0.9222, 0.9319, 0.9403, 0.9477, 0.9544,
0.9602, 0.9653};
double m_htHE2[16] = {1.5, 3.0, 4.7, 7.0, 10.2, 14.5, 20.5, 29.1, 41.1,
55.1, 70.6, 90.2, 115.1, 147.2, 187.9, 239.6};
double m_HE2a[16] = {1.7435, 1.3838, 1.1925, 1.0465, 0.9226, 0.8211,
0.7309, 0.6506, 0.5794, 0.5256, 0.4840, 0.4460, 0.4112, 0.3788, 0.3492,
0.3220};
double m_HE2b[16] = {0.1911, 0.4295, 0.5446, 0.6265, 0.6917, 0.7420,
0.7841, 0.8195, 0.8491, 0.8703, 0.8860, 0.8997, 0.9118, 0.9226, 0.9321,
0.9404};
	double m_N2tol[16];
	double m_HE2tol[16];

	double TheAlgorithm(double currentDepth, double pgN2, double
pgHE2);

	// For data logging purposes
	TissueLoading tissueData;
};

#endif /* INFRASTRUCTURE_BUHLMANN_H_ */
/*
 * Buhlmann.cpp
 *
 *  Created on: Aug 10, 2021
 *      Author: kirkb
 */

#include "Buhlmann.h"
#include <math.h>
```

```
#include <iostream>

Buhlmann::Buhlmann() {


}

Buhlmann::~Buhlmann() {
	// TODO Auto-generated destructor stub
}

void Buhlmann::Init(DataLogger* logger) {
	dataLoggerPtr_ = logger;
	m_commenceDiveFlag = false;

	//Set tissue pressures to 0.0
	for (int x = 0; x < 16; x++) {
		m_pcN2[x] = 0.0;
		m_pcHE2[x] = 0.0;
		m_pbN2[x] = 0.79;
		m_pbHE2[x] = 0.79;
	}
}

double Buhlmann::CalculateDecoStopDepth(double currentDepth, double
pgN2, double pgHE2) {
	double decoDepth = 0.0;
	if (currentDepth > 0.0 && !m_commenceDiveFlag) {
		//Start the dive
		m_commenceDiveFlag = true;
		m_printCounter = 0;
		m_previousTime = std::chrono::steady_clock::now();
	}

	//Convert depth into pressure
	double atmPressure = 1 + (currentDepth / 10.0);

	// Maintain 0.21 PPO2
	// The following code allows us to adjust the percentage of
oxygen
	// to maintain a PPO2 = 0.21.
	// By dividing 0.21 by the current pressure in atmospheres,
	// we reduce the percentage of oxygen in the mixture.
	// Then we subtract that reduced percentage from both
	// the nitrogen values and helium values.
	// This approach allows us to run two simulations at the same
	// time: one with a nitrogen diluent and one with a helium
	// diluent. We could also modify this code to provide results
	// based on a trimix (nitrogen/helium/oxygen).

	// By commenting out these lines, the percentage of oxygen
	// would be held constant, providing an effective simulation
	// of an open system.
	double ppo2 = 0.21 / atmPressure;
	pgN2 = 1 - ppo2;
```

```
	pgHE2 = 1 - ppo2;

	//Convert percent N2 and HE2 into partial pressures
	double ppN2 = atmPressure * pgN2;
	double ppHE2 = atmPressure * pgHE2;

	decoDepth = TheAlgorithm (currentDepth, ppN2, ppHE2);

	for (int x = 0; x < 16; x++) {
// Package up the results for data logging.
		tissueData.innerGasPressureN2[x] = m_pcN2[x];
		tissueData.innerGasPressureHE2[x] = m_pcHE2[x];
	}

	if (currentDepth > m_printCounter + 1) {
		dataLoggerPtr_->WriteData(tissueData, currentDepth,
decoDepth);
		m_printCounter = m_printCounter + 1;
	}

	return decoDepth;
}

double Buhlmann::TheAlgorithm(double currentDepth, double pgN2, double
pgHE2) {
	double decoDepth = 0.0;
	std::chrono::steady_clock::time_point now =
std::chrono::steady_clock::now();
	std::chrono::duration<double> te = now - m_previousTime;
	//Pc = Pb + (Pg - Pb) * (1 - 2^(-te/tht))
	//Pc = inner gas pressure after exposure time (bar)
	//Pb = inner gas pressure before exposure time (bar)
	//Pg = inner gas pressure in mixture (bar)
	//te = length of exposure time (minutes)
	//tht = compartment half-time (minutes)

	for (int x = 0; x < 16; x++) {
		// First calculate for nitrogen loading in each tissue
compartment.
m_pcN2[x] = m_pbN2[x] + (pgN2 - m_pbN2[x]) * (1 - std::pow(2.0, (-
(te.count() / m_htN2[x])) / 60 ));
		m_pbN2[x] = m_pcN2[x];
		//Now for HE2 loading.
m_pcHE2[x] = m_pbHE2[x] + (pgHE2 - m_pbHE2[x]) * (1 - std::pow(2.0, (-
(te.count() / m_htHE2[x])) / 60 ));
		m_pbHE2[x] = m_pcHE2[x];

// This section of the algorithm calculates the minimum pressure
		// that can be tolerated based on the current tissue
loading
		// of each of the compartments.
		m_N2tol[x] = (m_pcN2[x] - m_N2a[x]) * m_N2b[x];
		m_HE2tol[x] = (m_pcHE2[x] - m_HE2a[x]) * m_HE2b[x];
	}
```

```
	//Find the max tolerable pressure. That will be where we must
stop.
	for (int x = 0; x < 16; x++) {
		decoDepth = std::max(decoDepth, m_N2tol[x]);
	}

	for (int x = 0; x < 16; x++) {
			decoDepth = std::max(decoDepth, m_HE2tol[x]);
		}

// Convert atmospheres to meters.
	if (decoDepth > 1.0) {
		decoDepth = decoDepth * 10;
	}
	else {
		decoDepth = 0.0;
	}

	m_previousTime = now;

	return decoDepth;
}
```

Results. Two passes through the simulation were conducted. The first pass through demonstrates the tissue loading results in an open circuit system with 21% oxygen and either 79% helium or 79% nitrogen. The second set of results is from a pass where the percentage of oxygen was adjusted to maintain a partial pressure of 0.21 atm. The rate of descent for both cases was set to 10 m/min, which is about half the maximum suggested rate of descent (U.S. Navy, 2016).

As was previously discussed, nitrogen narcosis begins to affect divers below 30 meters at 79% nitrogen, or at a partial pressure of 3.16 atm, and oxygen toxicity becomes a risk above 1.60 atm, or about 66 meters at 21% oxygen (U.S. Navy, 2016); because of this, the open circuit data is primarily for comparison to the closed-circuit data. Closed-circuit data generated by the simulation shows that the saturation of tissues is greater with helium than with nitrogen, as would be expected due to the lower molecular weight of helium. What this means is that deeper decompression stops will be required while diving on a helium diluent as compared to nitrogen.

Slight modification to the simulation would allow for analysis of varying percentages of helium, nitrogen, and oxygen. It is also possible to further modify the simulation to examine the effect on decompression time by dynamically adjusting the diluent during the ascent phase of the dive.

Summary and Conclusions

Development of a digital twin allows for both physical and operational analysis and simulation prior to construction of a prototype. This approach greatly improves the likelihood of a successful program. By using computer software to simulate and analyze the fluid flow characteristics of the hull model, a drag coefficient can be calculated. With the drag coefficient calculated, it is then possible to estimate how well the vehicle design will meet the performance requirements. The life support simulation can predict the effects of varying diluent gas mixtures and ascent and descent rates. Future integration with the dynamic vehicle simulation will allow for end-to-end mission simulation with complete datasets that can be compared to actual completed data for model validation and adjustments.

CHAPTER 5

OPERATIONAL ANALYSIS OF THE CUTLASS VEHICLE

The current iteration of the CUTLASS vehicle meets the requirements of the scientific diver community. The platform provides the necessary lift capacity, it gives the users communications with the surface, reduces the workload of the dive team, and provides meaningful access to depths below 100 meters. While other vehicles exist which also provide such capabilities, this platform provides the ability for the divers to exit the vehicle and interact with the environment at depth; most other vehicles in existence today are pressurized and only allow for interaction through some sort of manipulator arm. The shape of the hull, size of the thrusters, and capacity of the battery provides the ability to accelerate to speeds around 6 knots with a cruising speed of just under 3 knots. The onboard closed-circuit rebreather life support system provides more than enough oxygen to support the dive team as they conduct missions up to 12-hours in duration. The dynamically adjustable diluent gas allows for bottom times of 20 minutes at 200 meters while meeting decompression obligations within the allotted 12-hour mission time. The battery capacity is such that there is sufficient power for those missions. This chapter will examine a typical cargo delivery mission profile and demonstrate how the design choices support a successful mission. The team will be tasked with diving to 200 meters, locating an acceptable location to deploy their single component, 100 kg cargo, and returning to the surface. Time to locate an acceptable location will be limited to 10 minutes with an additional 10 minutes allocated to cargo deployment.

Pre-dive Operations

Pre-dive operations begin with detailed dive planning. Dive planning will take place off the vehicle using surface support equipment and is outside of this scope of work. After dive planning is completed, the necessary life support gases will be loaded onto the vehicle life support tanks. The divers enter the vehicle, and the vehicle systems are then powered up to conduct a pre-dive checkout.

Pre-dive checks include:

- propulsion system
  - all thrusters and actuators functional
- power management
  - battery at required percentage for mission
  - remote circuit breakers functional
  - all components able to be powered on
- buoyancy and trim control
  - ballast tanks empty
  - trim tanks neutral
  - buoyancy air tanks fully charged
- life support
  - oxygen tanks fully charged
  - bottom gas properly mixed and tanks charged
  - ascent gas properly mixed and tanks charged
  - heaters functioning properly
  - new CO_2 scrubbing canisters installed

While powered up to conduct the pre-dive systems check, the mission plan will be loaded onto the vehicle via the data port identified in Figure 23. After successful completion of mission plan loading and pre-dive checks the crane will be connected, and the vehicle placed in the water.

Vehicle Launch

Once in the water, the divers will conduct final checks of life support and communications systems. Ensuring that the vehicle has both data and voice communications with the surface is specified by requirements S2 and S3. Functioning gas and suit heaters are specified in requirements CUTLASS35 and CUTLASS35, while a functioning rebreather system is specified in CUTLASS1. Once these remaining systems are verified to be functional, the vehicle will be released from the crane and begin its descent.

Descent

The descent phase of the operation will typically be handled by the vehicle computer. First, the ballast tanks will be flooded by opening the vent valves detailed in Figure 20. Air will be vented until neutral buoyancy is achieved and the rate of descent can be controlled explicitly by the thrusters. Neutral buoyancy is required to meet requirements BTC4 and CUTLASS12. The maximum allowable rate of descent (20 m/min) is achievable with approximately 926 N downward thrust. Given that there are four vertical thrusters, per the mapping in Figure 17, that translates to about 4 kW of power for all four thrusters. To ensure that the vehicle remains on target, the surface will continuously update the GPS position of the craft using ultra-short baseline acoustic positioning technology. Vehicle status will be reported to the surface.

With a target depth of 200 meters, the total power used by the propulsion system during the descent phase of operations would be about 0.66 kWh. The GN&C system is estimated to draw a maximum 500 watts, so 0.083 kWh is consumed during the 10-minute descent. Similarly, the gas and suit heaters are not expected to activate until the final two minutes of the descent phase, greatly reducing any potential impact on the power systems.

The average person has a lung capacity of 6 liters and a resting respiration rate of 15 breaths per minute (U.S. Navy, 2016). Given that the CUTLASS vehicle dive team consists of two divers, that is 180 l/min of gas consumption at sea level. Because of Boyle's Law

$$P_1V_1 = P_2V_2 \tag{22}$$

the volume of gas consumed at 200 meters would be 3780 l/min. Hence a closed-circuit rebreather system is the only feasible life support system, as captured in requirement P6. Since the percentage of oxygen would be set to around 2.5% to maintain the ppO_2 of 0.50, and since only about 5% of the oxygen inhaled is consumed, at 200 meters the rate of oxygen consumption would be less than 5 liters per minute. Since the time to reach 200 meters is 10 minutes, and we have a linear progression in the amount of oxygen consumed, it is reasonable to estimate that the descent phase of operations will result in the consumption of about 50 liters of oxygen.

Maneuvering

Once the vehicle arrives at the target depth, the maneuvering phase of operations is entered. Each phase of operations will result in a phase timer being displayed to the crew. As per the hypothetical mission plan, the crew will have 10 minutes to maneuver and locate an acceptable space to deploy their cargo. To facilitate the most efficient search, potential deployment areas would have been pre-mapped by either ROV or surface sonar. Assuming the crew visits several sites while operating at a cruising speed, and they use their allotted time, the total power consumed by propulsion will amount to only 1 kW and the dive team will have consumed an additional 50 liters of oxygen. Upon locating the most desirable location, the ballast tanks would be completely flooded, and the vehicle settled on the seafloor. In alternative scenarios, it is possible that the vehicle would be required to maintain a certain distance from the seafloor during unloading; this contingency is completely supported per the requirements in CUTLASS13 and CUTLASS14.

Cargo Deployment

With the vehicle safely settled on the seafloor the crew is free to exit the vehicle while maintaining attachment to the vehicle through the life support umbilical. The umbilical provides life support gas, heated water warmth, and communications between both divers as well as the surface. The divers can lift the cargo out of the cargo hold by inflating a lift bag using ballast air supplied via an external air hose. Because the vehicle ballast tanks have been flooded to settle the vehicle onto the seafloor, it is negatively buoyant and will not need any further adjustment. This phase of operations is ended when the divers return to the vehicle cockpit. Since only 10 minutes was allocated to this phase, the power consumed will be minimal and the oxygen consumed will be another 50 liters.

Ascent

During the ascent phase of operations, the vehicle computer will control the ascent rate, calculate the decompression stops, and adjust the breathing gas mixture to minimize the decompression time and reduce the workload on the divers. The example mission has a 10-minute descent phase and 20 minutes on the bottom. For the purposes of dive planning, square profiles are utilized, thus it is considered that the divers have spent 30 minutes at 200 meters.

Figure 29: *Dive Profile for Mission to 200 Meters* – This graph illustrates the difference between maintaining a single diluent gas mixture for such a deep and long duration dive, as opposed to utilizing a more dynamic mixture. The standard approach of changing out gas mixtures wholesale on ascent would yield a better curve than the Heliox but would still likely fall short of meeting the 12-hour mission goals.

Two dive plans were prepared: one using Heliox (helium and oxygen only) that maintains the partial pressure of oxygen at 0.50 atm, and one using Trimix (helium, nitrogen, and oxygen) that maintains the partial pressure of oxygen to 0.50 atm and the partial pressure of nitrogen to 3.00 atm while below 40 meters. The outcome of the different approaches to gas utilization were strikingly different.

Due to the lower molecular weight of helium, the Heliox dive results in higher tissue saturations in the slowest compartments. As previously referenced in Table 2, the helium half-time of compartments 15 and 16 are 187 minutes and 239 minutes, respectively; the half-times of nitrogen in those same compartments is two to three times longer. On ascent, the first three decompression stops are dictated by the saturation levels of compartments five, six, and eight. These deeper decompression stops dictated by the faster compartments allow the saturation levels in the slower compartments to continue to increase. As a result, the shallower decompression stops are driven by the saturation levels in the slower compartments which demand considerably longer decompression times than the faster compartments. When the 12-hour mission clock expires, CUTLASS is still at 50 meters depth.

By contrast, the Trimix dive profile has a much more desirable result. Controlling the partial pressure of oxygen to 0.50 atm and the partial pressure of nitrogen to 3.00 atm while below 40 meters results in a bottom mixture with approximately 2.5% oxygen, 14% nitrogen, and 83% helium. As a result of this lower concentration of helium, the first decompression stop on Trimix occurs at 99 meters for 70 minutes. As the depth decreases, the increasing percentage of nitrogen and decreasing percentage of helium in the mixture results in lower saturation levels in the slowest compartments. Using the square profile method, when the mission clock reaches 12-hours, the vehicle is at 6 meters depth and the final tissue loads are in Table 3. By allowing the computer to move the vehicle in shorter increments, as opposed to long duration decompression stops, those final numbers would likely be reduced to normal prior to expiration of the mission clock; but this hypothesis is only posed, and a possible answer is not explored.

Table 3: *Final Tissue Saturations After a 12-hour Mission* – Trimix nitrogen is slightly above normal levels and helium is nearly vacated completely. Heliox helium saturation is still elevated across all tissue compartments.

	Heliox Dive Profile	Trimix Dive Profile	
Compartment	Helium tissue saturation	Nitrogen tissue saturation	Helium tissue saturation
1	4.500	0.500	0
2	4.500	0.500	0
3	4.500	0.500	0
4	4.500	0.500	0
5	4.501	0.503	0
6	4.509	0.512	0
7	4.533	0.540	0
8	4.583	0.602	0
9	4.662	0.706	0.001
10	4.760	0.807	0.008
11	4.875	0.879	0.032
12	5.023	0.920	0.089
13	5.189	0.925	0.188
14	5.338	0.895	0.327
15	5.409	0.838	0.483
16	5.358	0.765	0.627

Vehicle Recovery

Once the vehicle is on the surface, the ballast tanks are emptied completely to provide maximum positive buoyancy. The divers stay with the vehicle until it is safely aboard and secured. All systems are powered down once the vehicle is aboard the support craft.

Post-dive Operations

After the divers exit the vehicle, the vehicle can be powered back up for data retrieval by the support team. The vehicle is cleaned, and any scheduled or required maintenance is conducted. The batteries are attached to the charging system. Processing of the data is conducted off platform.

Summary and Conclusions

Historically, crewed undersea exploration has left a gap in the 100 to 200 meters depth range. What exploration has occurred at these depths has generally been the realm of robots, or the occasional single-atmosphere pressurized submersible. The intent of the CUTLASS project was to address this gap by providing an unpressurized vehicle capable of supporting two divers to a depth of 200 meters while allowing a reasonable amount of time to accomplish real work. An unpressurized vehicle that could deliver that capability would allow unprecedented physical interaction with the environment.

Working with the scientific diver community, additional needs and desires were captured. Additional goals of the project included the ability to transfer cargo to and from the surface, reduce the workload of the dive team, and the system detailed in the preceding work meets that goal. The vehicle can reach 6 knots, 2 knots greater than required. The battery capacity of 105 kWh total is more than sufficient to support two divers for 12 hours, while operating the vehicle at a cruising speed of just under 3 knots. The range requirement detailed in CUTLASS17 is for 12 nautical miles; at 3 knots cruising speed, the CUTLASS vehicle has a round-trip capability of 18 nautical miles. As shown in the preceding section, the life support system, with its dynamically adjustable diluent, allows for the opportunity for divers to reach 200 meters and conduct meaningful work. While there is still work to be done, the functionality has been established and the design of the vehicle meets the requirements as defined.

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APPENDIX A

DIVER SURVEY

SCIENTIFIC DIVER ACTIVITY SURVEY

We are collecting information in an effort to better understand the needs of the scientific diver community to support development of a semiautonomous diver assistance vehicle. Your participation in this effort is greatly appreciated. Please return to kirk.b.bennett@asu.edu

1. Name:____

2. Email:____

3. Date:____

4. Approximate number of dives:____________________

5. How would you classify your primary science goals? (eg: archaeological, biological, geological):

6. Please list your dive certifications and corresponding certifying organization:

7. On a scale of 1 to 5, (1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree), please rate the following statements:

Navigation
a. The ability to accurately navigate is crucial. (____)
b. I often navigate without any external reference. (____)
c. I often miss judge distance during navigation. (____)
d. I can usually find my way back to my starting point during dives. (____)
e. Accurate navigation takes a great deal of my focus. (____)

Depth control
f. The ability to maintain accurate depth is crucial. (____)
g. I have no problems maintaining an accurate depth. (____)
h. My actual dive profile generally matches my planned dive profile. (____)
i. I check my depth gauge regularly to make sure I don’t exceed my planned depth. (____)
j. I would prefer to be able to focus more on my work and less on my depth. (____)

Technical
k. I often dive deep enough or long enough to require decompression stops. (____)
l. Completing prescribed decompression stops is crucial to safe technical diving. (____)
m. My primary dive equipment for long dives is a rebreather. (____)
n. I prefer to use a drysuit. (____)
o. I use a computer to manage my dive profile, ascent rate, deco stops and safety stop.

(____)

Equipment
p. I often carry extra tanks on dives. (____)
q. I often carry multiple cameras and lights on dives. (____)
r. My dives typically require survey equipment. (____)
s. My dives typically require heavy scientific equipment. (____)
t. My dives result in numerous biological/geological samples being collected. (____)

8. Considering the preceding statements, please rank the following activities in order of importance from most important to least important:
a. Accurate navigation (____)
b. Accurate depth control (____)
c. Accurate deco/safety stops (____)
d. Accurate ascent rates (____)
e. Ability to carry extra equipment and/or collected samples (____)

9. Which aspects of a typical dive do you believe require the most attention?

10. Which aspects of a typical dive do you find to be the most challenging?

11. How would you go about reducing your workload during a typical research dive?

12. How many times have you run out of air during a dive?

13. Have you ever experienced a decompression injury?

14. Have you ever experienced nitrogen narcosis?

15. Have you ever participated in a dive using a gas mixture other than air or nitrox?

16. Estimate your percentage of total dives using the following gases. Please total 100%.
a. Air (____)
b. Nitrox (____)
c. Trimix (____)
d. Heliox (____)

17. Do you participate in dives that require different gas mixtures at different stages of the dive?

18. Do you participate in dives that require multiple tanks?

19. If you answered yes to 17, what is the most number of tanks that you've carried on one dive?

20. If your dives result in sample collection, what is the average amount of samples collected by weight on a typical dive? Average number of samples?

21. In order to better understand the activities required for your dives, can you please explain a typical dive from start to finish?

22. What features would you like to see incorporated into a diver assistance platform?

23. I appreciate you taking the time to complete this survey. Would you be willing to participate in more in depth interviews in support of this effort?

APPENDIX B

REQUIREMENTS

Project Requirements

P1 Depth

ID: P.1
Risk: Low
Source: ConOps
Text: The program shall provide support for manned mission depths down to 200 meters.
Rationale: 200 meters is generally considered the maximum safe depth for closed circuit
rebreather equipment. Below that depth, saturation diving is necessary.
Verification Description: The final system will be deployed to 200 meters depth.
Verification Method: Demonstration

P2 Time

ID: P.2
Risk: Low
Source: ConOps
Text: The program shall provide support for manned mission durations of 12 hours.
Rationale: Due to the maximum depth, decompression times can be significant. This
allows for useable minutes at maximum depth.
Verification Description: The final system will be deployed for 12 hours.
Verification Method: Demonstration

P3 Surveying Accuracy

ID: P.3
Risk: Medium
Source: ConOps
Text: The program shall provide the ability for divers to survey underwater sites with accuracies of 1 meter/100 meters of depth.
Rationale: Research diver surveys revealed a desire to transfer accurate GPS coordinates to the sea floor and improve survey techniques to make them more accurate and less time consuming.
Verification Description: The final system will be deployed to known landmarks at different depths and the locations generated by the system will be compared to the known values. A curve will be generated to show compliance at 200 meters depth.
Verification Method: Demonstration

P4 Deployability

ID: P.4
Risk: Low
Source: UNOLS Small Research Vessel Compendium 2004, Appendix A (UNOLS, 2004)

Text: The program shall develop a system architecture that supports deployment from a small sized research vessel.
Rationale: This requirement allows for the greatest deployment options.
Verification Description: All components of the final system will be portable and fit within the constraints required by the definition of "small sized research vessel."
Verification Method: Analysis

P5 Cargo Capacity

ID: P.5
Risk: Medium
Source: ConOps
Text: The program shall provide the capability to move 300 kg from the surface to the sea floor or from the sea floor to the surface.
Rationale: Research diver surveys revealed a need to assist in the movement of equipment from the surface to the sea floor and to move equipment and samples from the sea floor to the surface.
Verification Description: The final system will be deployed with 300 kg of ballast and will demonstrate the ability to dump the ballast and maintain stability as well as the ability to retrieve the ballast and still surface safely.
Verification Method: Demonstration

P6 Life Support

ID: P.6
Risk: High
Source: BS EN 14143:2013 (European Committee for Standardization, 2013)
Text: All life support systems shall be in compliance with regulation EN-14143: Respiratory equipment — Self-contained re-breathing diving apparatus https://www.en-standard.eu/bs-en-14143-2013-respiratory-equipment-self-contained-re-breathing-diving-apparatus/
Rationale: Life support equipment requires strict compliance with accepted standards and best practices.
Verification Description: All life support equipment will meet the requirements and testing standards outlined in EN-14143.
Verification Method: Demonstration

P7 Operational Environment

ID: P.7
Risk: Medium
Source: ConOps
Text: The program shall develop a system architecture that is operable in sea state 3 or less and under 4 knots (2m/s) current speed.
Rationale: Sea state 3 is classified with wave heights up to 1.25 m. 4 knots current speed is four times a characteristic surface current per Encyclopedia Britannica.

Anything exceeding these two constraints would expose the divers and vehicle to unnecessary risk.
Verification Description: The system will be deployed in the appropriate environment.
Verification Method: Demonstration

System Requirements

S1 Architecture

ID: S.1
Risk: Low
Source: ConOps
Text: At a minimum, the system architecture shall consist of a two-person dive team, a powered platform, and the surface support equipment.
Rationale: This project is intended to support manned operations at depth and the inclusion of more than one diver is a standard dive safety practice.
Verification Description: The system architecture will be evaluated for compliance.
Verification Method: Analysis

S2 Voice communications

ID: S.2
Risk: Low
Source: P.1
Text: The system shall support uninterrupted voice communications between the surface and the dive team.
Rationale: Voice communications between the dive team and the surface is essential to the safe deployment of the system.
Verification Description: The final system will be deployed, and voice communications will be verified continuously during testing.
Verification Method: Demonstration

S3 Data communications

ID: S.3
Risk: Low
Source: P.1
Text: The system shall support uninterrupted data communications between the surface and the dive team.
Rationale: Data communications between the dive team and the surface is essential to the safe deployment of the system.
Verification Description: The final system will be deployed, and data communications will be verified continuously during testing.
Verification Method: Demonstration

S4 RESERVED

S5 Dimensional constraint

ID: S.5
Risk: Low
Source: P.4
Text: The CUTLASS system shall be capable of being disassembled such that each subassembly will fit within a standard sized shipping container (2.43m x 2.59m x 6.09m).
Rationale: The system needs to be shippable.
Verification Description: The system will be disassembled and packaged for shipping.
Verification Method: Demonstration

S6 Deployed equipment constraint

ID: S.6
Risk: Low
Source: P.4
Text: The CUTLASS system shall be deployable onto a research vessel with:

- 1500 sq ft of working deck area (8x20)
- 1000 sq ft of laboratory space
- SCUBA support facilities
- capacity of 12-16 science personnel

Rationale: These constraints are requirements for UNOLS small sized research vessels.
Verification Description: Deployment plans will be developed and analyzed for a typical research deployment.
Verification Method: Analysis

S7 Location

ID: S.7
Risk: Medium
Source: P.3
Text: The CUTLASS system shall transfer GPS coordinates from the surface with an accuracy of 3 m per 100 m depth.
Rationale: Site surveys will be conducted with points relative to each other. The accuracy of earth-centered, earth-fixed (ECEF) reference points is less critical. GPS receivers vary in accuracy, with the most accurate “survey grade” receivers capable of accuracy of 1 millimeter.
Verification Description: The system will be deployed, and a known location will be referenced for system accuracy.
Verification Method: Demonstration

S8 Reliability

ID: S.8
Risk: High
Source: P.2

Text: Mission critical systems shall be designed with sufficient redundancy to protect against loss of life or loss of the vehicle.
Rationale: 12 hours mission time implies a level of reliability and redundancy.
Verification Description: The system will be analyzed for appropriate redundancy.
Verification Method: Analysis

CUTLASS Vehicle Requirements

CUTLASS1 Onboard life support

NOTE: EN-14143 covers diver worn closed circuit rebreathers to 100 meters. Additional requirements and test procedures will need to be developed to support 200 meters depth certification.
ID: CUTLASS.1
Risk: High
Source: P.6
Text: Onboard life support equipment shall be in compliance with EN-14143 (European Committee for Standardization, 2013).
Rationale: Testing to EN-14143 is necessary to prove that the CCR life support systems provide sufficiently safe functionality.
Verification Description: All onboard life support equipment will be tested per the procedures in EN-14143.
Verification Method: Demonstration

CUTLASS2 Pressure safety buffer

NOTE: Testing to design depth may weaken the structure, thereby limiting its deployed life span.
ID: CUTLASS.2
Risk: Low
Source: OPNAVINST 9110.1D (Chief of Naval Operations, 2017)
Text: All pressure vessels shall maintain structural integrity to 150% of maximum mission depth.
Rationale: USN operational/test depths limited to 2/3 design depth thus providing a safety factor of 1.5.
Verification Description: Pressure hulls will be designed to 150% of operational depth but will only be tested to operational depth.
Verification Method: Analysis

CUTLASS3 Mass constraint

ID: CUTLASS.3
Risk: Low
Source: P.4
Text: The CUTLASS platform shall weigh no more than 3000 kg.
Rationale: Per UNOLS requirements, a small sized research vessel should have a crane capable of deploying and retrieving up to 3628 kg of equipment over the side.

Verification Description: The platform will be weighed.
Verification Method: Inspection

CUTLASS4 Structural integrity

ID: CUTLASS.4
Risk: Medium
Source: CUTLASS.3
Text: The CUTLASS platform shall be capable of being lifted out of the water, with ballast tanks full and with 300 kg of cargo, without structural failure.
Rationale: Vehicle recovery even after failure of the buoyancy management systems.
Verification Description: Following structural analysis of computer models, a flooded and loaded CUTLASS will be lifted out of the water and observed for structural failure.
Verification Method: Demonstration

CUTLASS5 Minimum displacement

ID: CUTLASS.5
Risk: Low
Source: CUTLASS.3
Text: The CUTLASS platform shall displace enough mass to cover the mass of the vehicle plus 300 kg of payload.
Rationale: 300 kg was identified during requirements gathering as a reasonable maximum payload capacity.
Verification Description: CUTLASS will be submerged, 300 kg loaded, and then commanded to resurface.
Verification Method: Demonstration

CUTLASS6 Impact resistance

ID: CUTLASS.6
Risk: High
Source: P.8
Text: The CUTLASS platform shall be capable of surviving a head on impact with a rigid plane at 2 m/sec without loss of functionality.
Rationale: The vehicle will reach maximum speed while moving forward and is most likely to either impact either a wall or the research vessel.
Verification Description: A test will be constructed to generate and measure the required impact force and then CUTLASS will execute a subsequent series of functional tests to demonstrate no loss of capability.
Verification Method: Demonstration

CUTLASS7 Inversion survivability

ID: CUTLASS.7
Risk: Medium
Source: Safety

Text: The CUTLASS platform shall recover from the state of being inverted without any loss of functionality.
Rationale: Unplanned vehicle inversion should not result in the loss of the vehicle.
Verification Description: The CUTLASS vehicle will be mounted to a fixed rig underwater and rotated about the x-axis until the vehicle is upside down. Vehicle functionality will be evaluated during the rotation. Similarly, the vehicle will be rotated about the y-axis and evaluated as well.
Verification Method: Demonstration

CUTLASS8 Pitch/roll limitation exceedance analysis

ID: CUTLASS.8
Risk: Medium
Source: CUTLASS.7
Text: The CUTLASS design documentation shall include a detailed analysis of predicted behavior if the pitch and/or roll limits are exceeded. This analysis shall include predicted self-righting behavior analysis as well as a failure analysis of each subsystem.
Rationale: Understanding the impact of exceeding designed pitch/roll limitations is necessary to determine the safety and survivability of the vehicle.
Verification Description: The design documentation will be examined to determine the necessary analysis work has been completed.
Verification Method: Inspection

CUTLASS9 Descent rate

ID: CUTLASS.9
Risk: Low
Source: SS521-AG-PRO-010 (U.S. Navy, 2016)
Text: The CUTLASS platform shall have a controllable descent rate between 0 and 20 m/min.
Rationale: The maximum recommended diver descent rate is 20 m/min.
Verification Description: The CUTLASS design will be inspected for compliance.
Verification Method: Analysis

CUTLASS10 Descent rate consistency

ID: CUTLASS.10
Risk: Medium
Source: SS521-AG-PRO-010 (U.S. Navy, 2016)
Text: The CUTLASS platform shall maintain commanded descent rates within +0.0/-0.5 m/min.
Rationale: Exceeding planned descent rate is dangerous to the diver.
Verification Description: Dive test will be conducted.
Verification Method: Demonstration

CUTLASS11 Ascent rate

ID: CUTLASS.11
Risk: Medium
Source: SS521-AG-PRO-010 (U.S. Navy, 2016)
Text: The CUTLASS platform shall have a controllable ascent rate between 0 and 9 m/min.
Rationale: The maximum recommended diver ascent rate is 9 m/min.
Verification Description: The CUTLASS design will be inspected for compliance.
Verification Method: Analysis

CUTLASS12 Ascent rate consistency

ID: CUTLASS.12
Risk: Medium
Source: SS521-AG-PRO-010 (U.S. Navy, 2016)
Text: CUTLASS shall maintain commanded ascent rates within +0.0/-0.5 m/min.
Rationale: Exceeding planned ascent rate is dangerous to the diver.
Verification Description: Surface test will be conducted.
Verification Method: Demonstration

CUTLASS13 Depth hold

ID: CUTLASS.13
Risk: Medium
Source: SS521-AG-PRO-010 (U.S. Navy, 2016)
Text: The CUTLASS platform shall maintain commanded depths to +/- 0.25 m.
Rationale: CUTLASS will need to conduct survey operations without impacting the coral below it.
Verification Description: CUTLASS will be directed to maintain a commanded depth for 10 minutes and the data logs examined for compliance.
Verification Method: Demonstration

CUTLASS14 Position hold

ID: CUTLASS.14
Risk: Medium
Source: ConOps
Text: The CUTLASS platform shall maintain a commanded position with drift that does not exceed a radius of 1 m/hr when a visual reference is available, 2% of the slant range to the surface ship per hour when a visual reference is not available.
Rationale: The ability to maintain a position is essential platform functionality.
Verification Description: CUTLASS will be directed to maintain a commanded position for 20 minutes, the position monitored and then the drift extrapolated to determine the one-hour drift.
Verification Method: Demonstration

CUTLASS15 Maneuverability

ID: CUTLASS.15
Risk: Low
Source: CUTLASS.14
Text: The CUTLASS platform shall be fully maneuverable in X, Z, and yaw axes.
Rationale: Maneuverability is essential for position hold.
Verification Description: A series of functional demonstration tasks will be developed to show compliance.
Verification Method: Demonstration

CUTLASS16 Maneuverability limits

ID: CUTLASS.16
Risk: Low
Source: CUTLASS.15
Text: The CUTLASS platform shall be limited to intentional movements of +/- 20 degrees in the pitch and roll axes.
Rationale: CUTLASS.15 implies that the platform is not fully maneuverable in the pitch and roll axes. By limiting movement, we improve stability and simplify position hold functionality.
Verification Description: CUTLASS will be commanded to maximum pitch and roll angles and the data logs examined for compliance.
Verification Method: Demonstration

CUTLASS17 Vehicle range

ID: CUTLASS.17
Risk: Medium
Source: ConOps
Text: The CUTLASS platform shall have sufficient power to travel 12 nautical miles, underwater, under ideal (no current) situations.
Rationale: CUTLASS is designed to support underwater site surveys. These sites may span several nautical miles. CUTLASS should be capable of traversing geographically dispersed sites.
Verification Description: CUTLASS will traverse an underwater course of appropriate distance.
Verification Method: Demonstration

CUTLASS18 Horizontal speed

ID: CUTLASS.18
Risk: Medium
Source: P.7
Text: The CUTLASS platform shall have a horizontal speed of at least 2 m/sec.
Rationale: 2 m/sec is approximately 4 knots, which is greater than 90% of the ocean currents around the world.
Verification Description: CUTLASS will maneuver between two points 100 meters apart and the average speed between them will be calculated.

Verification Method: Demonstration

CUTLASS19 Inherent ascent stability

ID: CUTLASS.19
Risk: Medium
Source: Safety
Text: The CUTLASS platform shall maintain stability about the pitch and roll axes during unpowered ascent.
Rationale: With loss of power, the CUTLASS vehicle still needs to be capable of conducting a safe ascent to the surface.
Verification Description: The CUTLASS vehicle will be submerged to an appropriate depth and will then ascend without using the thrusters for stability. The telemetry data will be analyzed to ensure the pitch/roll limitations are not exceeded.
Verification Method: Demonstration/Analysis

CUTLASS20 Deployment dimensional constraint

ID: CUTLASS.20
Risk: Low
Source: S.6
Text: The CUTLASS platform shall not exceed an 8 ft x 20 ft footprint.
Rationale: The deck space available on a small research vessel is 1500 sq. ft (8x20).
Verification Description: The CUTLASS platform dimensions will be measured.
Verification Method: Inspection

CUTLASS21 Shipping dimensional constraint

ID: CUTLASS.21
Risk: Low
Source: S.5
Text: The CUTLASS platform shall be capable of being disassembled such that each subassembly fits within a standard sized shipping container (2.43m x 2.59m x 6.09m).
Rationale: The system needs to be shippable.
Verification Description: CUTLASS will be disassembled and packed.
Verification Method: Demonstration

CUTLASS22 Operational depth

ID: CUTLASS.22
Risk: Medium
Source: P.1
Text: All submersible subsystems shall maintain operability while under 21 atm of absolute pressure.
Rationale: Maximum operational depth is 200 meters. This depth provides human access to a depth range that has typically been the domain of unmanned platforms.

Verification Description: CUTLASS will be directed to 200 meters depth, unattended, and will resurface after one hour. Data logs will be examined for anomalies. Telemetry will be monitored real time during the testing.
Verification Method: Test

CUTLASS23 Mission time

ID: CUTLASS.23
Risk: Medium
Source: P.2
Text: The CUTLASS platform shall capable of continuous operations of all subsystems for a minimum of 12 hours.
Rationale: CUTLASS is designed to operate for up to 12 hours.
Verification Description: An appropriate mission will be designed to demonstrate a 12 hour start to finish mission time.
Verification Method: Demonstration

CUTLASS24 Voice communications

ID: CUTLASS.24
Risk: Low
Source: S.2
Text: The CUTLASS platform shall support voice communication.
Rationale: Untethered operation is essential; therefore, an acoustic voice communications system is required to meet the voice communications requirements.
Verification Description: The CUTLASS design will be analyzed for compliance.
Verification Method: Analysis

CUTLASS25 Data communications

ID: CUTLASS.25
Risk: Low
Source: S.3
Text: The CUTLASS platform shall support data communications with the surface support equipment.
Rationale: Collection of platform telemetry allows for improved safety.
Verification Description: The CUTLASS design will be analyzed for compliance.
Verification Method: Analysis

CUTLASS26 RESERVED

CUTLASS27 RESERVED

CUTLASS28 Platform power system redundancy

ID: CUTLASS.28
Risk: Medium
Source: S.8

Text: The life support and mobility subsystems shall be independently powered.
Rationale: Life support systems should have a dedicated source of power.
Verification Description: The CUTLASS design will be inspected for compliance.
Verification Method: Analysis

CUTLASS29 Self-righting

ID: CUTLASS.29
Risk: Medium
Source: CUTLASS.16
Text: The CUTLASS platform shall be designed to be self-righting to 0 degrees pitch and roll.
Rationale: The vehicle is limited to +/- 20 degrees intentional pitch and roll motion so, without power, the vehicle should return to a stable, 0-degree pitch/roll position.
Verification Description: The vehicle will be forced to an angle in excess of 20 degrees and observed to return to 0.
Verification Method: Demonstration

CUTLASS30 Platform redundant computer systems

ID: CUTLASS.30
Risk: High
Source: S.8
Text: The CUTLASS platform control computer system shall consist of redundant computers, with fail-over capability so that the loss of one computer does not impact the operation of the platform.
Rationale: Loss of a single computer should not result in a mission abort.
Verification Description: Integration testing will include fail-over validation.
Verification Method: Demonstration

CUTLASS31 Life support system redundant computers

ID: CUTLASS.31
Risk: High
Source: S.8
Text: The CUTLASS platform onboard life support system shall have redundant computers with fail-over capability so that the loss of one has no impact on the life support systems.
Rationale: Loss of a single computer should not result in a mission abort.
Verification Description: Integration testing will include fail-over validation.
Verification Method: Demonstration

CUTLASS32 Degraded navigation

ID: CUTLASS.32
Risk: High
Source: S.8

Text: CUTLASS shall be able to maintain positional knowledge to an accuracy of 1 m per 100 m of depth without GPS positional knowledge.
Rationale: Loss of GPS functionality should not result in a mission abort.
Verification Description: CUTLASS shall be commanded to navigate to a known location while operating under degraded navigation conditions and the final position measured for compliance.
Verification Method: Demonstration

CUTLASS33 Emergency power

ID: CUTLASS.33
Risk: High
Source: International Consensus Standards for Commercial Diving and Underwater Operations (Association of Diving Contractors International, 2016)
Text: CUTLASS shall have sufficient power to maintain life support functionality for 24 hours.
Rationale: 24 hours of life support should be sufficient to allow for a rescue operation if needed.
Verification Description: CUTLASS power consumption rates will be analyzed and compared to capacity to show compliance.
Verification Method: Analysis

CUTLASS34 Life support capacity

ID: CUTLASS.34
Risk: High
Source: International Consensus Standards for Commercial Diving and Underwater Operations (Association of Diving Contractors International, 2016)
Text: CUTLASS shall have sufficient life support capacity to support each diver for 24 hours at maximum depth.
Rationale: 24 hours of life support should be sufficient to allow for a rescue operation if needed.
Verification Description: The CUTLASS design will be inspected for compliance.
Verification Method: Analysis

CUTLASS35 Heated breathing gas

ID: CUTLASS.35
Risk: Low
Source: International Consensus Standards for Commercial Diving and Underwater Operations (Association of Diving Contractors International, 2016)
Text: CUTLASS shall provide a method for heating onboard life support gas to 29 degrees Celsius when below 152 meters depth.
Rationale: Below 152 meters, pressure dictates usage of higher levels of helium which results in greater heat loss.
Verification Description: The output temperature of the breathing gas will be tested.
Verification Method: Test

CUTLASS36 Hot water supply

ID: CUTLASS.36
Risk: Low
Source: International Consensus Standards for Commercial Diving and Underwater Operations (Association of Diving Contractors International, 2016)
Text: CUTLASS shall provide a system to provide water heated to 29 degrees Celsius to each diver for warmth.
Rationale: Cold was identified as a serious impediment to research divers at depth.
Verification Description: The output temperature of the water heater will be tested.
Verification Method: Test

CUTLASS37 User interface

ID: CUTLASS.37
Risk: Medium
Source: S.8
Text: CUTLASS shall provide the operators with real time display information necessary to operate the vehicle safely during dive operations.
Rationale: A well designed user interface is essential to success.
Verification Description: The user interface will be subjected to testing from users for usability.
Verification Method: Demonstration

CUTLASS38 Survey

ID: CUTLASS.38
Risk: Medium
Source: P.3
Text: CUTLASS shall provide a method for computing the WGS84 coordinate value of any location within 5 meters from the nose of the CUTLASS platform with an accuracy of 10 mm/m.
Rationale: One purpose of CUTLASS is to make site surveys more accurate and efficient. By computing locations relative to CUTLASS, efficiency is greatly improved.
Verification Description: CUTLASS measurements will be compared against a known standard.
Verification Method: Demonstration

CUTLASS39 Dive profile calculation

ID: CUTLASS.39
Risk: Medium
Source: CUTLASS.40

Text: CUTLASS shall calculate an appropriate dive profile including the adjustment of life support gas mixtures, platform ascent/descent rates, and decompression stop times for any given dive within the capabilities of the vehicle.
Rationale: The primary purpose of CUTLASS is to reduce diver workload; calculating a dive profile is necessary to provide something that the vehicle can execute.
Verification Description: A dive will be planned, and the resulting plan will be compared to plans created using other commercially available software.
Verification Method: Test

CUTLASS40 Dive profile execution

ID: CUTLASS.40
Risk: Medium
Source: ConOps
Text: CUTLASS shall execute the calculated dive profile including the adjustment of life support gas mixtures, platform ascent/descent rates, and decompression stop times.
Rationale: The primary purpose of CUTLASS is to reduce diver workload; semi-autonomous execution of a dive plan that includes diluent gas mixing, ascent/descent rates, and decompression stops accomplishes that goal.
Verification Description: An appropriate data file will be executed to simulate a dive and the data logs will be analyzed for compliance.
Verification Method: Test

Hull Requirements

Hull1 Watertight barrier

ID: Hull.1
Risk: Low
Source: ConOps
Text: The hull shall provide a watertight barrier between the external environment and the internal spaces contained within the hull.
Rationale: The hull will be used to house all the vehicle subsystems and components.
Verification Description: The completed vehicle will be submerged to 200 m and monitored for leaks.
Verification Method: Demonstration

Hull2 Pressure resistance

ID: Hull.2
Risk: Medium
Source: CUTLASS.2
Text: The hull shall withstand 30 bar differential pressure between the external environment and the internal, watertight spaces.

Rationale: The vehicle is designed to reach 200 m depth and OPNAVINST 9110.1D requires vehicles be designed with 50% greater theoretical depth capability than operational depth (Chief of Naval Operations, 2017).
Verification Description: The design of the hull will be analyzed to determine the theoretical maximum depth.
Verification Method: Analysis

Hull3 Displacement

ID: Hull.3
Risk: Medium
Source: ConOps
Text: The vehicle hull shall provide displacement volume equivalent to the mass of the vehicle +/- 100 kg. Actual displacement required for the CUTLASS MK1REV3 is 6265 kg.
Rationale: Maneuverability of a neutrally buoyant vehicle is greatly improved over one that is either positively or negatively buoyant. By using the mass displacement of fresh water, we will achieve neutral buoyancy in fresh water and maintain a positive buoyancy in sea water. This positive buoyancy will be offset by ballast tanks controlled by the buoyancy control system. The +/- 100 kg tolerance is reasonable, and any additional ballast required can be added.
Verification Description: The estimated displacement of the hull will be calculated and compared to the estimated mass of the vehicle.
Verification Method: Analysis

Hull4 Cockpit

ID: Hull.4
Risk: Medium
Source: CUTLASS.18
Text: The vehicle hull shall provide cockpit space for the two operators within the forward projection of the hull.
Rationale: This vehicle is designed to achieve 4 knots submerged with two divers onboard. In order to achieve this speed safely, the divers will require some protection from the full force of the water as the vehicle moves.
Verification Description: The design of the cockpit will be evaluated for sufficient space to seat two operators.
Verification Method: Inspection

Hull5 Cargo Hold Size

ID: HULL.5
Risk: Medium
Source: P.5
Text: The CUTLASS cargo hold shall measure no less than 122 x 61 x 31 cm.
Rationale: CUTLASS is required to transport cargo to and from the sea floor.
Verification Description: The CUTLASS cargo hold will be measured.
Verification Method: Test

Hull6 Cargo Hold Enclosure

ID: HULL.6
Risk: Medium
Source: CUTLASS.18
Text: The CUTLASS cargo hold shall be enclosed by a removable/retractable hard cover.
Rationale: CUTLASS needs to reduce the drag coefficient as much as possible. Enclosing the cargo hold when possible, will improve the drag profile of the vehicle.
Verification Description: The CUTLASS vehicle design will be analyzed for compliance.
Verification Method: Analysis

Hull7 Access to expendables

ID: Hull.7
Risk: Low
Source: ConOps
Text: The hull shall provide watertight access to the electrical system charging connection, data access ports, and the life support systems.
Rationale: This vehicle is designed to be used daily in the field. This requires the ability to rapidly recharge and reload any expendables.
Verification Description: Battery charging, data upload/download, and gas replenishment will be demonstrated.
Verification Method: Demonstration

Hull8 Maintenance

ID: Hull.8
Risk: High
Source: ConOps
Text: The hull shall provide access to remove and replace every subassembly contained within the hull.
Rationale: The vehicle is expected to be maintainable to extend its service life.
Verification Description: Maintenance procedures will be developed to provide detailed troubleshooting procedures as well as the removal and installation of each field replaceable unit (assembly, subassembly, or component).
Verification Method: Inspection

Hull9 External Cargo Mount Points

ID: HULL.9
Risk: Medium
Source: P.5
Text: The CUTLASS hull shall include mounting points to add additional, external cargo racks as needed.
Rationale: Inclusion of additional mounting points increases mission flexibility.

Verification Description: The hull design will be evaluated for reasonable placement of additional mounting points.
Verification Method: Analysis

Propulsion Requirements

PROP1 Thruster force

ID: PROP.1
Risk: Low
Source: CUTLASS.18
Text: The propulsion system shall provide sufficient thrust in the forward direction for the vehicle to reach 4 knots speed.
Rationale: CUTLASS has an operational requirement to reach 4 knots.
Verification Description: The submerged speed of the vehicle will be measured.
Verification Method: Test

PROP2 Power consumption

ID: PROP.2
Risk: Low
Source: CUTLASS.23, PMD.1
Text: The propulsion system shall generate the minimum required thrust while consuming no more than 8 kW of power.
Rationale: The CUTLASS primary systems battery capacity is 60-kWh. CUTLASS is required to operate for 12 hours. If we assume that the thrusters run 50% of the time, 48-kWh will be consumed.
Verification Description: During thruster power testing, the amount of electrical power consumed will be measured.
Verification Method: Test

PROP3 Reserved

PROP4 Yaw power

ID: PROP.4
Risk: Medium
Source: CUTLASS.15
Text: The propulsion system shall provide thrust sufficient to rotate the CUTLASS vehicle 180 degrees in 20 seconds.
Rationale: CUTLASS is designed to operate in fragile environments and the ability to avoid contact with obstacles in that environment is a mission priority.
Verification Description: The amount of time required to rotate CUTLASS 180 degrees will be measured.
Verification Method: Test

PROP5 Maximum thrust

ID: PROP.5
Risk: Medium

Source: CUTLASS.15, CUTLASS.16
Text: The propulsion system shall provide equal maximum thrust in the forward, aft, up, and down directions with a tolerance of +/- 5%.
Rationale: Typical thruster design allows for maximum thrust in one direction. This requirement sets the standard that maximum thrust will be available in both directions of the x and z axis. This will also allow for maximum torque in the pitch, roll, and yaw axis as well.
Verification Description: Bollard pull testing in forward, backward, up, and down directions will be done, and the results recorded.
Verification Method: Test

PROP6 Thrust unit configuration
ID: PROP.6
Risk: Medium
Source: International Consensus Standards for Commercial Diving and Underwater Operations 8.3.3.2.1 (Association of Diving Contractors International, 2016)
Text: Platform thrusters shall be installed such that the thrust does not interfere with other thrusters, sensor systems, dive systems or divers.
Rationale: This is an accepted industry design standard.
Verification Description: Thrust flows will be modeled, and the platform design will be analyzed for flow interference.
Verification Method: Analysis

Power Management and Distribution Requirements
PMD1 Energy storage capacity
ID: PMD.1
Risk: Low
Source: CUTLASS.23
Text: The energy storage capacity of the Power Management and Distribution System shall be at least 100-kWh.
Rationale: The vehicle is expected to operate for 12 hours.
Verification Description: The energy storage capacity of the system will be estimated and totaled.
Verification Method: Inspection

PMD2 Power delivery
ID: PMD.2
Risk: Low
Source: Power analysis
Text: The Power Management and Distribution System shall deliver a peak demand of 130 kw of power.
Rationale: Meeting the maximum power requirements allows us to be confident in the ability to meet the steady state power requirements.

Verification Description: The current being delivered will be measured and the power delivery will be calculated.
Verification Method: Test

PMD3 Battery charging
ID: PMD.3
Risk: Low
Source: SAEJ1772
Text: The power management and distribution system include onboard charging to convert 240 VAC to 400 VDC for primary battery storage.
Rationale: 240 VAC onboard ships is readily available and 400 VDC is a standard battery voltage for electric vehicles.
Verification Description: The onboard batteries will be recharged using 240 VAC power.
Verification Method: Demonstration

PMD4 SAEJ1772 standard compliance
ID: PMD.4
Risk: Low
Source: Risk reduction
Text: The external power supply interface shall comply with the SAEJ1772 standard (SAE International, 2010).
Rationale: The SAEJ1772 standard defines the interface between the vehicle and the external power supply equipment. It further defines what charging components are required onboard the vehicle. Compliance with SAEJ1772 allows us to use readily available off-the-shelf components.
Verification Description: The design will be checked for compliance with the standard.
Verification Method: Analysis

PMD5 Remote operation of circuit breakers, relays, and switches
ID: PMD.5
Risk: Low
Source: ConOps
Text: All circuit breakers, relays, and switches shall be controllable from the user interface.
Rationale: Since the electrical components are sealed inside the pressure hull, it is necessary to provide the ability to actuate and reset each component designed to break an electrical circuit.
Verification Description: Each component designed to break an electrical circuit will be actuated and reset via the user interface.
Verification Method: Demonstration

PMD6 Circuit breaker load
ID: PMD.6

Risk: Low
Source: Industry standard
Text: The designed load of a circuit breaker shall not exceed 80% of its rated capacity.
Rationale: 80% design load on a circuit breaker is an industry standard.
Verification Description: Each circuit breaker will have its theoretical maximum load calculated at the time the wiring harness is designed.
Verification Method: Analysis

Buoyancy and Trim Control Requirements

BTC1 Lift capacity

ID: BTC.1
Risk: Low
Source: P.5
Text: The buoyancy and trim control subsystem shall provide 300 kg adjustable displacement.
Rationale: CUTLASS is required to lift 300 kg of payload and maintain neutral buoyancy.
Verification Description: CUTLASS will be submerged, and 300 kg loaded onto the cargo platform. The ballast tanks will be emptied, and CUTLASS will resurface.
Verification Method: Demonstration

BTC2 Longitudinal trim capacity

ID: BTC.2
Risk: Medium
Source: ConOps
Text: The buoyancy and trim control system shall compensate for +/- 5 degrees of pitch due to shifts in the center of gravity.
Rationale: Loading the cargo bay of the vehicle can result in changes to the center of gravity. The ability to correct for this is fundamental to maintaining stable control of the vehicle.
Verification Description: Weight will be added to CUTLASS to cause it to list. When the desired degree of list is reached, the trim control will be activated and observed.
Verification Method: Demonstration

BTC3 Lateral trim capacity

ID: BTC.3
Risk: Medium
Source: ConOps
Text: The buoyancy and trim control system shall compensate for +/- 5 degrees of roll due to shifts in the center of gravity.

Rationale: Loading the cargo bay of the vehicle can result in changes to the center of gravity. The ability to correct for this is fundamental to maintaining stable control of the vehicle.
Verification Description: Weight will be added to CUTLASS to cause it to change pitch. When the desired degree of pitch is reached, the trim control will be activated and observed.
Verification Method: Demonstration

BTC4 Maintain neutral buoyancy
ID: BTC.4
Risk: Medium
Source: CUTLASS.9, CUTLASS.11, CUTLASS.13
Text: The buoyancy and trim control system shall automatically adjust vehicle buoyancy to compensate for the addition/removal of cargo or personnel when loading/unloading of the vehicle occurs while the vehicle is engaged in depth hold mode of operation.
Rationale: CUTLASS is not required to land on the seafloor to engage in cargo loading/unloading operations so maintaining neutral buoyancy is necessary to meet the depth hold requirements.
Verification Description: Cargo will be added and removed while submerged to validate that the system can make buoyancy compensations.
Verification Method: Demonstration

BTC5 Maintain balance
ID: BTC.5
Risk: Medium
Source: Safety
Text: The Buoyancy and Trim Control System shall adjust the center of mass to provide platform stability resulting from changes to the cargo load.
Rationale: CUTLASS operators will be required to add/remove cargo during normal operations. CUTLASS is not required to be in contact with the seafloor during cargo operations.
Verification Description: BTC.TEST.1
Verification Method: Demonstration/Analysis

Life Support Requirements

LS1 Platform life support system power
ID: LS.1
Risk: Low
Source: CUTLASS28
Text: The platform life support system shall have a dedicated power supply.
Rationale: Breathing systems are critical to the survival of the operators and needs to be protected from failure of the primary power system.
Verification Description: The life support system will be inspected for compliance.

Verification Method: Inspection

LS2 FMECA

ID: LS.2
Risk: Medium
Source: CUTLASS1
Text: The system design shall be supported by a Failure Mode Effect and Criticality Analysis (FMECA).
Rationale: This is required by section 5.1 in EN-14143: Respiratory equipment - Self-contained re-breathing diving apparatus (European Committee for Standardization, 2013).
Verification Description: A completed FMECA will be included with the System Design Documentation.
Verification Method: Demonstration

LS3 Life support system component placement

ID: LS.3
Risk: Low
Source: CUTLASS1
Text: All components, except for those necessary to provide breathing gas delivery to the divers, shall be contained within the pressure hull of the vehicle.
Rationale: EN14143 requires that all components be protected from mechanical damage caused by external influence (European Committee for Standardization, 2013). By including as many components as possible within the pressure hull, the components are protected.
Verification Description: The design will be analyzed for compliance.
Verification Method: Analysis

LS4 Operable component accessibility

ID: LS.4
Risk: Low
Source: CUTLASS1
Text: All parts, which have to be actuated by the diver during use, shall be accessible and controllable even when wearing protective gloves (three fingers, with 6 mm to 7 mm padding on either side).
Rationale: This is a direct pass-through from EN14143 (European Committee for Standardization, 2013).
Verification Description: The life support system functionality will be demonstrated to be working while wearing 7mm thick gloves.
Verification Method: Demonstration

LS5 Inadvertent operation

ID: LS.5
Risk: Low
Source: CUTLASS1

Text: User operable life support components shall be designed such that their setting cannot be altered inadvertently during use.
Rationale: This is a direct pass-through from EN14143 (European Committee for Standardization, 2013).
Verification Description: User operable components will be shown to be protected from adjustment by vibration or impact.
Verification Method: Demonstration

LS6 Breathing gas out of water functionality

ID: LS.6
Risk: Low
Source: CUTLASS1
Text: The life support breathing gas systems shall function within required parameters while out of the water.
Rationale: EN14143 requirement (European Committee for Standardization, 2013).
Verification Description: The life support breathing gas systems will be tested while on the surface.
Verification Method: Demonstration

LS7 Life support functionality at all orientations

ID: LS.7
Risk: High
Source: CUTLASS1
Text: The life support system (breathing gas, breathing gas heaters, suit heaters) shall function within required parameters at all orientations in the water.
Rationale: This is a requirement from EN14143 to apply to closed-circuit re-breathers (European Committee for Standardization, 2013). Extending this requirement to apply to all subsystems of the life support system.
Verification Description: CUTLASS will be loaded onto a 3-axis rotating jig and submerged to a depth necessary to be completely submerged during testing. The vehicle will be rotated through all orientations and the system performance recorded and analyzed.
Verification Method: Demonstration

LS8 Adverse effects

ID: LS.8
Risk: High
Source: CUTLASS1
Text: The life support system shall be designed to prevent any chemicals, saliva, condensation or ingress of water from adversely affecting the operation of the life support systems or causing harmful effect to the diver.
Rationale: This is a requirement from EN14143 on the closed-circuit re-breather component of the life support system (European Committee for Standardization,

2013). This requirement is being extended to apply to all subsystems of the life support system.
Verification Description: This will be demonstrated during the testing of LS7.
Verification Method: Demonstration

LS9 Breathing gas system component material selection

ID: LS.9
Risk: Medium
Source: CUTLASS1
Text: Each component in the breathing gas subsystem shall be made of appropriate material for the pressure, temperature, and composition of the gas it will be exposed to.
Rationale: Not all materials are rated for all gases.
Verification Description: We will ensure that each component selected is capable of functioning within the environment it will be exposed to.
Verification Method: Inspection

LS10 Operational temperature range

ID: LS.10
Risk: Medium
Source: P1
Text: The life support system shall function within required parameters between -2 and +34 degrees C.
Rationale: CUTLASS is designed to operate in the neritic zone (0 to 200 meters depth), this temperature range represents the expected range of the neritic zone.
Verification Description: The life support systems will be tested in temperature controlled facilities to ensure compliance across the temperature range.
Verification Method: Demonstration

LS11 Oxygen capacity

ID: LS.11
Risk: Low
Source: CUTLASS34
Text: The life support system shall contain at least 2160 liters of oxygen per diver.
Rationale: An average diver will consume 1-1.5 liters per minute of oxygen. This 2160 liters represents 1.5 liters per minute for 24 hours.
Verification Description: Oxygen tanks will be selected such that their pressurized oxygen capacity meets or exceeds the required amount.
Verification Method: Inspection

LS12 Diluent capacity

ID: LS.12
Risk: Low
Source: ConOps

Text: Diluent tanks shall contain at least 3000 liters of gas.
Rationale: Diluent usage for breathing is typically minimal in a closed-circuit re-breather; however, if the diluent is used for dry-suit inflation, gas usage will be considerably higher.
Verification Description: Diluent tanks will be selected such that their pressurized capacity meets or exceeds the required amount.
Verification Method: Inspection

LS13 Partial pressure of oxygen - operational limits
ID: LS.13
Risk: High
Source: CUTLASS1
Text: The life support system shall maintain the inspired partial pressure of oxygen between 0.20 bar and 1.60 bar.
Rationale: The partial pressure of oxygen at sea level is approximately 0.21 bar. Oxygen toxicity becomes a problem as partial pressure increases and can cause seizures and death rapidly at pressures above 1.60 bar.
Verification Description: Rebreather gas will be analyzed for concentrations at various depths.
Verification Method: Demonstration

LS14 CO2 removal - minimum capacity
ID: LS.14
Risk: Medium
Source: LS11
Text: The minimum total volume of CO_2 able to be removed from the exhaled gas shall be the same as the total O_2 supplied.
Rationale: People exhale approximately the same amount of CO_2 as the O_2 they inhale.
Verification Description: The CO_2 processing capability of the system will be calculated for compliance.
Verification Method: Analysis

LS15 CO2 removal - liters per minute
ID: LS.15
Risk: Medium
Source: EN14143 (European Committee for Standardization, 2013)
Text: The life support system shall remove up to 0.5 liters of CO_2 per minute.
Rationale: EN14143 restricts inspired CO_2 to a maximum of 20 mbar.
Verification Description: The CO_2 removal rate will be measured.
Verification Method: Test

LS16 CO2 removal - escapement into inhalation gas
ID: LS.16
Risk: Medium

Source: EN14143 (European Committee for Standardization, 2013)
Text: The CO_2 scrubber shall allow no more than 20 mbar CO_2 to remain in the breathing gas after processing.
Rationale: EN14143 restricts inspired CO_2 to a maximum of 20 mbar.
Verification Description: The amount of CO_2 remaining in the breathing gas after processing will be measured.
Verification Method: Test

LS17 Counter lung capacity
ID: LS.17
Risk: Low
Source: Physical constraint
Text: Each of the two counter lungs shall be the same size and have a capacity ranging from 3 liters to 4 liters.
Rationale: The counter lungs need to closely match to the lung capacity of the user. By allowing them to be replaceable and providing a range of 3-4 liters, we cover most users.
Verification Description: The capacity of the counter lungs will be tested for compliance.
Verification Method: Test

LS18 Reduced power consumption for emergency use
ID: LS.18
Risk: Low
Source: CUTLASS.33
Text: The life support system shall automatically reduce the operation cycles of the suit heater component in an emergency to allow the heater to run no more than 12 minutes per hour.
Rationale: The suit heater uses 9 kW when energized. By cycling the heaters to run no more 12 minutes per hour, we will draw only 1.8 kW power per hour and meet the 24-hour emergency power requirement.
Verification Description: The vehicle will be operated in emergency mode for 24 hours and the battery levels will be monitored.
Verification Method: Demonstration

Guidance, Navigation, and Control Requirements
GNC1 Architecture Constraint
ID: GNC.1
Risk: Low
Source: 10 U.S.C. 2446a.(b), Sec 805
Text: The GN&C system shall consist of a distributed computing architecture.
Rationale: The USG is a potential customer and is interested in modular hardware and software solutions. While it does add some complexity, it also allows for more redundancy.
Verification Description: The system design will be evaluated for compliance.

Verification Method: Inspection

GNC2 Reliability

ID: GNC.2
Risk: Low
Source: Safety
Text: Each safety critical computer shall have a backup.
Rationale: Life support and the ability to retrieve the vehicle are necessary.
Verification Description: Each function will be analyzed to determine the impact of a failure. Functions where failure results in loss of life or vehicle will need a backup computer.
Verification Method: Inspection

GNC3 Software Architecture

ID: GNC.3
Risk: Low
Source: GNC.1
Text: The software shall be designed to support the distributed computing architecture.
Rationale: This is necessary because of GNC.1.
Verification Description: The software design will be analyzed for compliance.
Verification Method: Inspection

GNC4 GPS Location

ID: GNC.4
Risk: Medium
Source: ConOps
Text: The GPS position shall be updated every 5 seconds at a minimum.
Rationale: DVL and IMU position extrapolation errors will grow with time. It is desirable to fix the known position (within GPS system errors) periodically. NOTE – The rate of required update will be determined after the DVL and IMU hardware components are tested and the error calculated.
Verification Description: CUTLASS software will be tested to ensure
Verification Method: Analysis

APPENDIX C

ACTIVITY DIAGRAMS

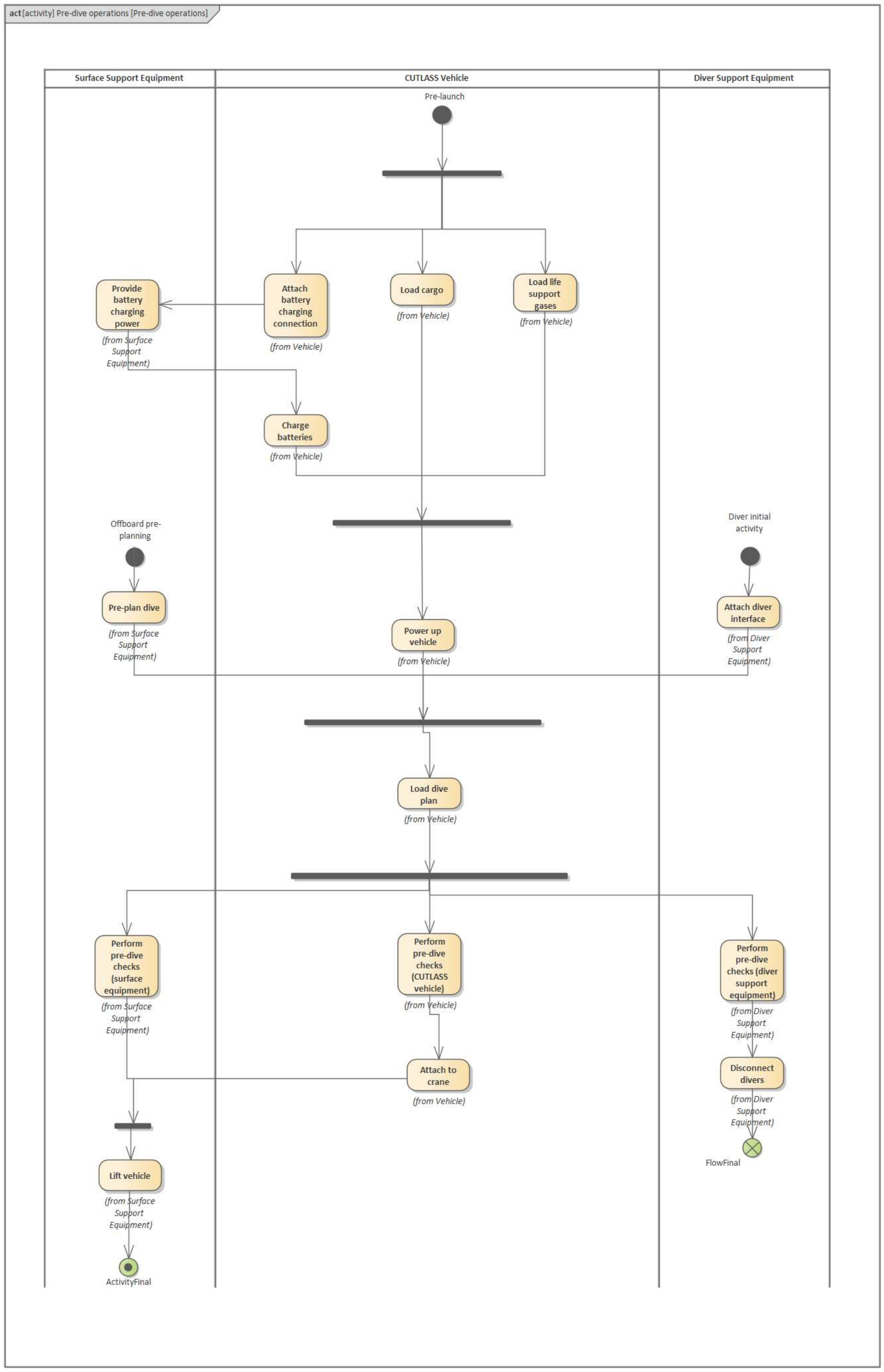

Figure C1: *Pre-dive Operations Activity Diagram* – Pre-dive operations include such activities as charging the batteries, loading the cargo, loading the air bottles, and checking that all systems are functional prior to placing the vehicle in the water.

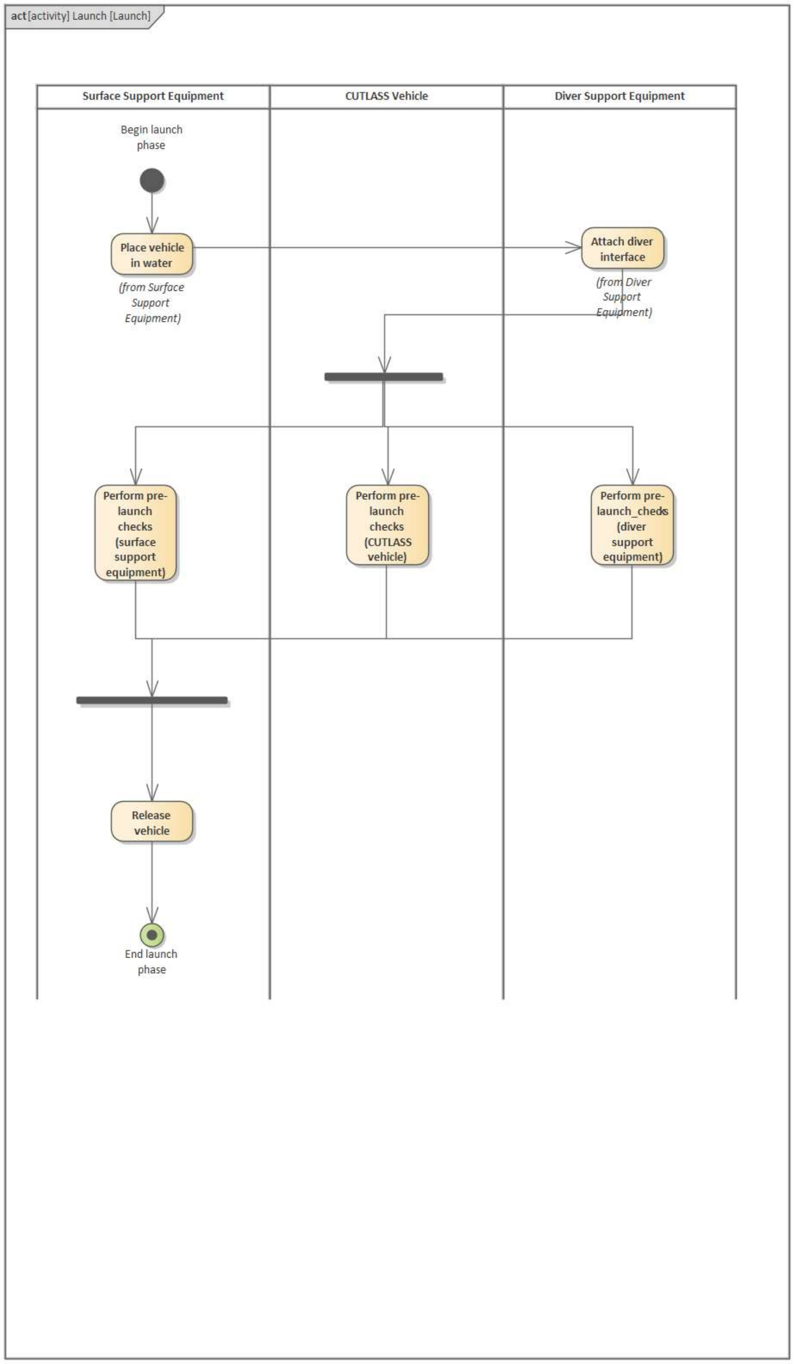

Figure C2: *Launch Activity Diagram* – The launch activity begins when the vehicle is placed in the water. All remaining functional checks that were unable to be performed while still aboard the surface support craft are conducted at this point.

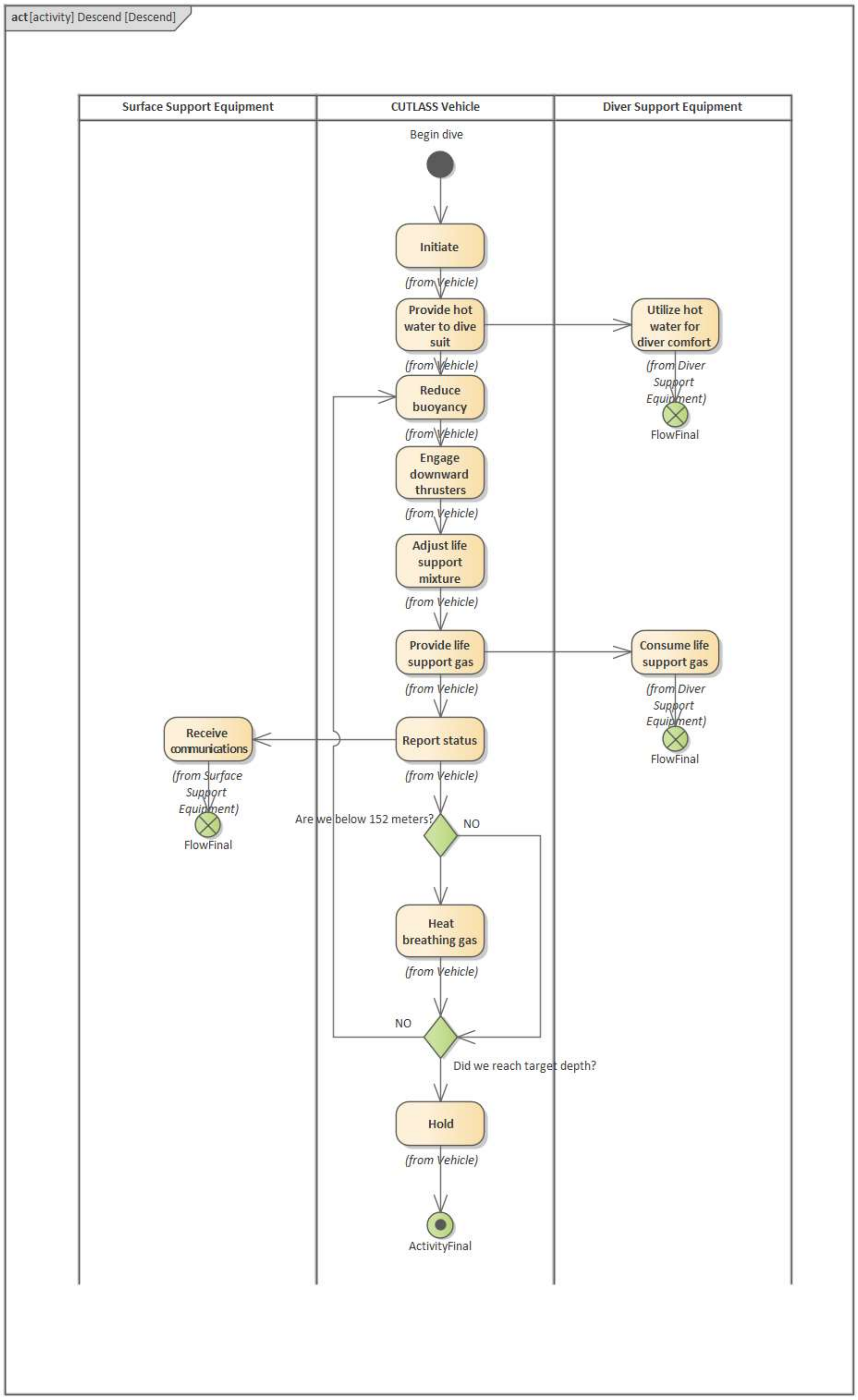

Figure C3: *Descend Activity Diagram* – The descend activity begins when the vehicle is detached from the surface support craft and starts its dive. The activities covered here include providing life support, controlling the descent rate, and communicating with the surface.

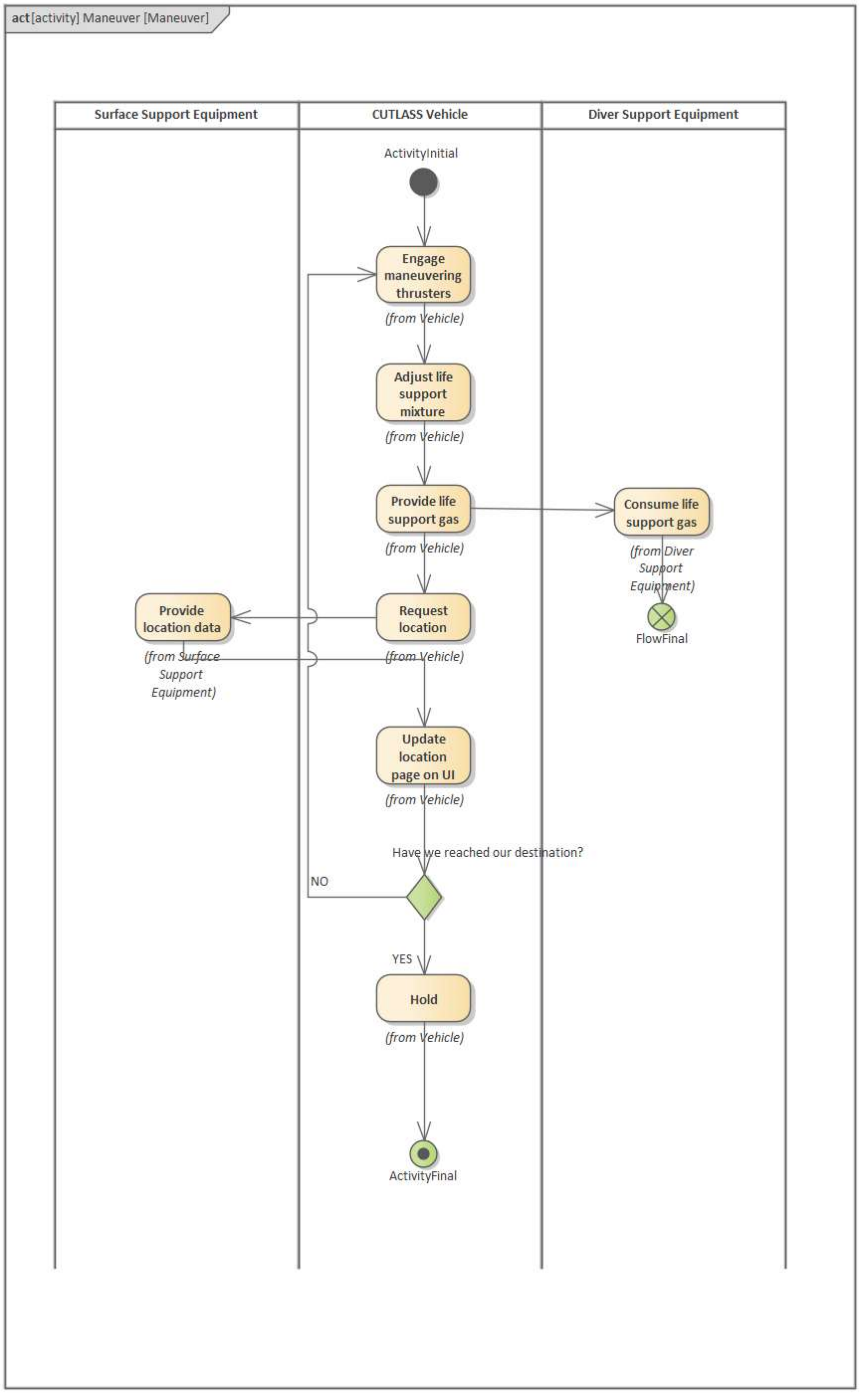

Figure C4: *Maneuver Activity Diagram* – Maneuvering the vehicle continues activities such as engaging the thrusters and providing life support to the dive team, but also includes providing GPS coordinates to the vehicle from the surface.

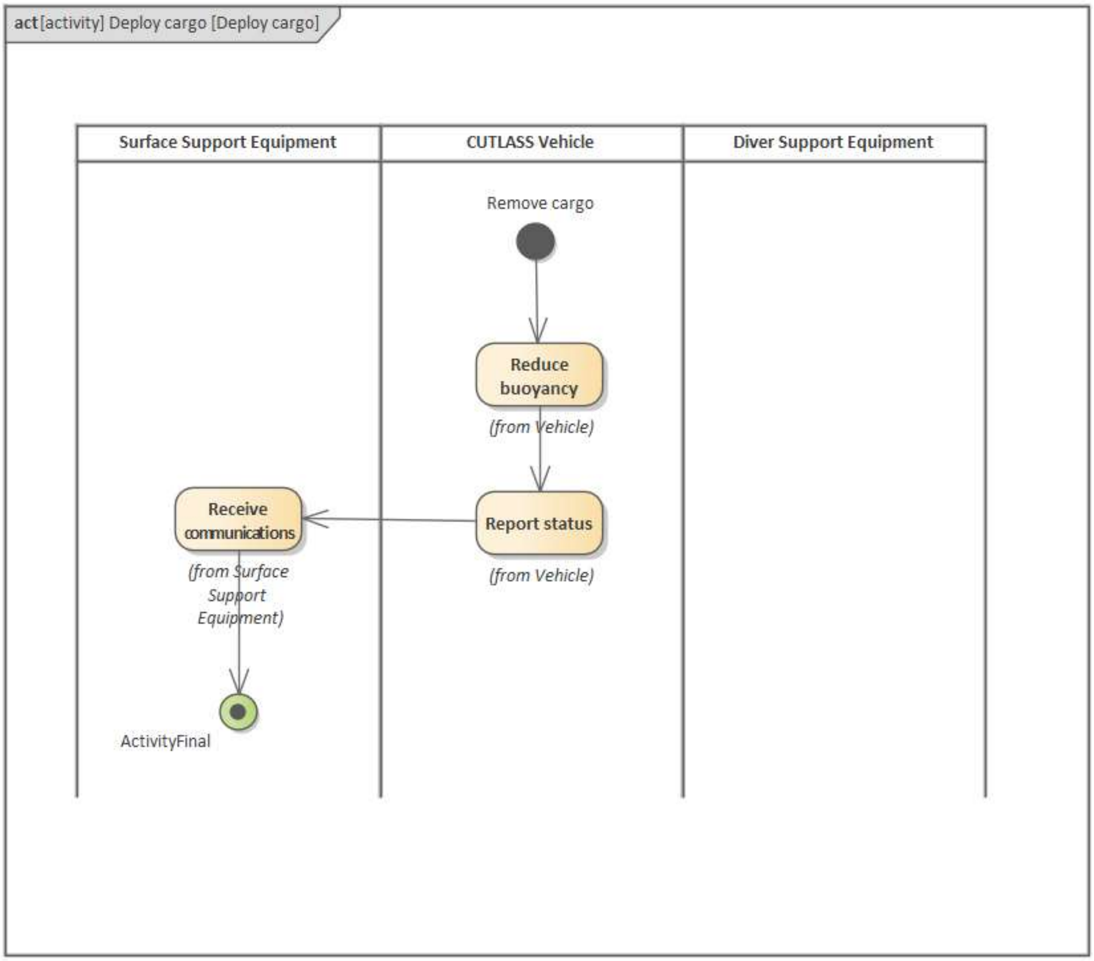

Figure C5: *Deploy Cargo Activity Diagram* – Cargo deployment engages buoyancy and trim control activities.

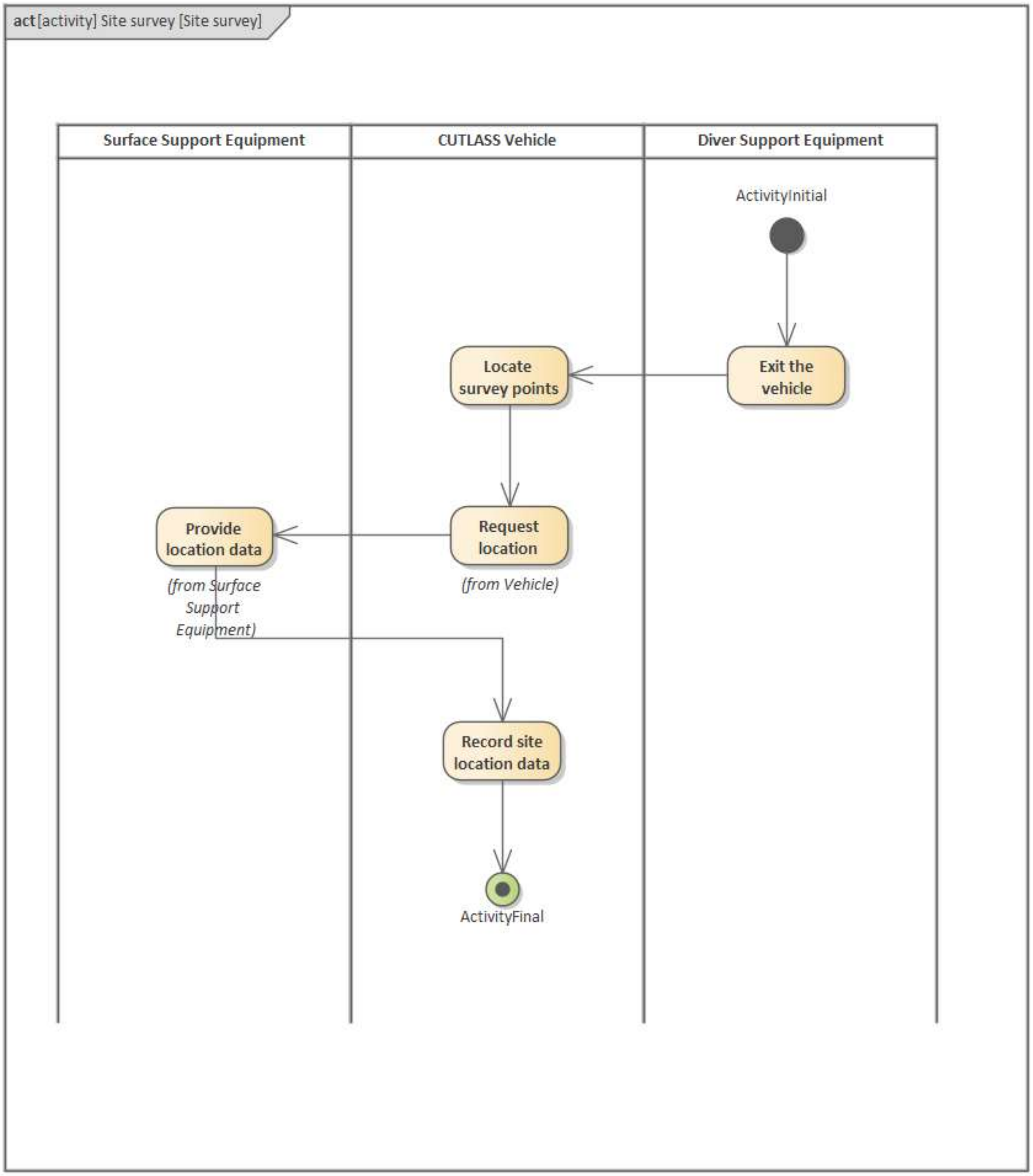

Figure C6: *Conduct Site Survey Activity Diagram* – Conducting a site survey with the vehicle is a simple variation of the maneuver activity. This method of conducting a site survey requires the diver(s) to exit the vehicle to perform such activities themselves.

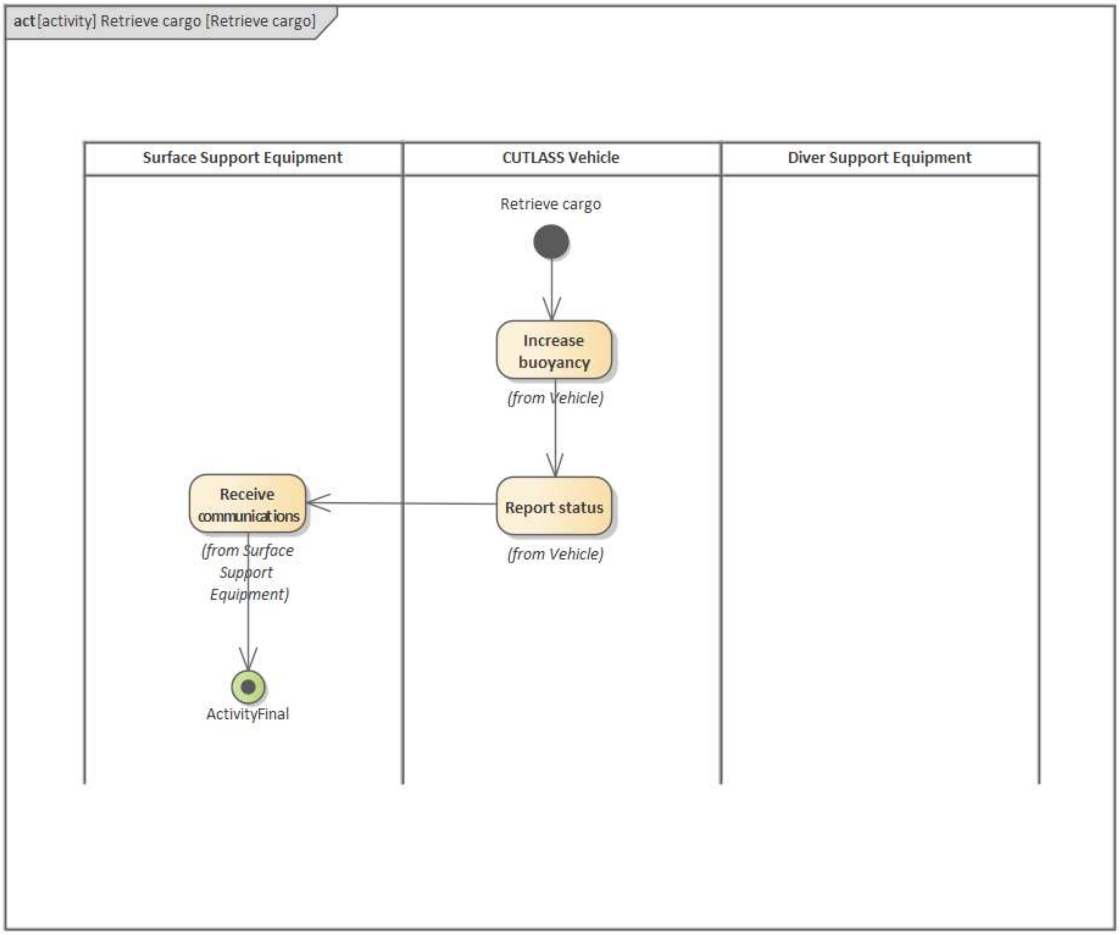

Figure C7: *Retrieve Cargo Activity Diagram* – Retrieving cargo from the seafloor engages the buoyancy and trim activities just like deploying cargo did.

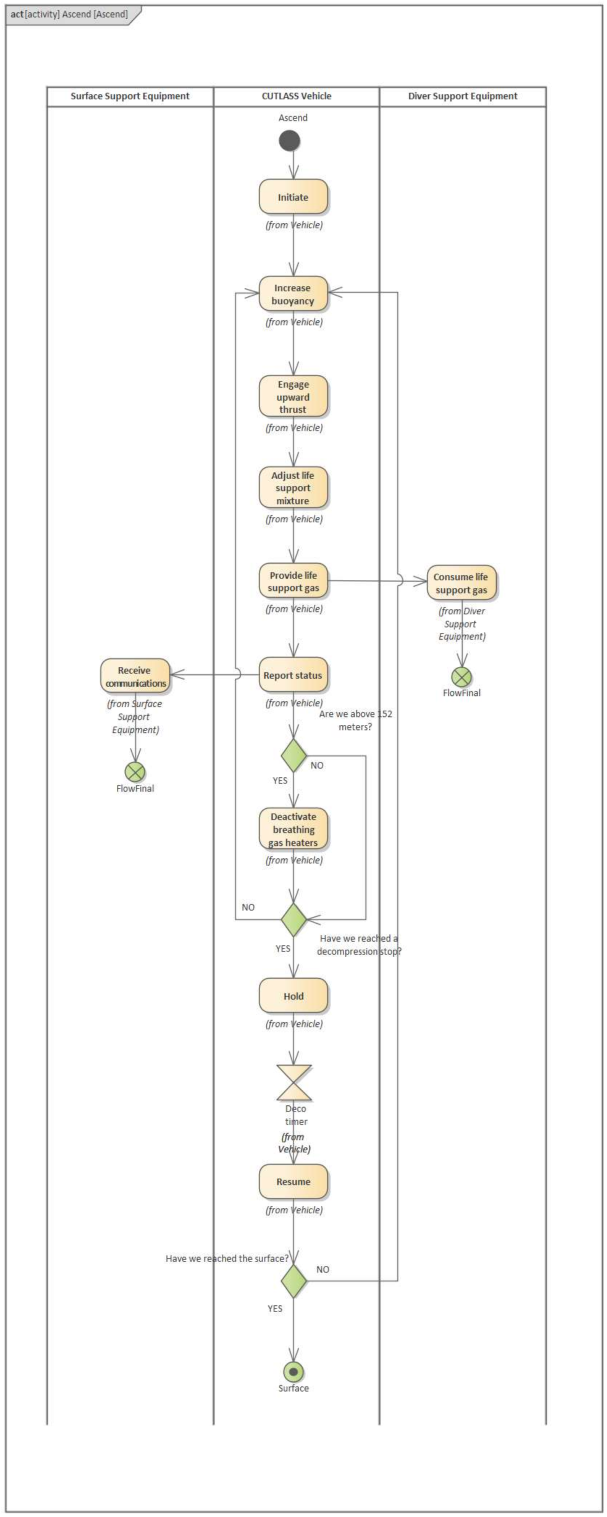

Figure C8: *Ascend Activity Diagram* – The ascend activity is one of the more critical activities. This activity requires careful control of the ascent rate and execution of any required decompression stops. The air mixture must also be adjusted to optimize decompression time and maintain the health and safety of the dive team.

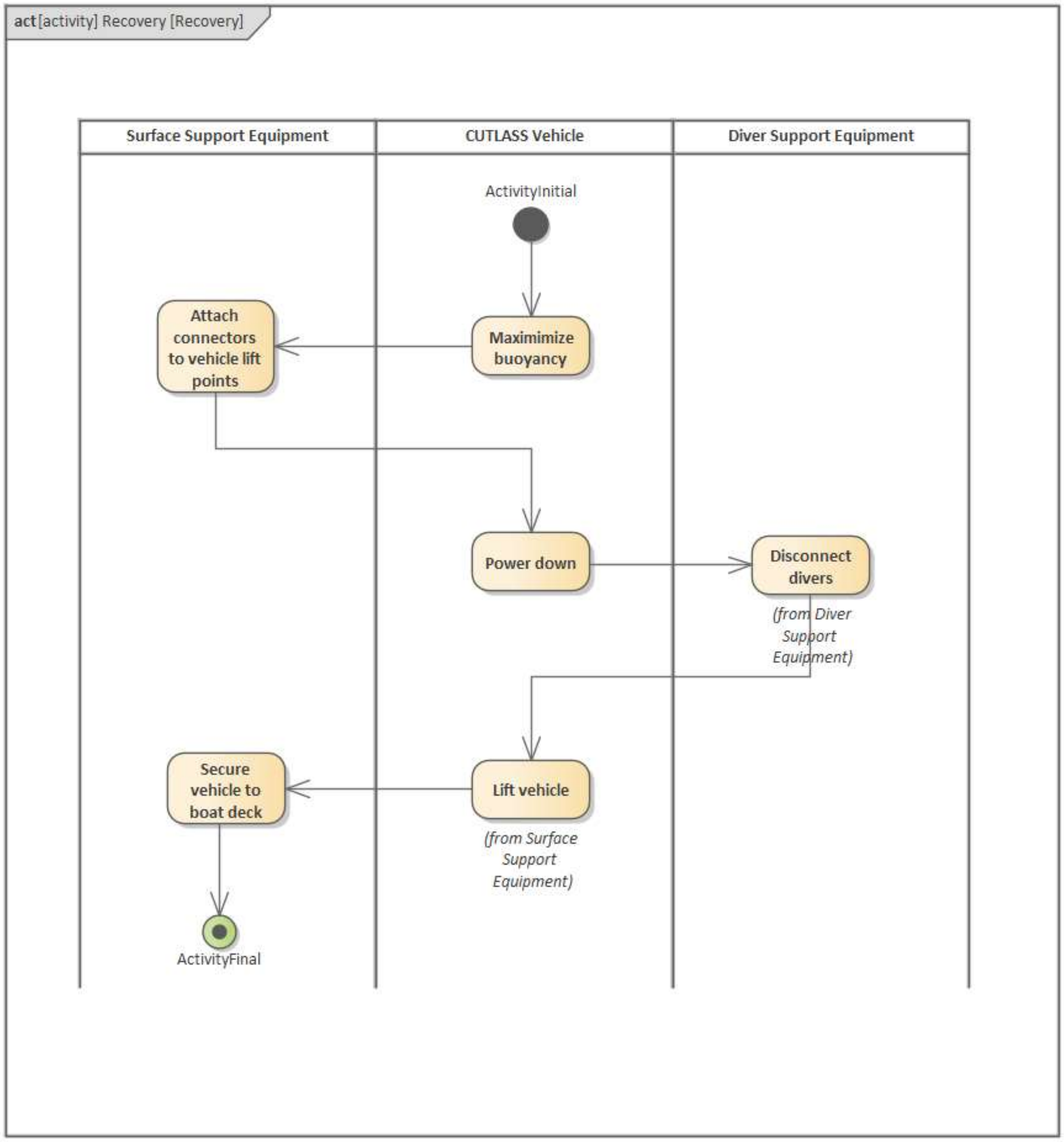

Figure C9: *Recovery Activity Diagram* – The recovery activity begins with connecting the vehicle to the lift system and includes disconnecting the divers from the life support system and powering down the vehicle.

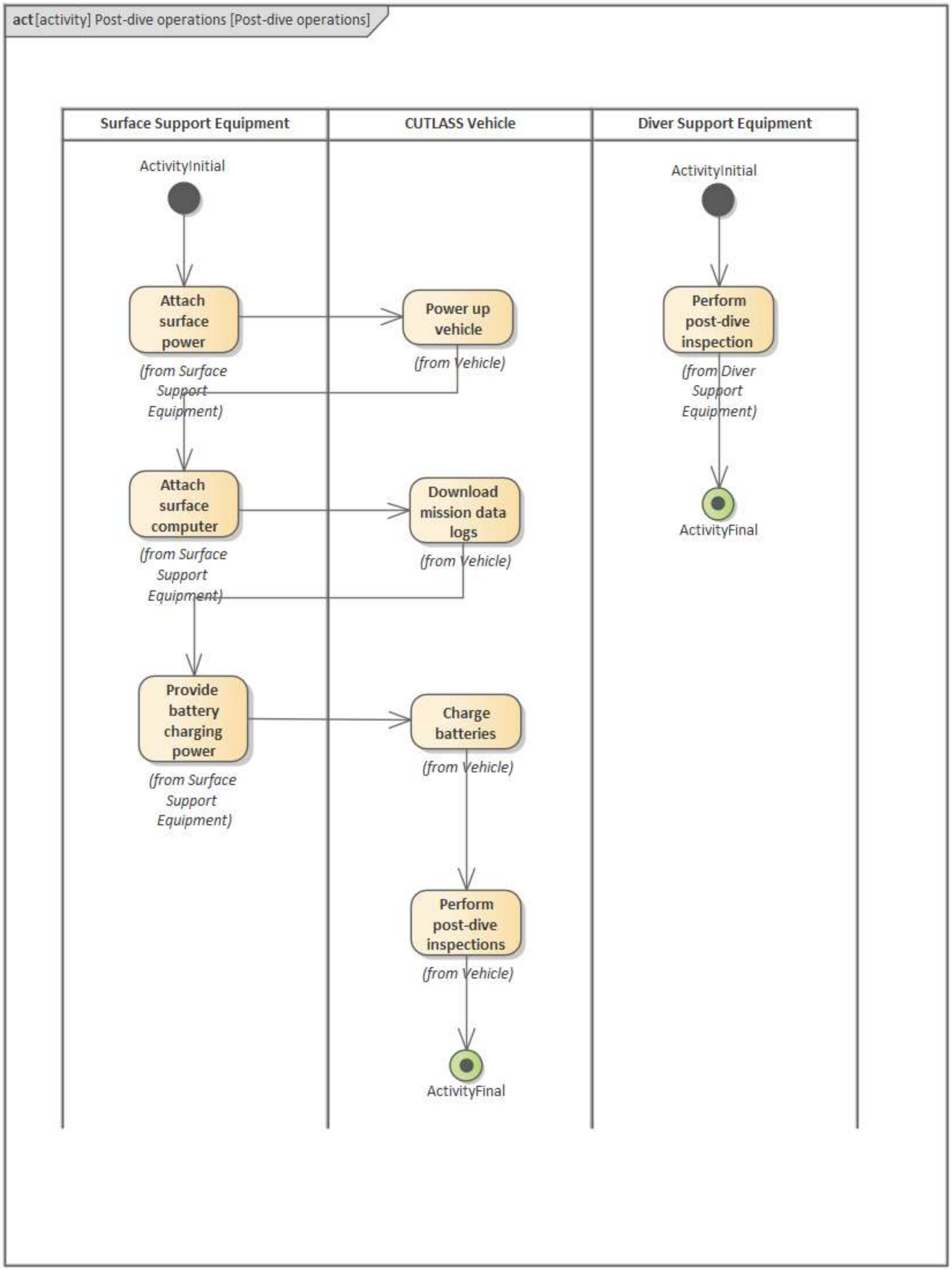

Figure C10: *Post-dive Operations Activity Diagram* – The final operational activity is post-dive operations. In this activity the data is downloaded from the vehicle, the battery recharging begins, the vehicle is cleaned, and any required maintenance is performed.

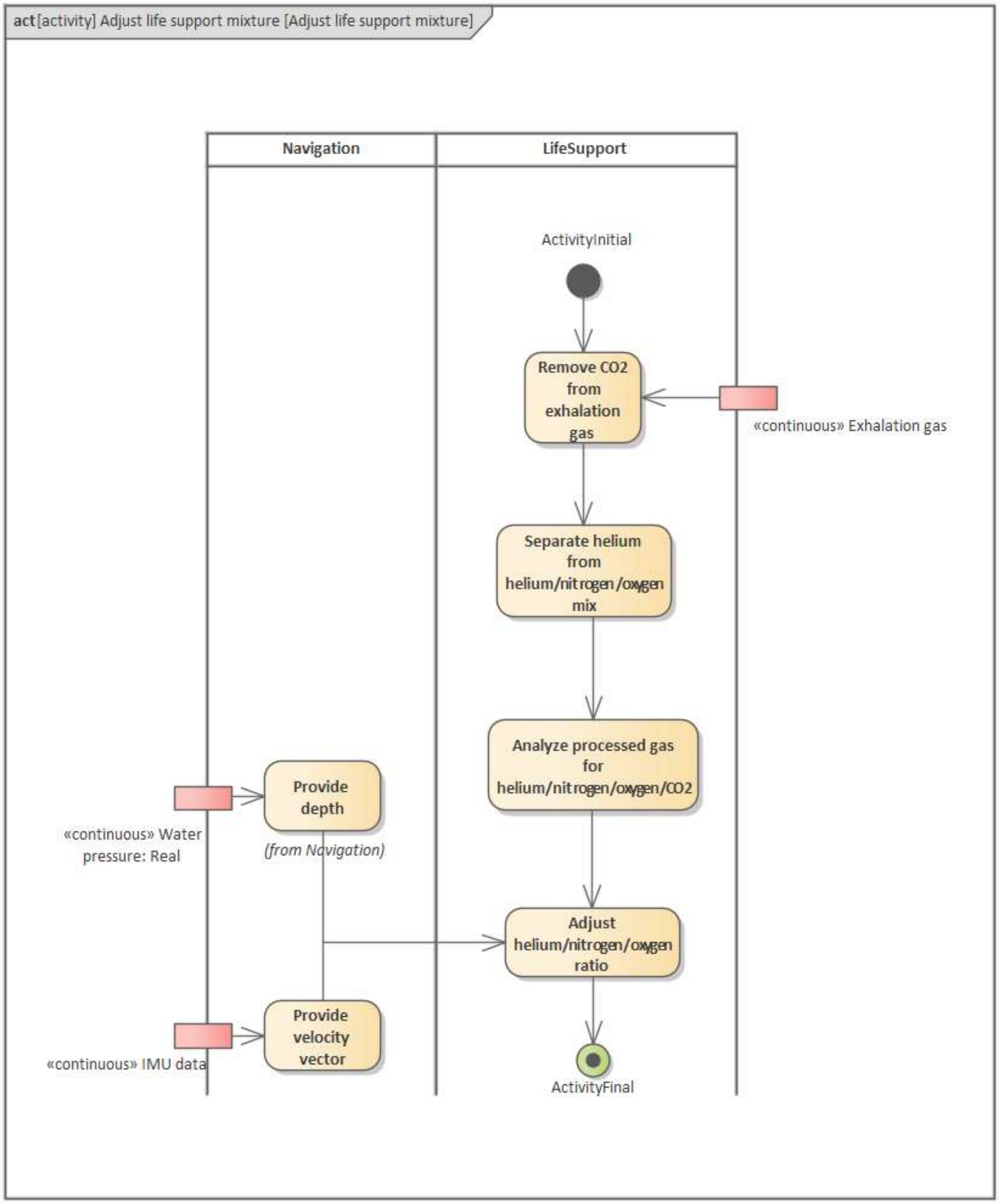

Figure C11: *Adjust Life Support Mixture* – Activity diagram that shows removal of CO_2 followed by analysis and adjustment of the diluent gas and injection of oxygen into the system as needed.

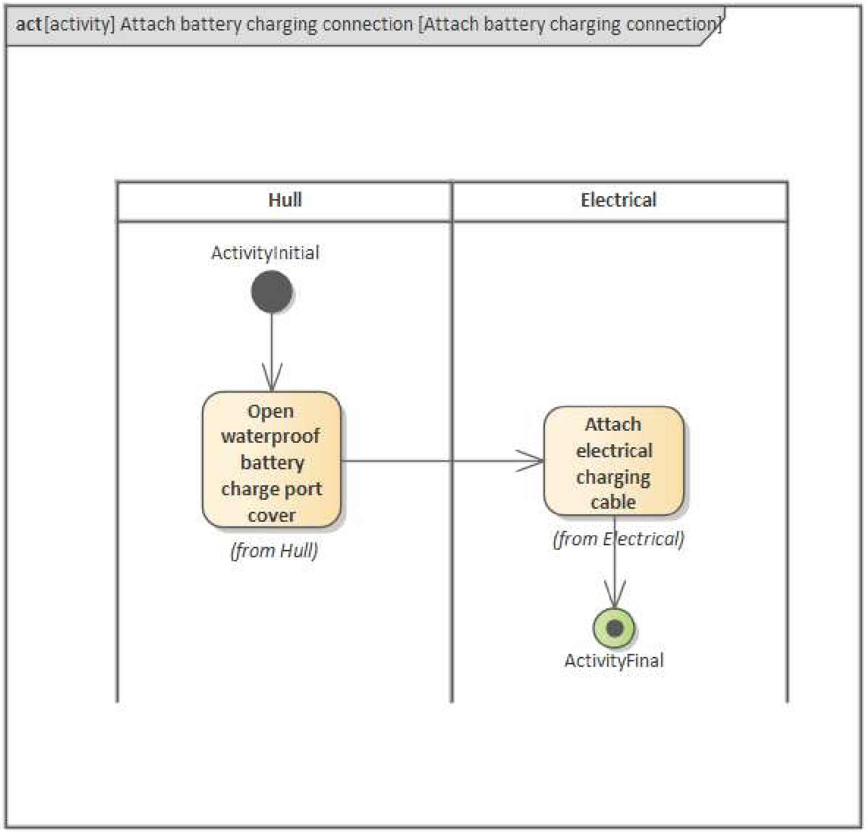

Figure C12: *Attach Battery Charging Connection* – The battery charge port is behind a portion of the pressure hull to protect the charging systems.

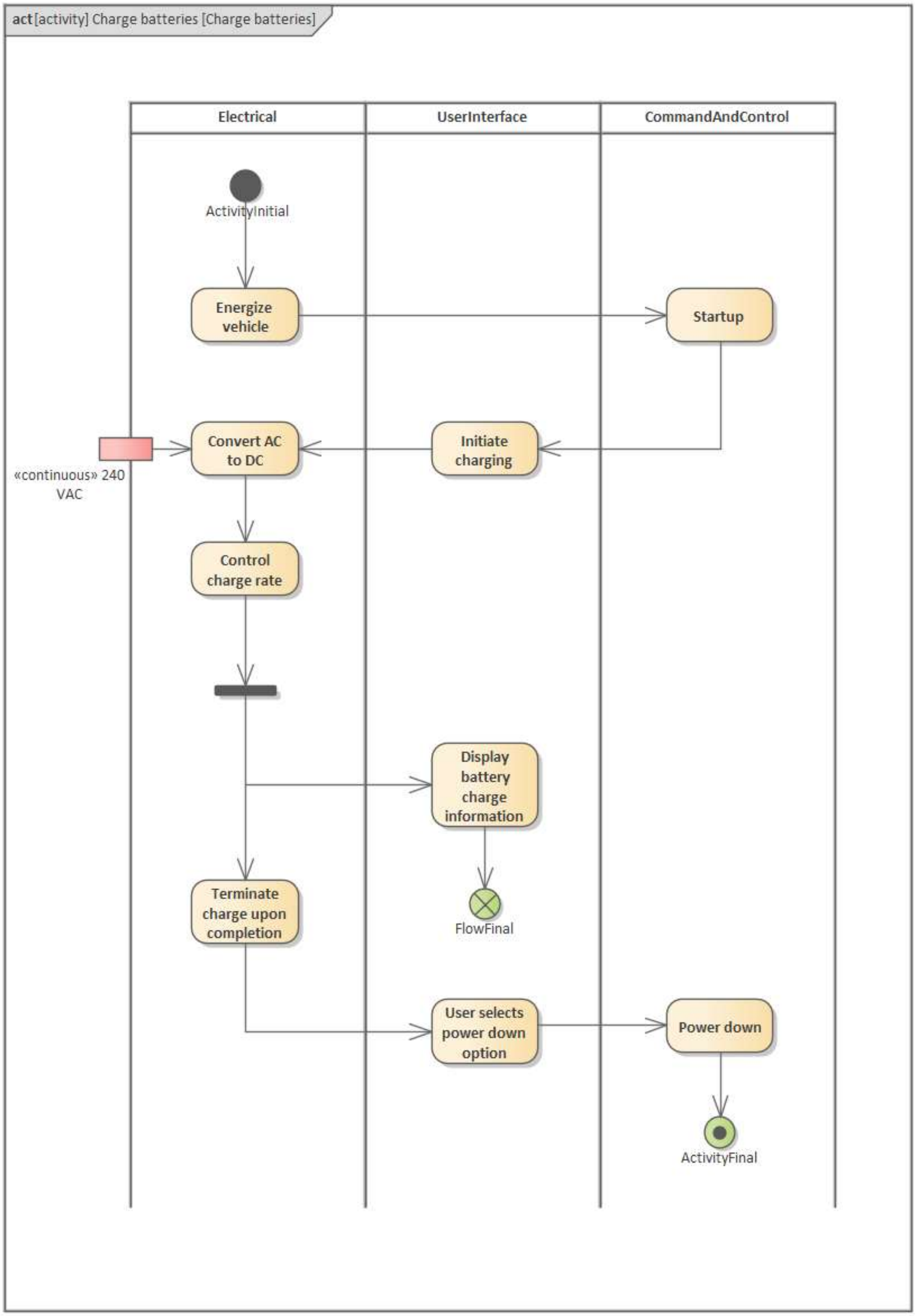

Figure C13: *Charge Batteries* – Charging the CUTLASS batteries follows the same activity flow as charging any other electric vehicle. AC power is converted to DC power via the onboard systems and the primary batteries are charged.

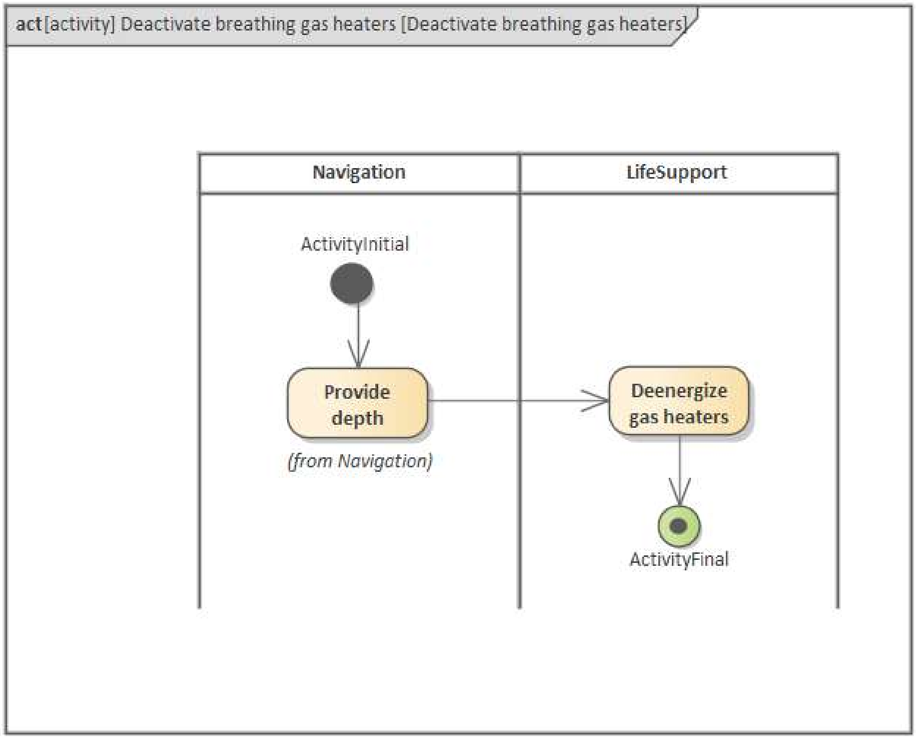

Figure C14: *Deactivate Breathing Gas Heaters* – Gas heaters are not required above 152 meters since the concentration of helium will be reduced.

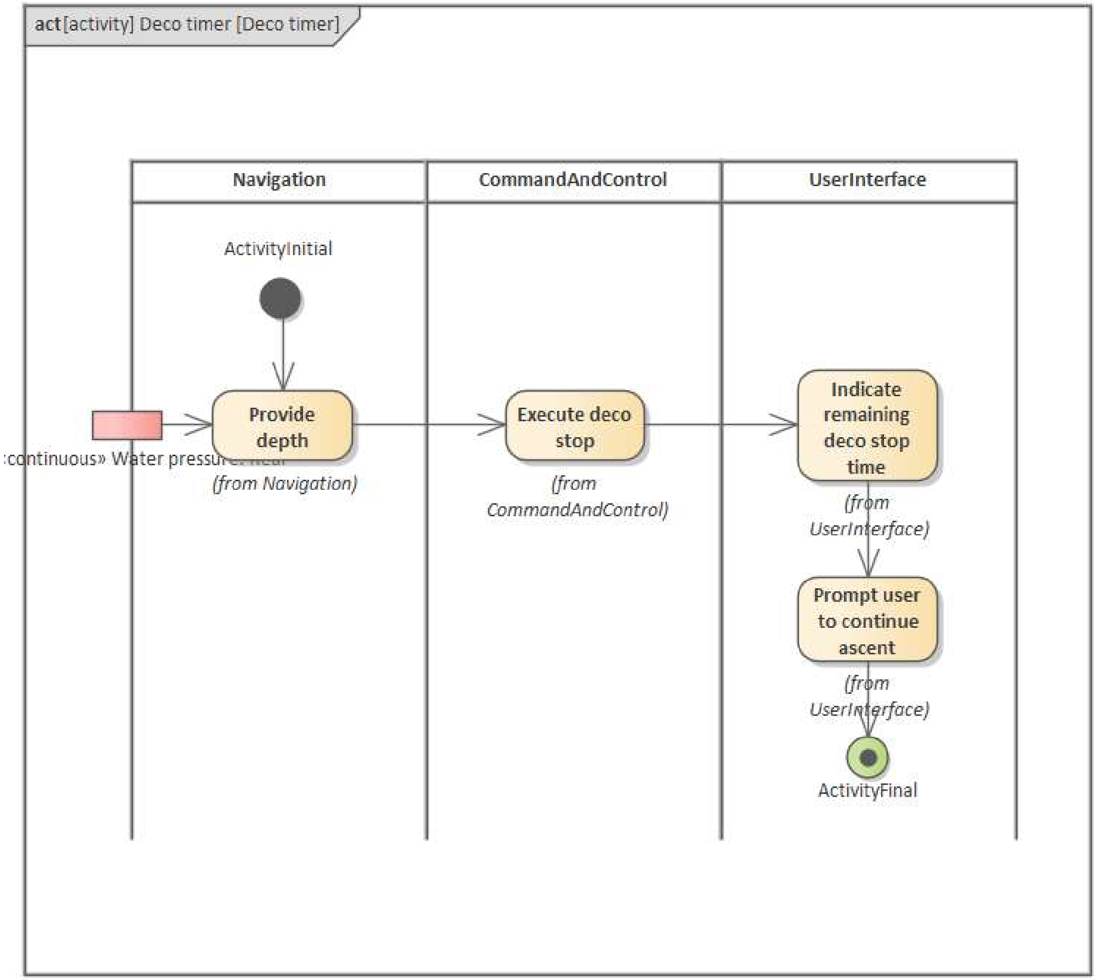

Figure C15: *Decompression Timer* – The computer will automatically execute mandated decompression stops thereby both reducing workload and increasing vehicle functionality. To ensure diver safety, the ascent will not continue without the explicit authorization of the operator.

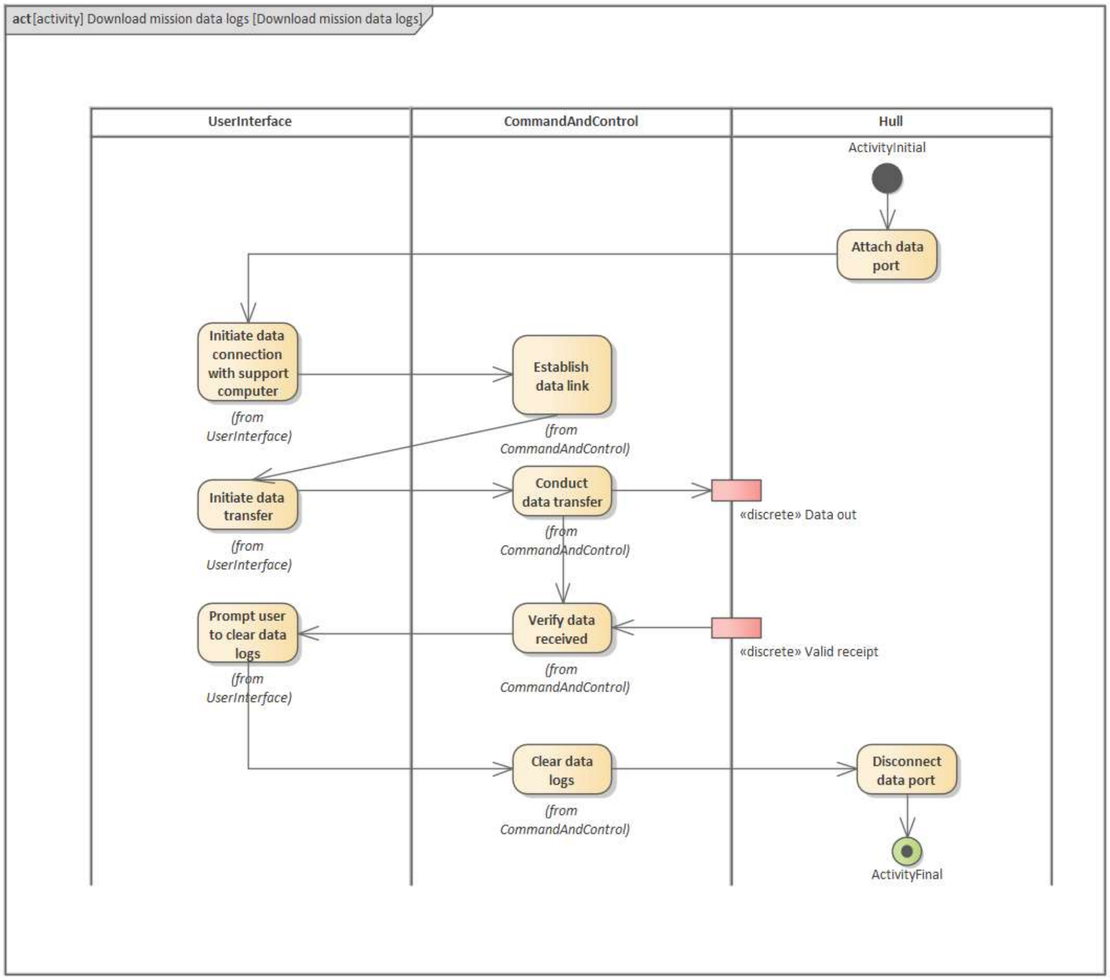

Figure C16: *Download Mission Data* – Mission data plugs are behind access hatches in the pressure hull. At the conclusion of each mission, all data collected and generated logs will be removed from the onboard computers for processing and to free up storage capacity for the next mission.

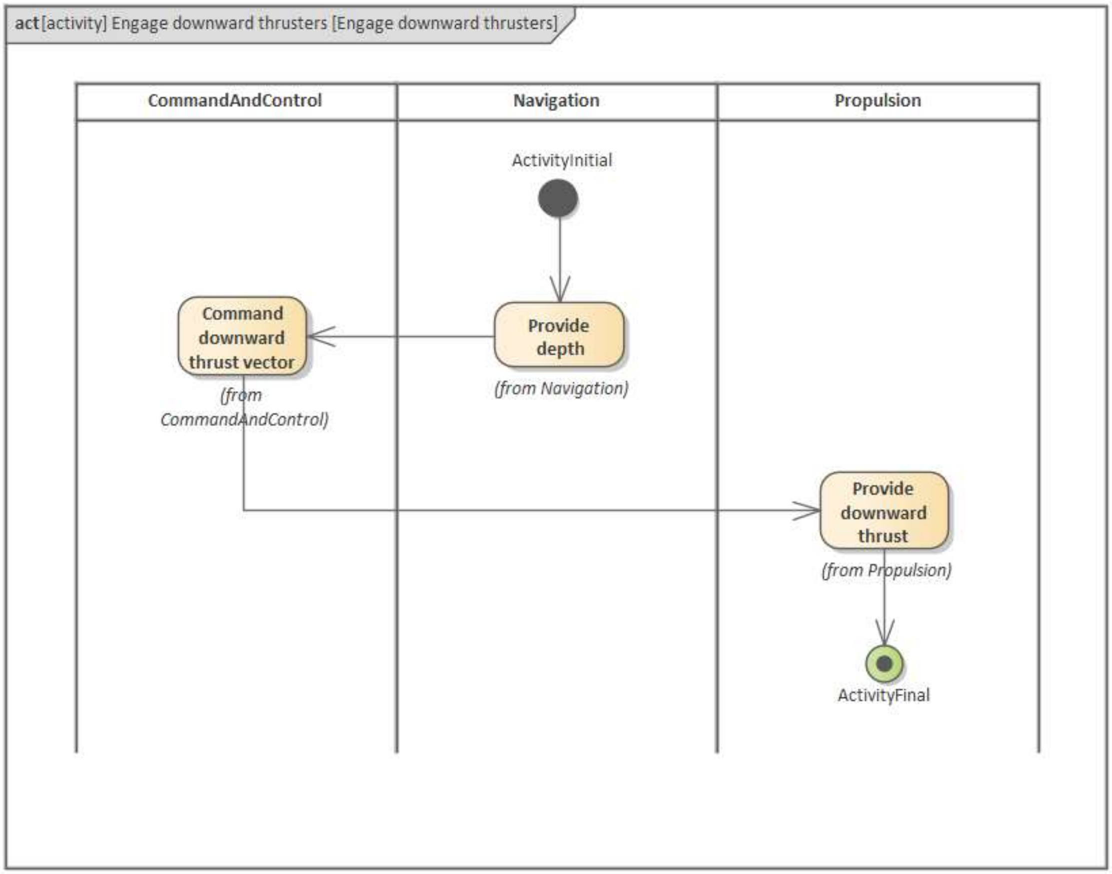

Figure C17: *Engage Downward Thrusters* – One potential operational scenario is autonomous descent control. In this case, a programmed depth is provided and the thrusters are engaged by the computer until the desired depth is met.

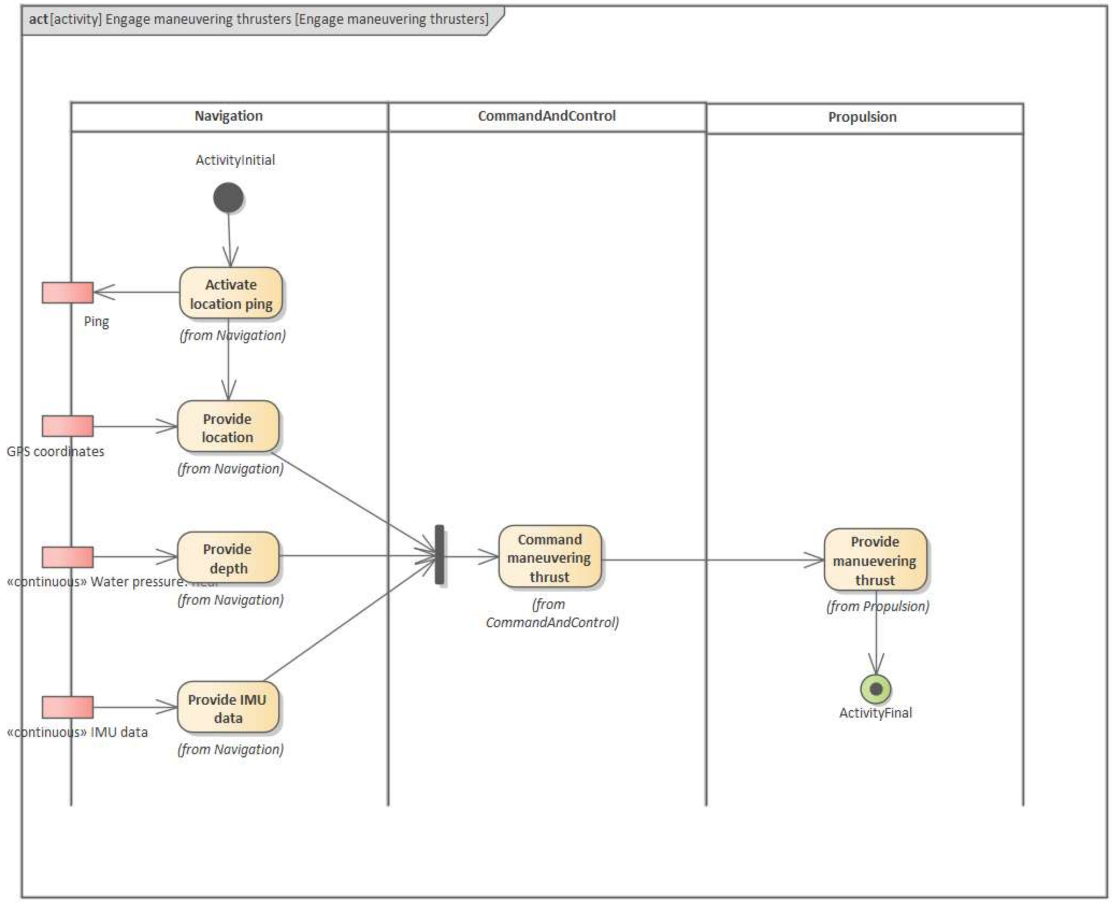

Figure C18: *Engage Maneuvering Thrusters* – Most maneuvering will likely take place under manual controls; however, that is not required. This activity diagram illustrates the sensor data required for the control systems to safely and effectively maneuver the vehicle.

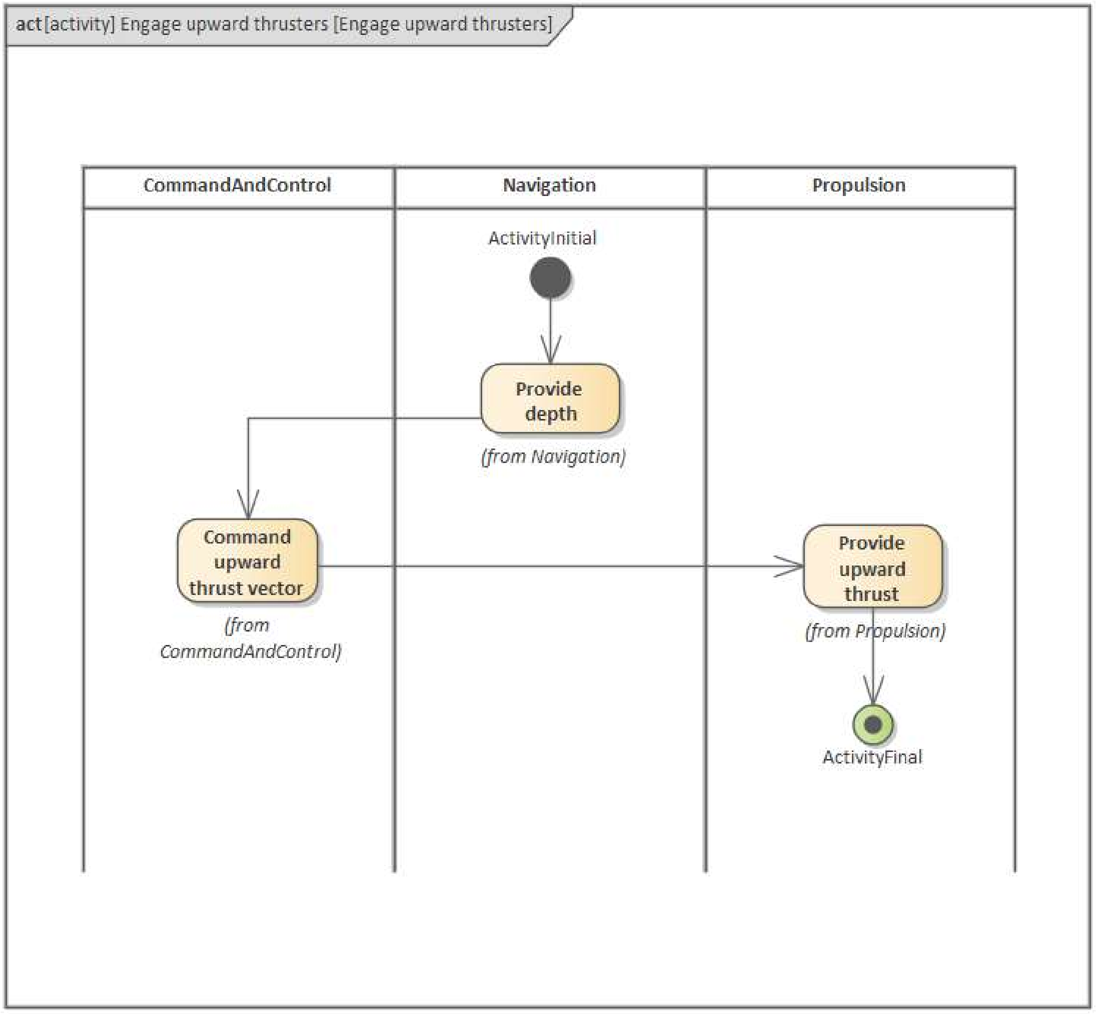

Figure C19: *Engage Upward Thrusters* – As with the downward thrusters, it is intended that the vehicle will autonomously control the ascent at the desired rate while stopping for the required decompression stops.

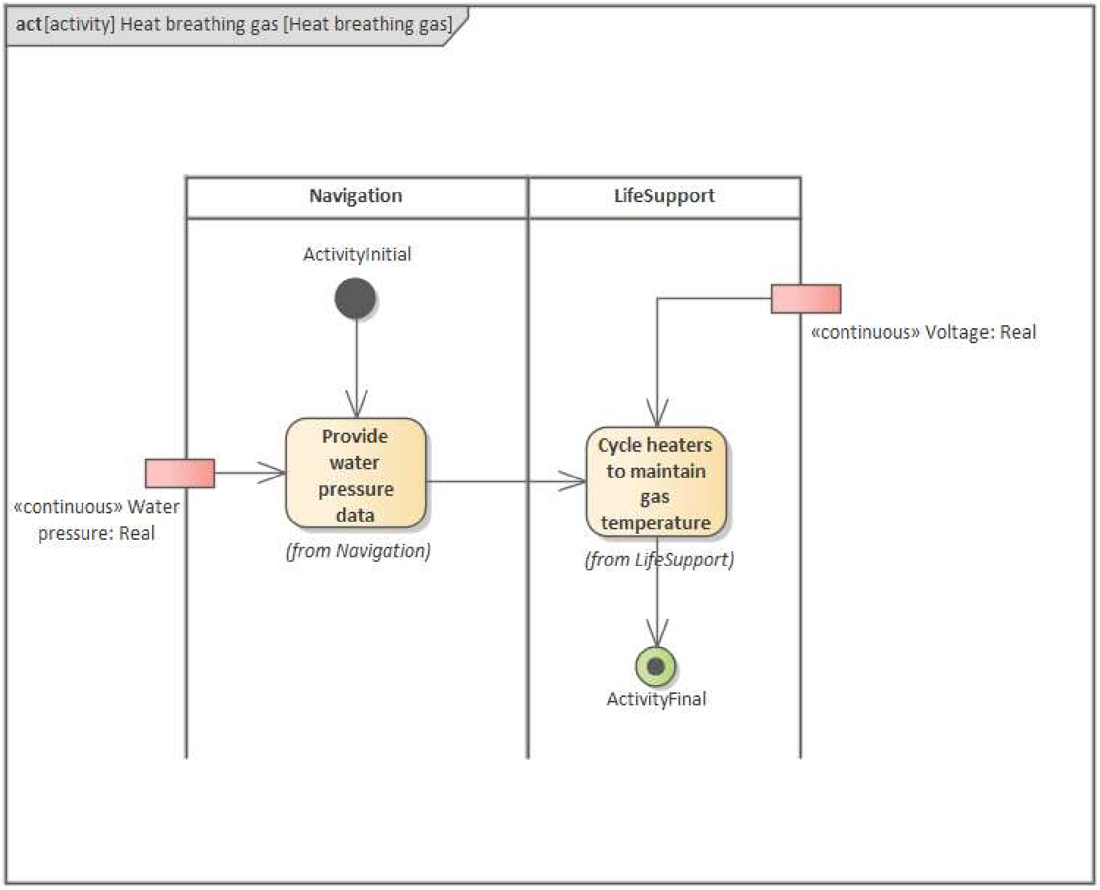

Figure C20: *Heat Breathing Gas* – Gas heaters are not required above 152 meters. To conserve power the heaters will be automatically cycled.

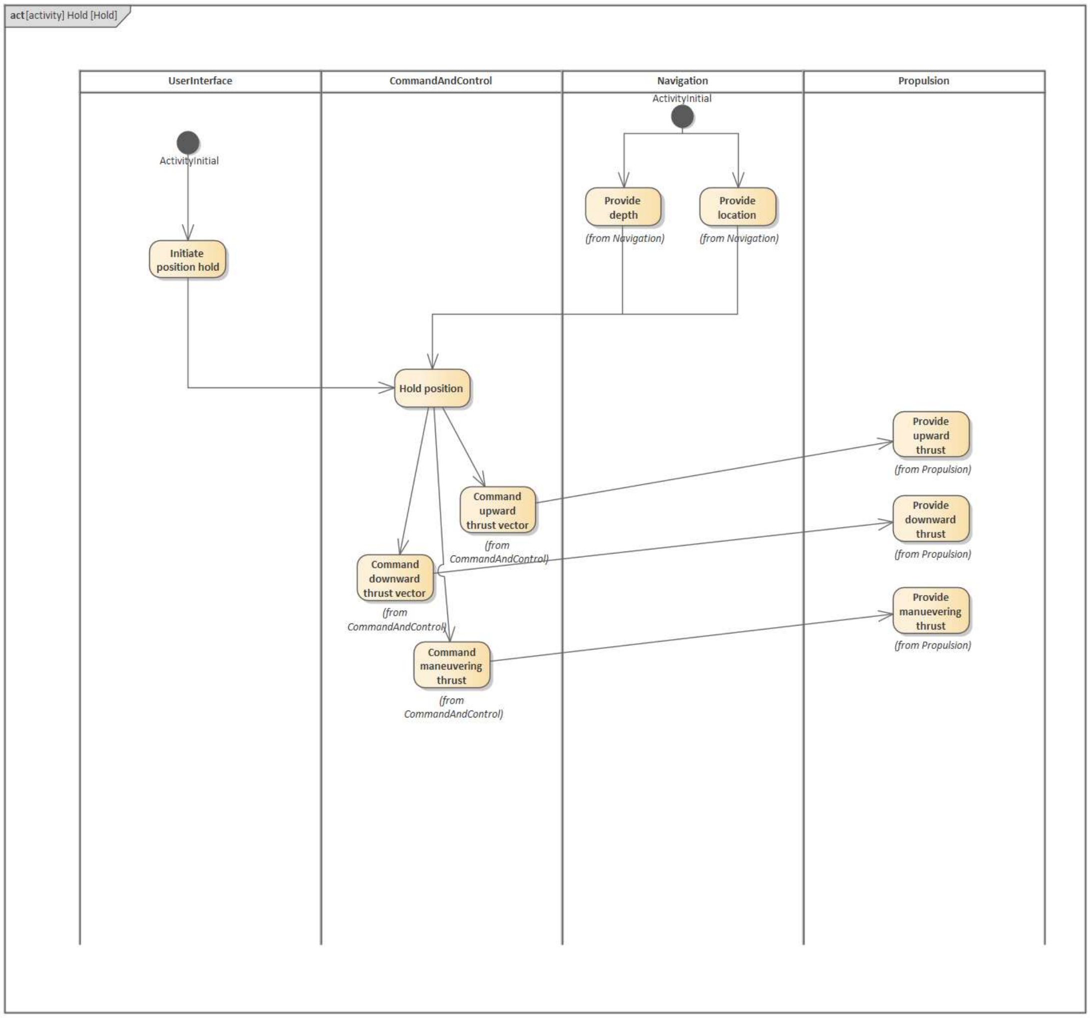

Figure C21: *Hold Position* – Holding a position in three-dimensional space requires the potential activation of all maneuvering thrusters at the same time. It will also require an understanding of the vehicle's location.

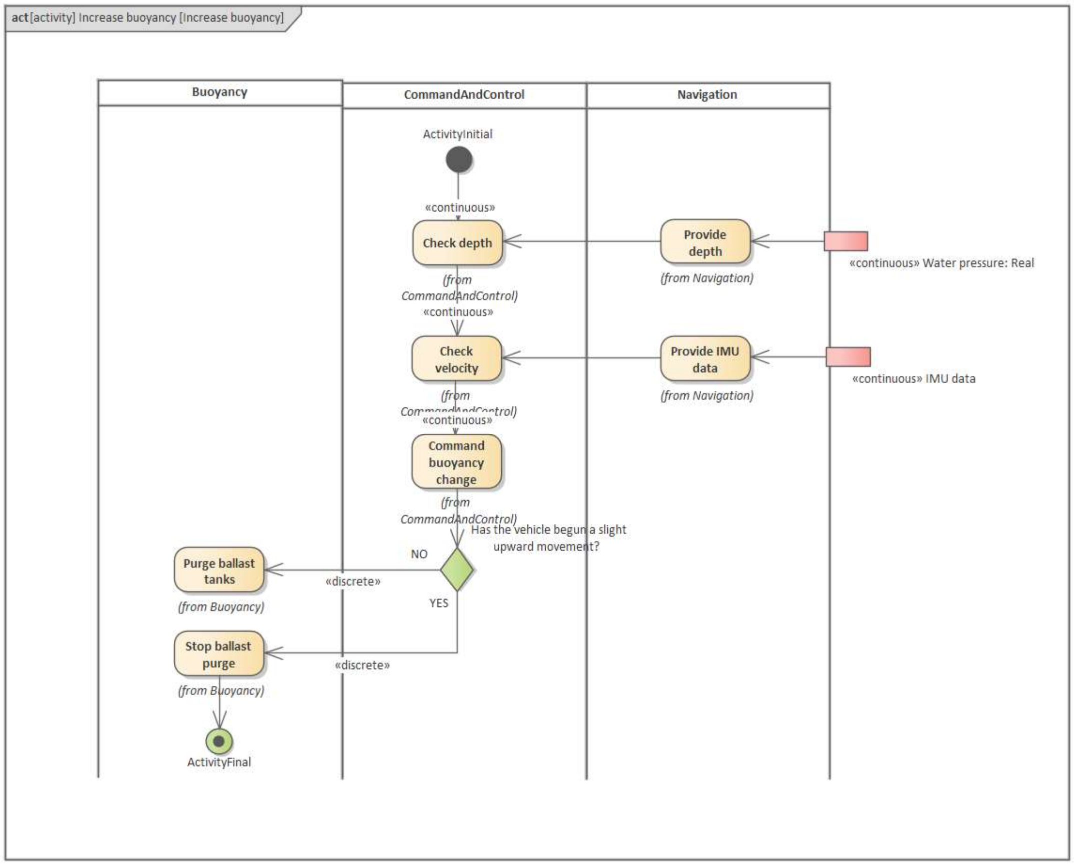

Figure C22: *Increase Buoyancy* – Ascent will likely require an increase in buoyancy. One operational scenario calls for the flooding of the ballast tanks so the vehicle can rest securely on the ocean floor; if that happens, it will be necessary to purge the tanks to get back to neutral buoyancy. This diagram illustrates the process by which that will occur.

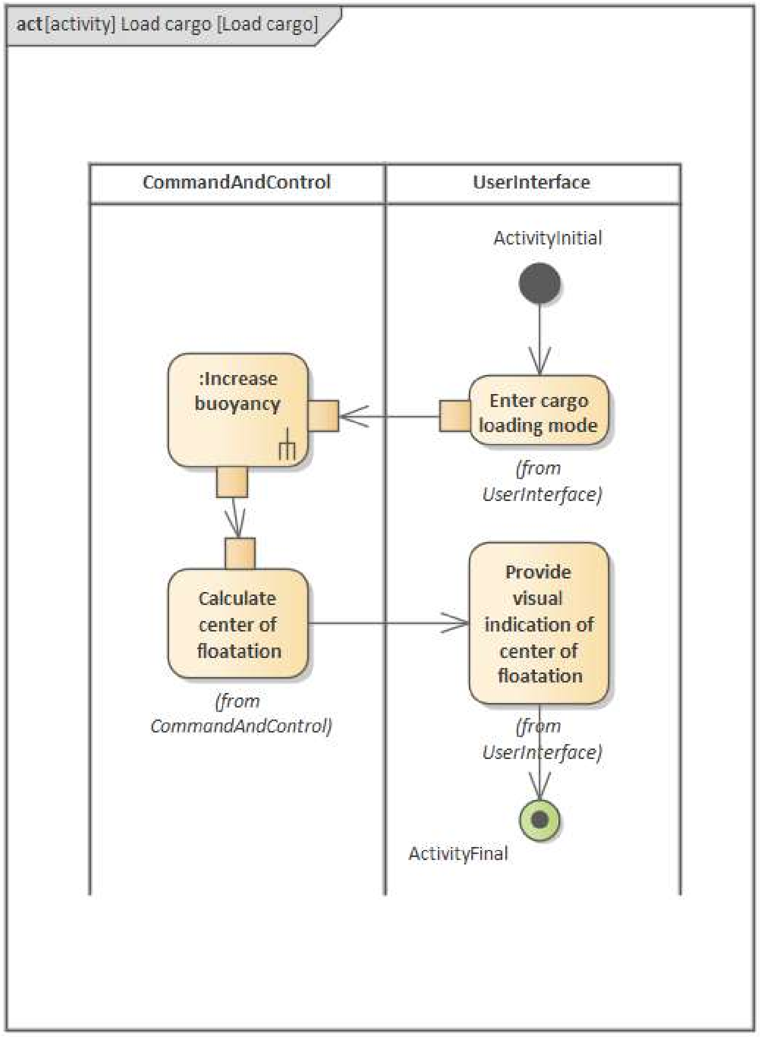

Figure C23: *Load Cargo* – Loading cargo is another use case that will require increases in buoyancy. Loading cargo will also potentially require trim adjustments to make the vehicle float level again.

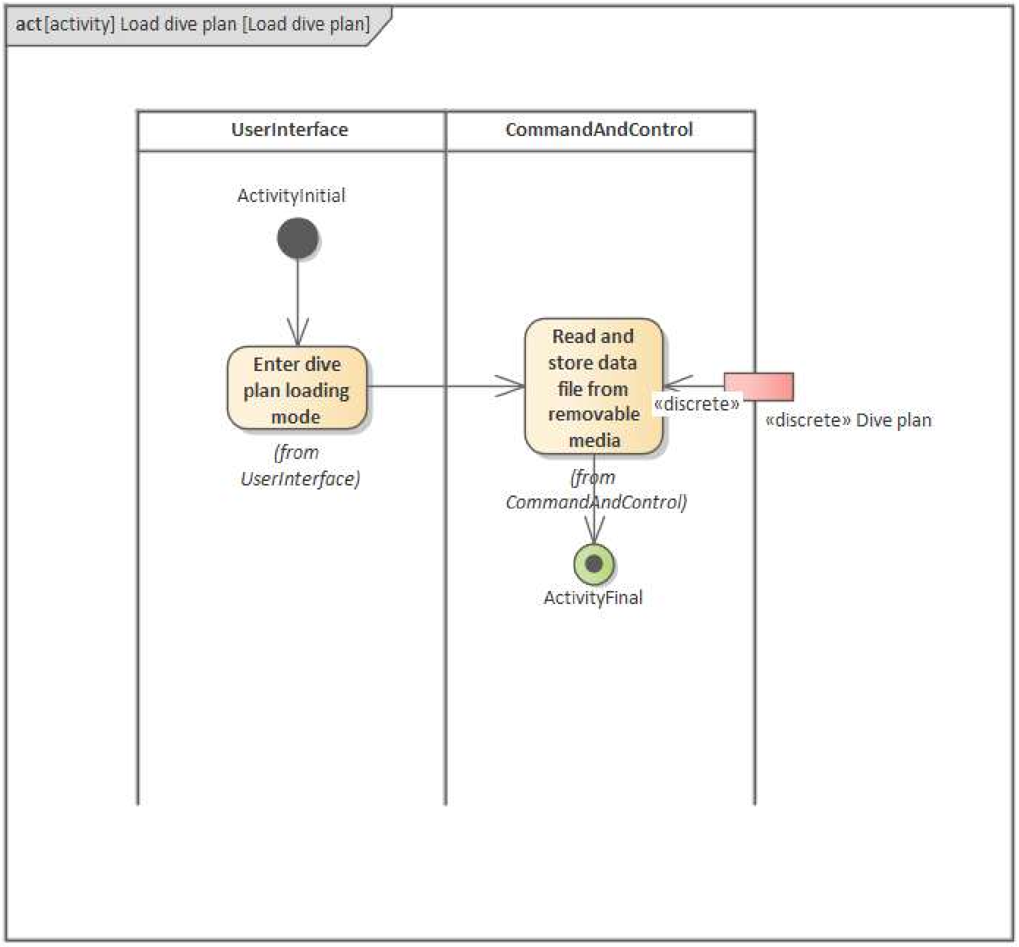

Figure C24: *Load Dive Plan* – Dive planning is more efficient off-platform. CUTLASS provides the ability to upload plans onto the vehicle.

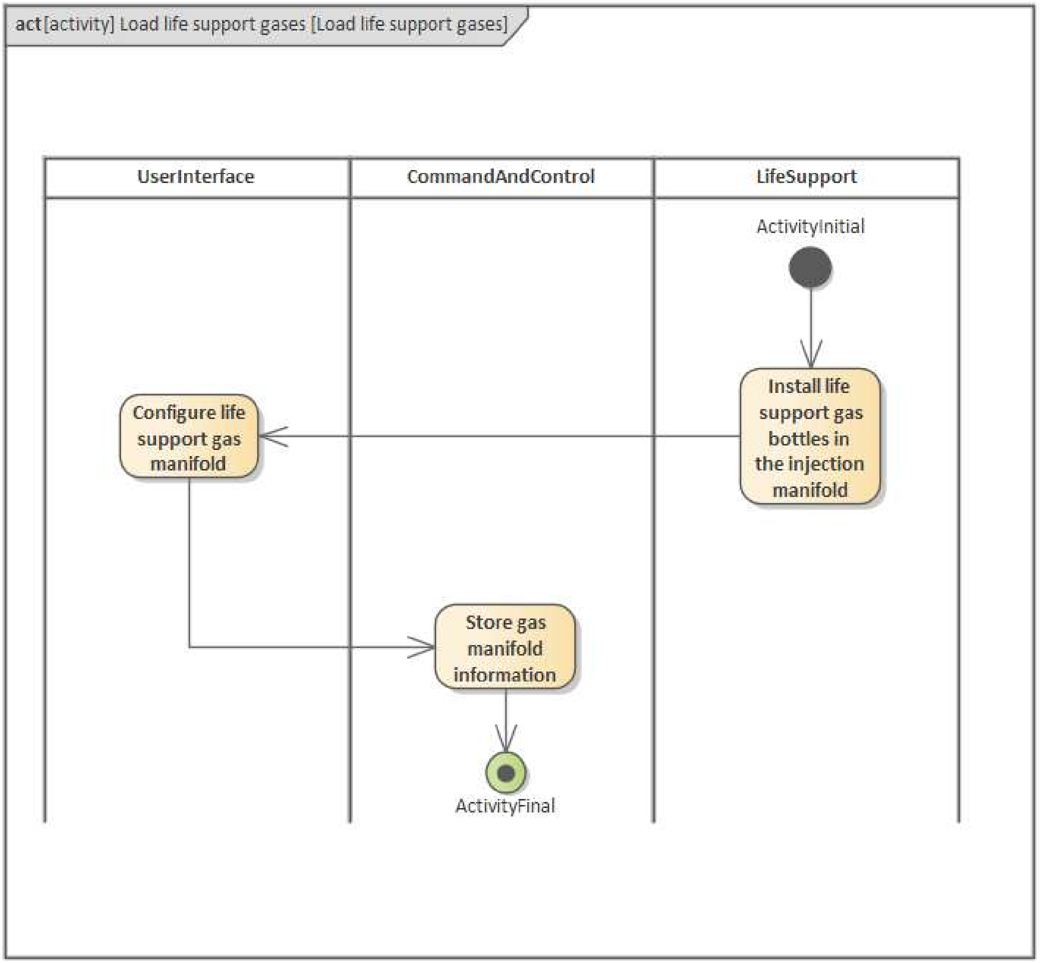

Figure C25: *Load Life Support Gases* – Life support gases will typically consist of a pre-mixed bottom gas, nitrogen, and oxygen. The user will configure the computer after the gas is loaded onto the vehicle.

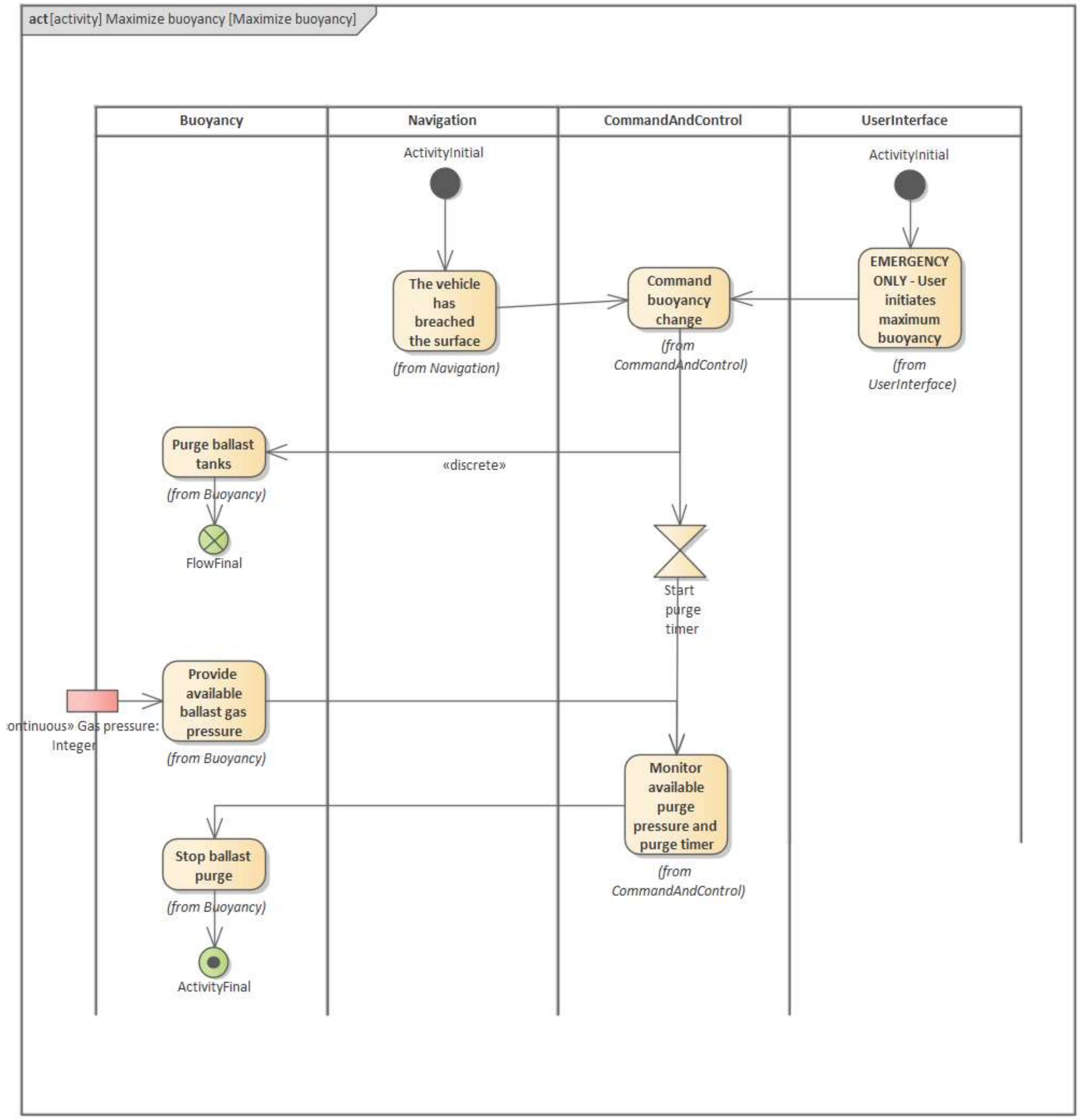

Figure C26: *Maximize Buoyancy* – It is possible to completely purge the ballast tanks upon surfacing or in the event of an emergency. This will ensure that the vehicle will surface.

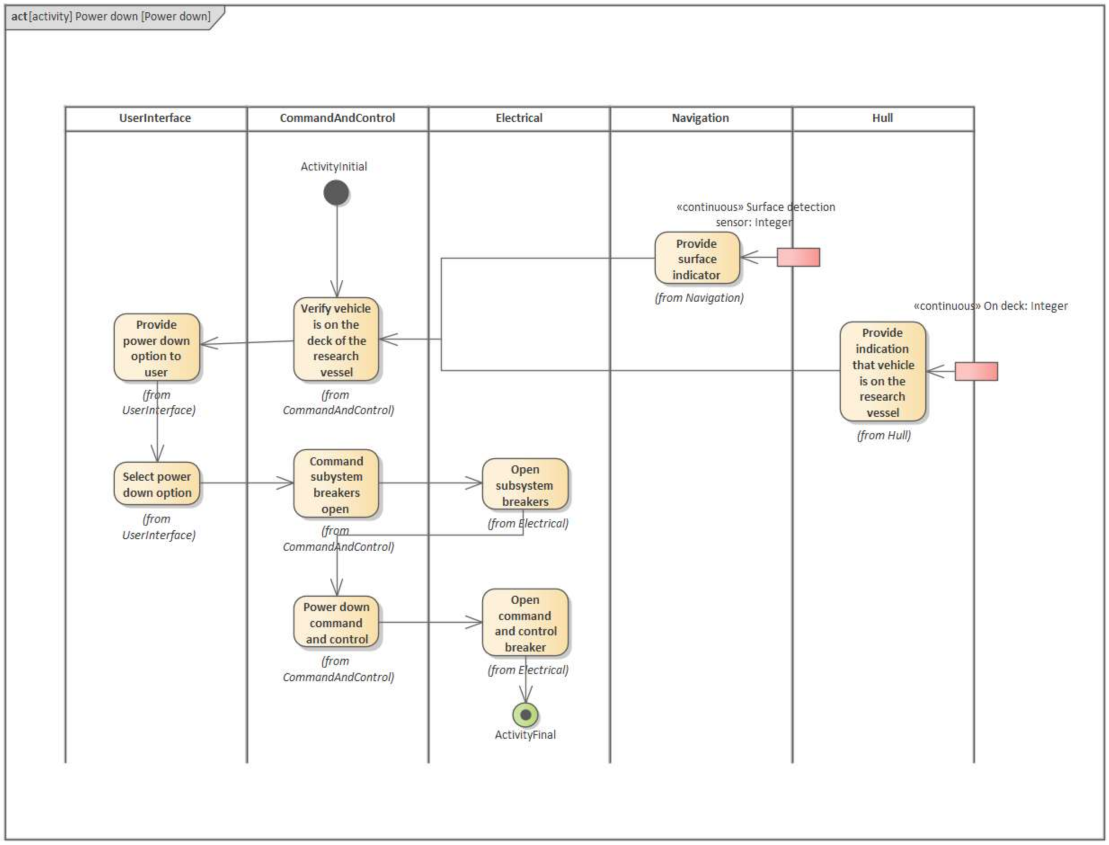

Figure C27: *Power Down* – Powering down the vehicle after the vehicle is safely aboard the surface ship allows for safe maintenance to occur.

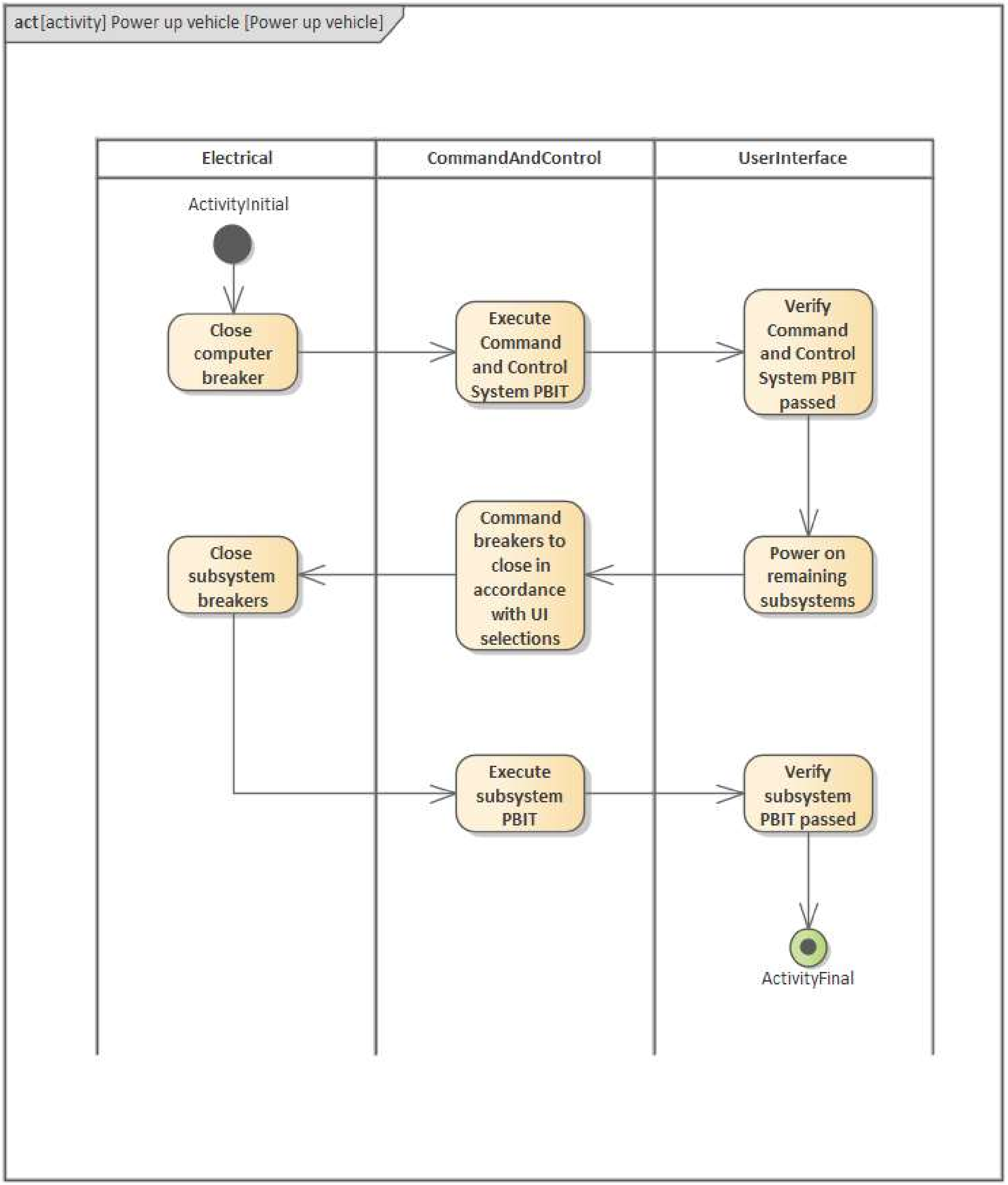

Figure C28: *Power Up Vehicle* – On startup, the vehicle will execute built-in test routines in the software to verify that all systems are functioning as expected.

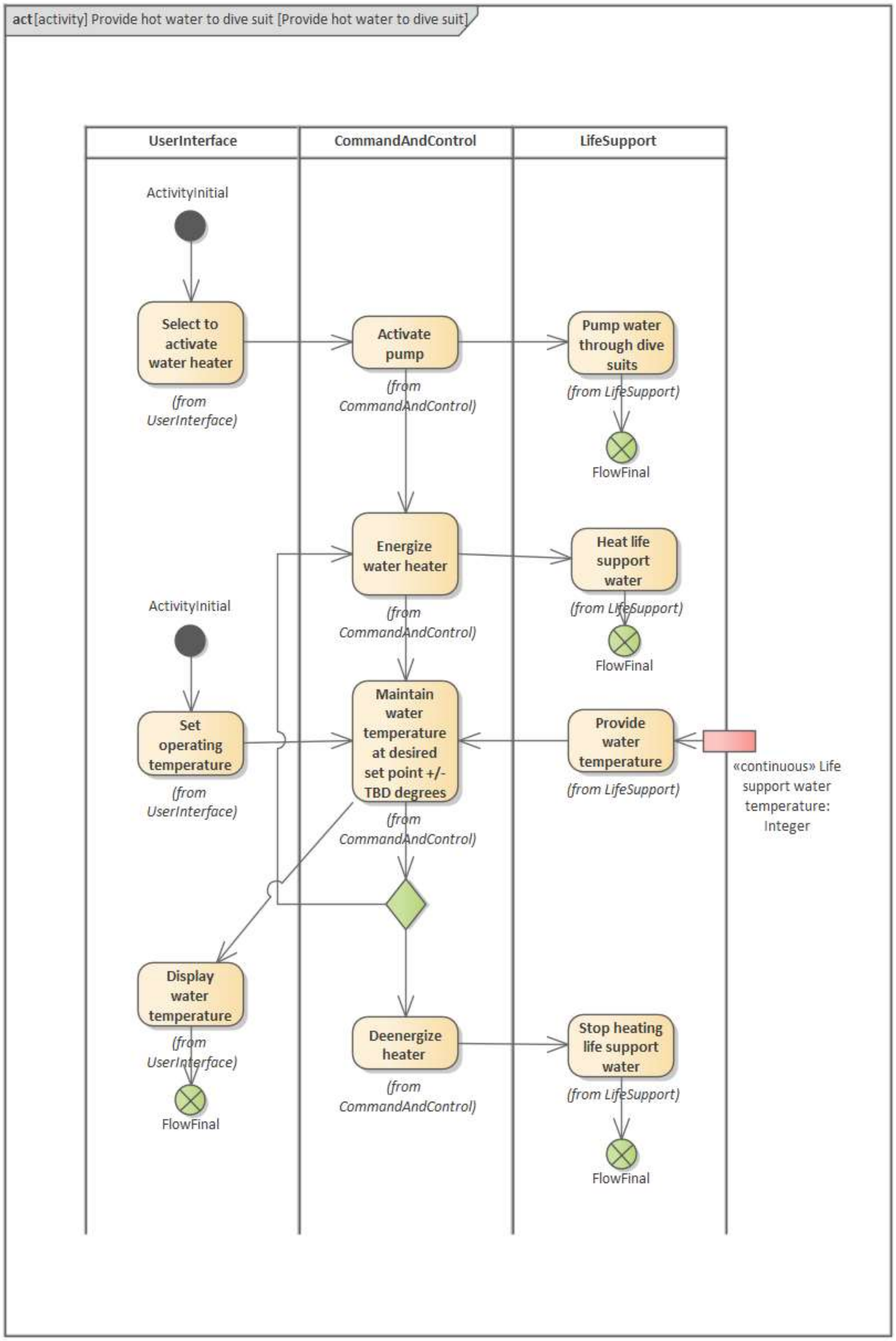

Figure C29: *Provide Hot Water to Dive Suit* – Unlike the gas heaters that will turn on automatically, the suit heaters will need to be activated by each diver.

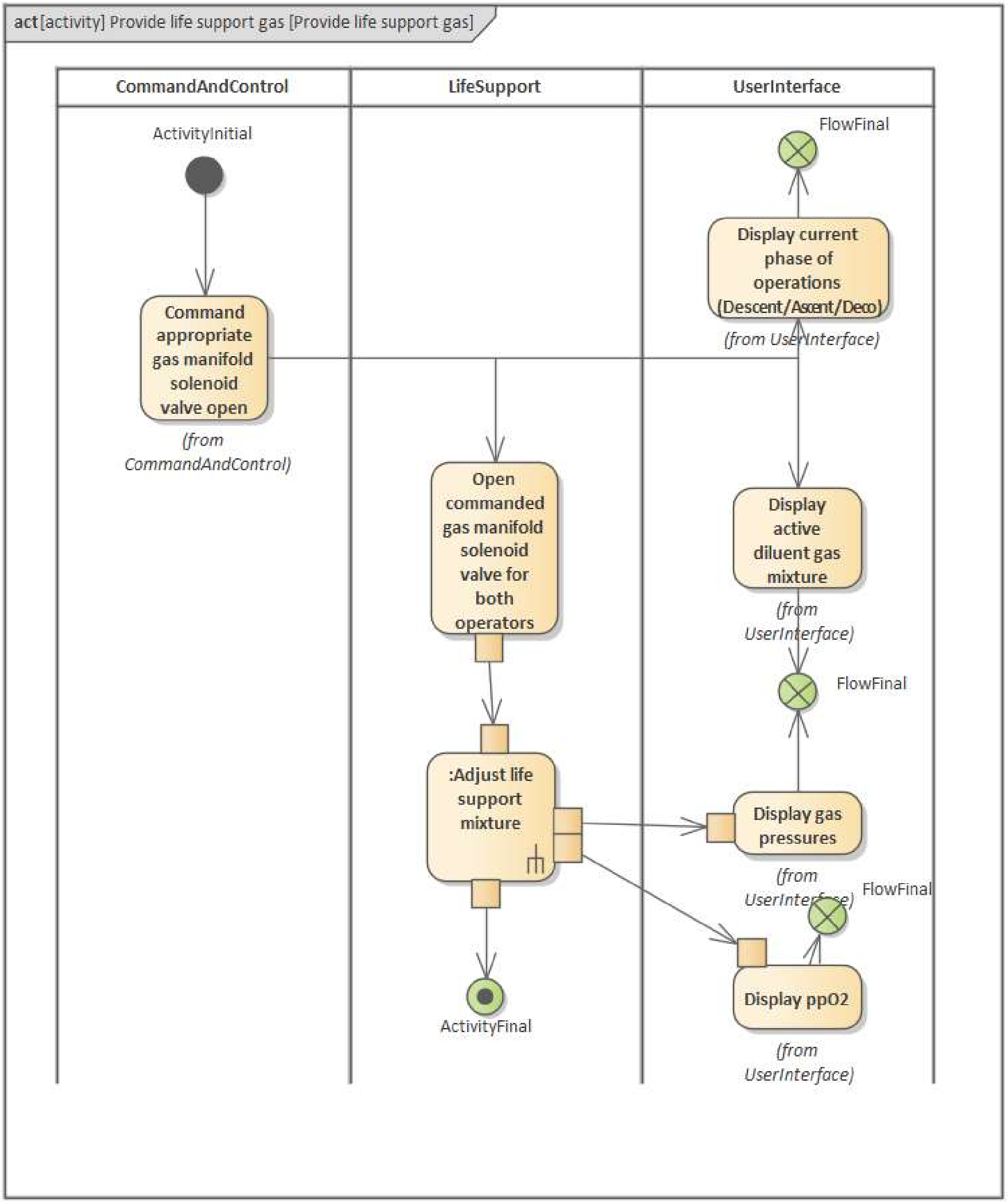

Figure C30: *Provide Life Support Gas* – This diagram illustrates how the computer will adjust the gas mixture and provide the divers with critical gas information.

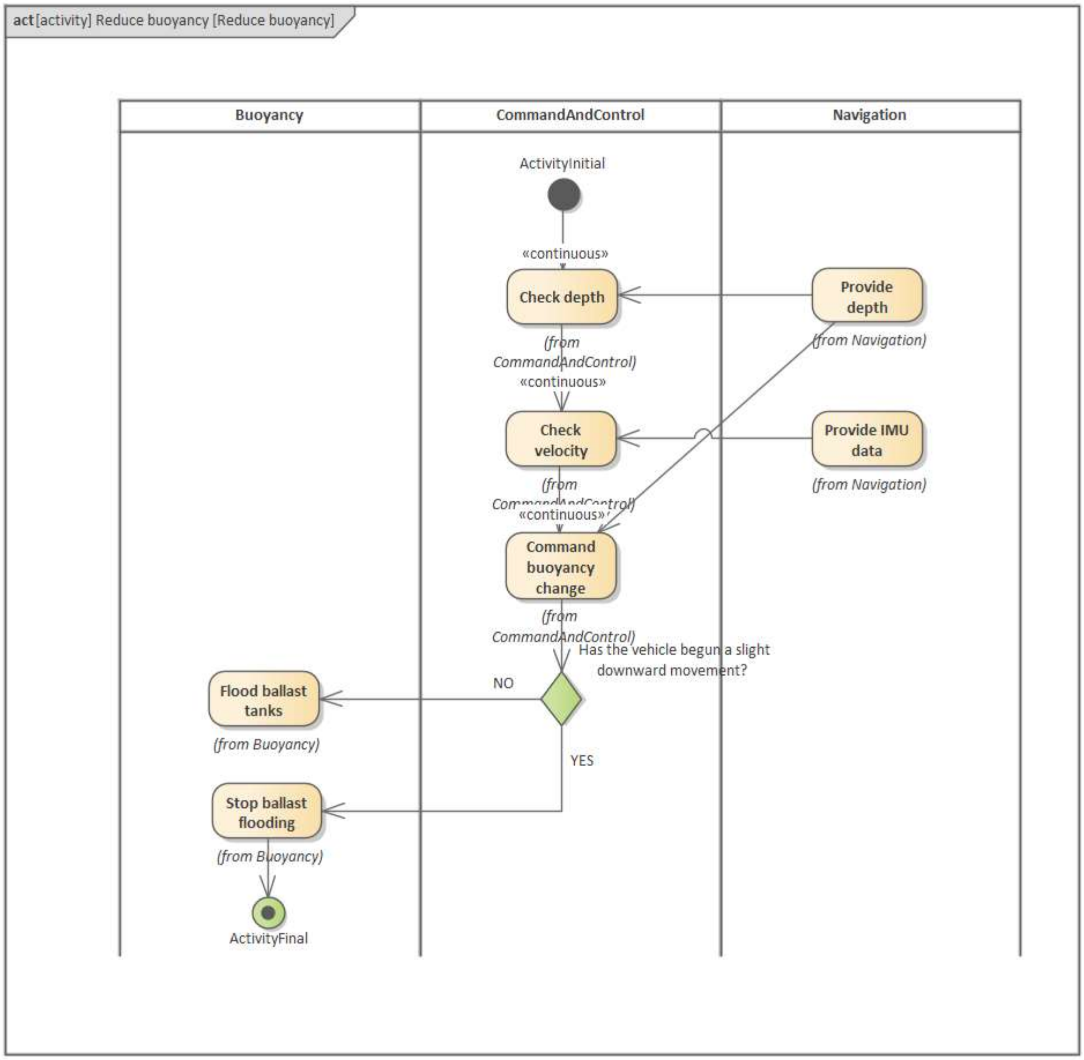

Figure C31: *Reduce Buoyancy* – Buoyancy reduction is necessary to commence the dive. The vehicle is designed to be positively buoyant and will need to take on water to achieve neutral buoyancy.

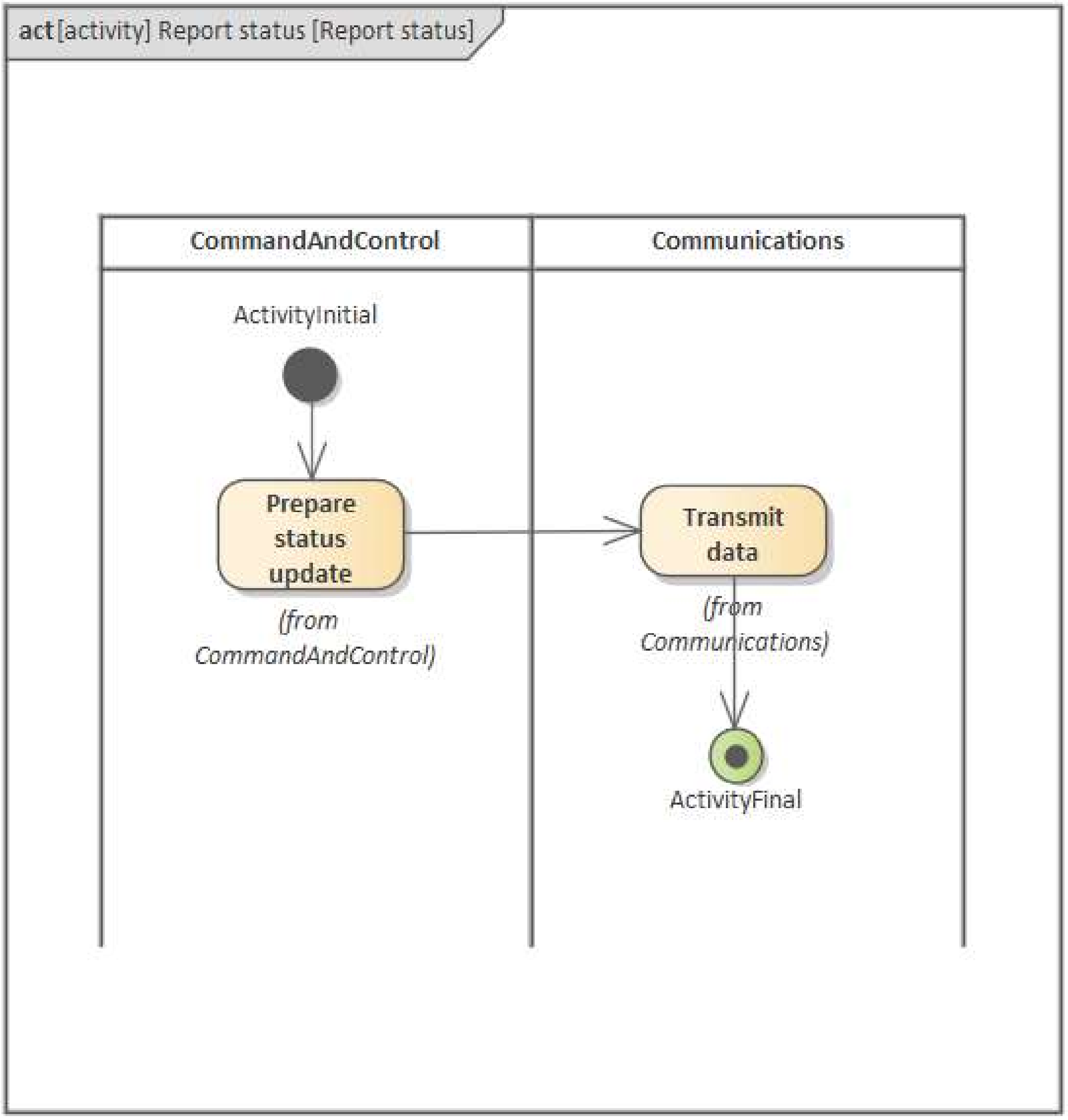

Figure C32: *Report Status* – Constant communications with the surface will be maintained via an acoustical modem.

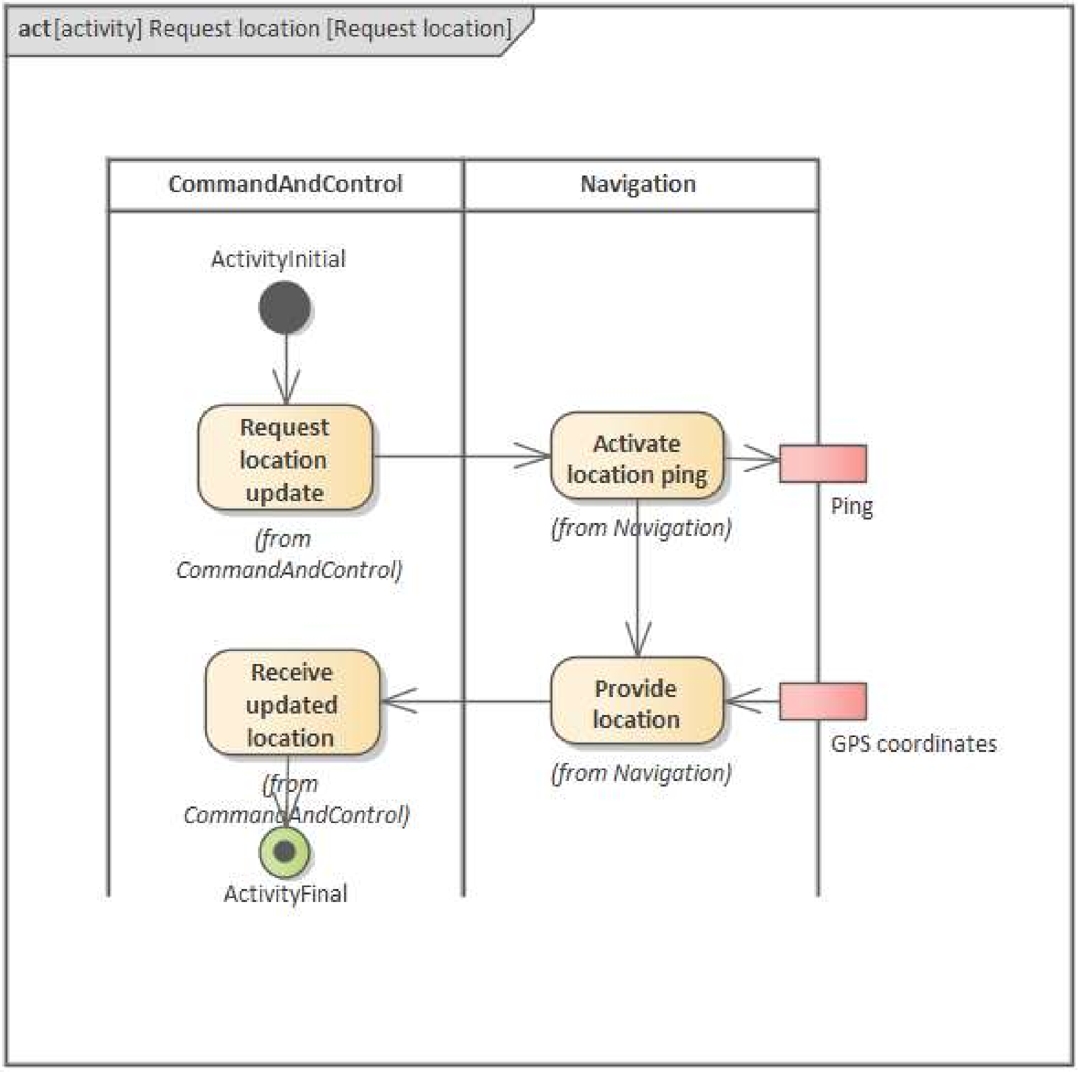

Figure C33: *Request Location Information* – Utilization of ultra-short baseline acoustical location technology can allow for highly accurate location information to be provided up to 11 km away.