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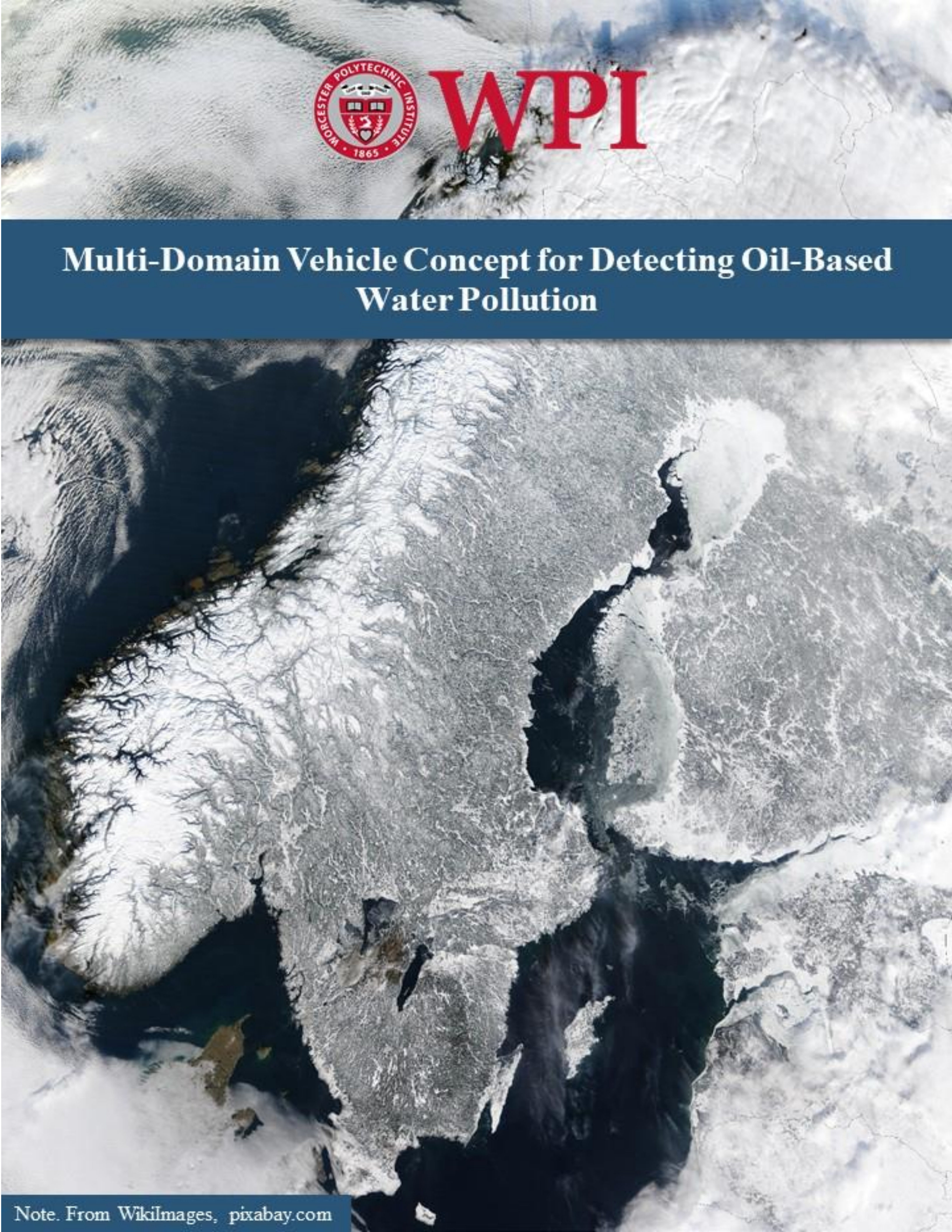
Multi-Domain Vehicle Concept for Detecting Oil-Based Water Pollution



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Multi-Domain Vehicle Concept for Detecting Oil-Based Water Pollution

An Interactive Qualifying Project

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfilment of the requirements for the

Degree of Bachelor of Science

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April 29, 2022

ABSTRACT

This project explores the environmental issue of chronic oil-based water pollution in the Baltic Sea. The goal of this project was to consider deign options and propose solutions for a sustainable autonomous aerial-aquatic vehicle (AAV) that can survey the Baltic Sea and detect and map oil pollution. Literature reviews and interviews with experts were conducted to compile an applicable set of considerations and propose a concept for an AAV. This became part of into a concept fixed-wing design composed of carbon fiber composites featuring oil detection sensors, a suite of navigation sensors, a single dual-environment propeller, all powered by batteries.

ACKNOWLEDGEMENTS

The success of our project was largely dependent on the contribution and assistance from many individuals. We would like to thank those that helped and supported us throughout the past four months in completing this project.

First, we would like to thank our advisors Professor Ivan Mardilovich, Professor Svetlana Nikitina, and Professor Carol Stimmel. They spent a great amount of time helping us revise, plan, and execute our project. Their guidance was instrumental in the overall execution of our project.

We especially appreciated the help of all of those who participated in our interviews and provided us with the knowledge and background required to complete the project. Specifically, Professor John Bergendahl the Director of the Environmental Engineering Program at Worcester Polytechnic Institute (WPI), Professor Paul Mathisen the Director of Sustainability at WPI, Robotics Engineering Professor Nicholas Bertozzi, Professor and AAV pioneer Mark Patterson. Each of them provided us with significant background and experience-based knowledge integral to the development and conclusion of our project. Additionally, we would like to thank the members of the US Coast Guard, Petty Officer Third Class Colt Cotton, US Coast Guard Marine Science Technician Michael Lypen, and Anne McGoldrick. They each gave real world examples and experience in the field of oil pollution and are direct contributors to the US Coast Guard's oil pollution detection and prevention teams. We would also like to thank Nippon Chair in Marine Environmental Management at the World Maritime University (WMU) and Professor Olof Lindén from WMU. Professor Lindén aided in our knowledge of the project and feasibility of our design recommendations.

Finally, we wanted to thank Worcester Polytechnic Institute for giving us the opportunity to conduct and complete our project. It has been a once in a lifetime opportunity for each of us and something that will make us all better future professionals. Our team is grateful to Global School Dean Kent Rissmiller for allowing our cohort to travel to Berlin, Germany after our initial travel plans were canceled.

EXECUTIVE SUMMARY

The goal of this project was to weigh design considerations, provide example designs, and gauge feasibility for a sustainable autonomous aerial-aquatic vehicle (AAV) that can survey the Baltic Sea and detect oil pollution. Oil-based contaminants, such as petroleum, are composed almost exclusively of hydrocarbon compounds. Hydrocarbons have an incredibly low solubility in water and are extremely hydrophobic, not allowing for the hydrocarbons to mix with the water and leaving it difficult to remove. This makes it dangerous to the environment and proves deadly to marine life. Directly following an oil spill, the oil in the water creates a thin layer on the surface that smothers seabirds, entraps and kills small sea creatures and poisons larger marine animals through oil inhalation or sticking to an animal's gills (Jernelöv, 2010). Long-term, a spill can require considerable time for the environment to return to its natural state. Contamination of seawater, shores, sediments, and beaches in this area stays prevalent from several months to several years after a spillage occurs (Kostianoy, 2020). The Baltic Sea is a mostly enclosed body of water that touches nine European countries including Russia and Germany. This sea is an incredibly busy and has forty oil terminals and large ports. It sees nine percent of the world's trade and eleven percent of the world's oil transportation. A large contribution of oil that enters the Baltic Sea comes from intentional discharges along the main travel routes in the water (Krek et al., 2021). There exists a need for additional surveillance within the Baltic Sea to prevent further ecological damage.

There are two circumstances where oil pollution originates: dumping out in the open water or leaking from a source, almost always a pipe or duct. Most modern commercial vehicles are implemented to limit their search along areas near pipes, mainly excluding vast open water. Current human involvement in the detection of oil pollutants includes many examples of groups or teams developing a form of robotic aquatic underwater vehicle (AUV) or unmanned aerial vehicle (UAV) that are being used, each with their own unique set of capabilities and limitations. We have found however, that most still require a large amount of human involvement, whether having to control the robot throughout its duration or having to travel into the ocean to send it out into the body of water manually and retrieving it once it has completed travel. With a myriad of technologies available for implementing controls into environmental surveillance drones, it is helpful to consider specific sensors or sensing techniques that can be applied. Using specific sensors and photographic techniques allows the pinpointing of properties within images and data.

This project introduces several challenges that must be considered when evaluating our desired goal. With gas and liquid being different mediums, maneuvering between the two environments will require distinctive design considerations to allow for the vehicle to perform and withstand the impact forces effectively. These challenges also produce additional specific requirements for the propulsion system of the vehicle. In the transition between environments, many problems arise that include the vehicles propellors interaction with the water.

Due to the advances in technology over time, engineers have discovered various methods of storing energy for mobile applications which have distinctive characteristics that can affect performance. Two critical considerations that will be analyzed across the various power sources are energy density and specific energy. These sources define how much weight (specific energy) and volume (energy density) that they consume compared to how much power they hold. In addition to the specific power and energy density, there are also logistical concerns that can determine the efficacy of each fuel cell. The perfect power supply does not exist for every application and therefore must be carefully chosen based on the limitations of the system and its environment.

To meet our project goals, we conducted semi-structured interviews with experts in the field of oil pollution surveying, professionals familiar with sustainable practices, and engineering professionals. Among the 30 people that were contacted, we were able to conduct nine interviews and gathered a large amount of detailed information about their specialties. Our interviewees included:

- The Director of the Environmental Engineering Program at Worcester Polytechnic Institute (WPI), John Bergendahl
- The Director of Sustainability at WPI, Paul Mathisen
- Robotics Engineering Professor Nicholas Bertozzi
- Professor and AAV Pioneer Mark Patterson
- US Coast Guard Petty Officer Third Class Colt Cotton
- US Coast Guard Marine Science Technician Michael Lypen
- Nippon Chair in Marine Environmental Management at the World Maritime University (WMU), Olof Lindén
- Engineering professional employed within the aeronautics industry who asked to remain anonymous

Additionally, we performed in-depth research into peer-reviewed journal articles and other published sources. We developed the following objectives for our research:

1. Assess Current Technologies in the Operational Space.
2. Identify Limiting Aspects of an AAV Design.
3. Assess the Materials and Sensors in Air and Water Environments.
4. Investigate Design Considerations for an AAV.

All our collected data was then compiled into separate specific systems of an AAV that we determined to be of the most importance following the interviews. Our key recommendations are as follows:

1. The main source of oil pollution in the Baltic Sea is illegal dumping. To help mitigate the effect of this pollution, the designed AAV must be able to aerially monitor the body of water. With photographic limitations, any detected pollutants must be confirmed with an additional detection. It was discovered that IR thermal imaging cameras with machine learning algorithms is the best technology in the air, and fluorometers can detect oil products in bodies of water.
2. It is recommended that the required sensors on-board the craft would include an inertial measurement unit (IMU). The IMU is made up of sensors that help the vehicle to know its orientation and position, namely: gyroscopes, magnetometers, accelerometers, and GPS. A barometer is also an important sensor, allowing the user to calculate the altitude both above and below the water, but it is not the most accurate. Implementing a radar system for aerial use and a side scanning sonar for underwater to aid in detecting altitude has been proven to be an efficient method to achieve more accurate readings.
3. For overall wing design, a fixed wing system with two degrees of freedom was determined to be the most applicable system for oil pollution detection in the Baltic Sea. The first degree of freedom will be a deflecting flap at ¾ of the wing (elevator) and the second degree of freedom will be a wing rotation along the longitudinal axis of the vehicle changing the angle of attack. The elevators will add smooth travel in aerial environments and were found to perform optimally between -10 to 10 degrees. The adjusting wing angle of attack performed better than the deflecting flap in marine environments and were designed to rotate a full rotation (360 degrees).
4. A materials life cycle must be considered when evaluating which materials to utilize to minimize harm within an environment. It is important to take into consideration the length of time a material will be efficient before it degrades, releases toxic chemicals or negatively affect the environment. Certain inorganic coatings, such as cadmium used for corrosion resistance, have been proven to disperse dangerous toxic chemicals into the environment over time. However, the use of fiber-based composites and metals is recommended with benefits found in their long-life cycle and corrosion resistance that does not have the same negative affect on the environment. Some metals alloys, such as the aluminum alloy (AA6060) and the titanium alloy (Ti-6Al-4V), commonly used in aerospace applications for example, possess desirable corrosion resistance.
5. For the purposes of this project, only sustainable power sources such as batteries and renewable fuels like hydrogen and oxygen were evaluated. Green systems require extra consideration because they have lower flight operation time compared to non-renewable energy sources (gasoline). Even though fuels like hydrogen and oxygen have higher energy densities and specific energies, they require additional infrastructure to harness the energy. For their simplicity and reliability, batteries without solar panels were determined to be the optimal sustainable power source. With various internal compositions, specialty batteries can be chosen based on the required energy density, specific density, and environment.

Additionally, the lack of solar panels removes the performance of the vehicle from being dependent on the environment.

6. Not every method of propulsion can operate in aerial and aquatic environments sufficiently. It was found that aerial-based propellers spun by motors can function in both mediums. No clear underwater optimization of aerial propellers has been made but could prove to be beneficial to explore. The size of the propellers will vary based on each unique vehicle design but operating at lower rotational speeds with relatively larger blade sizes have been found to provide the most efficient travel speed in both environments.
7. For an aerial vehicle, weight is a critical concern that must be fully accounted for and minimized. Whether it is a power source, a bolt, or even a painted coating, all components add weight to the vehicle and therefore require substantially larger power sources, changes the classification of the vehicle, and reduce operation time.
8. Since this vehicle is meant to be submerged underwater, the buoyancy of the vehicle is extremely important. Contemporary vehicles tend to either implement active systems that allow them to be variably buoyant or are designed to be neutrally buoyant. There are advantages to either system, but due to weight concerns and the limited depths the vehicle would need to traverse, it was determined that the system should be neutrally buoyant.

These recommendations if implemented, lay the foundation for future designers to develop and construct an AAV for the use of oil detection. Other areas of future inquiry include extending our single vehicle into a multi-vehicle system to cover a large area of ocean very quickly. It was however determined that due to current technology, an AAV is not the most realistic. The detection of oil spills and leaks could lead to the prevention of further ecological effects caused by mass amounts of oil in the ocean. A cleaner ecosystem will allow for a healthier natural environment leading to more growth and sustainability.

AUTHORSHIP

Section	Author	Editor
Abstract	Abigail Berube	Tyler Guertin
Acknowledgements	Drake Hamblin	Nicholas Grumski
Executive Summary	Drake Hamblin	Zachary Rivernider
1. Introduction	All	Jeremy Trembly
2. Background	Zachary Rivernider	Abigail Berube
2.1 Oil Contamination in the Baltic Sea & the Environmental Impact	Zachary Rivernider	Abigail Berube
2.1.1 Environmental Impacts of Oil-Based Water Pollution Through Animal Life	Abigail Berube	Zachary Rivernider
2.1.2 Chronic Pollution in the Baltic Sea	Abigail Berube	Zachary Rivernider
2.2 Current Oil-Pollution Detection Technologies with Robotic Vehicles	Jeremy Trembley	Drake Hamblin
2.2.1 Human Involvement in the Search Limiting Potential	Zachary Rivernider	Tyler Guertin
2.2.2 Environmental Perception	Nicholas Grumski	Tyler Guertin
2.2.3 Photographic Techniques	Tyler Guertin	Nicholas Grumski
2.3 Multi-Environment Engineering Challenges	Jeremy Trembley	Drake Hamblin
2.4 Geometric Design & Fluid Mechanics in Both Environments	Drake Hamblin	Tyler Guertin
2.4.1 Aquatic & Aerial Material Applications	Drake Hamblin	Tyler Guertin
2.5 Renewable Power Source Characteristics	Zachary Rivernider	Nicholas Grumski
2.6 Conclusion to the Background	Tyler Guertin	Zachary Rivernider
3. Methodology	All	Tyler Guertin
3.1 Assessing Current Technologies in the Operational Space - Objective #1	Zachary Rivernider	Tyler Guertin
3.1.1 Interviews with Experts in the field of Oil Pollution Surveying and Identification	Zachary Rivernider	Abigail Berube
3.1.2 Inductive Coding and Development of Codebook	Zachary Rivernider	Abigail Berube
3.2 Objective #2 – Identify Limiting Aspects of AAV Design	Nicholas Grumski	Drake Hamblin
3.2.1 Interviews with Professionals Familiar with Sustainable Practices	Nicholas Grumski	Drake Hamblin
3.2.2 Inductive Coding and Development of Codebook	Nicholas Grumski	Drake Hamblin
3.3 Assessing AAV Subsystems in Air and Water Environments - Objective #3	Tyler Guertin	Zachary Rivernider
3.3.1 Interviews with Engineering Professionals	Tyler Guertin	Zachary Rivernider
3.3.2 Inductive Coding and Development of Codebook	Tyler Guertin	Zachary Rivernider
3.4 Investigation into Optimizing Design Considerations - Objective #4	Jeremy Trembly	Tyler Guertin
3.4.1 Literature Analysis of Academic Articles	Jeremy Trembly	Tyler Guertin
3.4.2 Software for Engineering Analysis	Jeremy Trembly	Tyler Guertin
3.5 Evaluation Justifications & Limitations of Used Methods	All	Tyler Guertin
3.5.1 Justification for Semi-Structured Interviews with Professionals	All	Tyler Guertin

3.5.2 Justification of Literature Review of Engineering and Environmental Topics	All	Tyler Guertin
3.5.3 Discussion of Overall Limitation Within These Methods	All	Tyler Guertin
4. Findings	Tyler Guertin	Tyler Guertin
4.1 Sustainability of Vehicle Design Aspects	Tyler Guertin	Abigail Berube
4.1.1 Material Degradation & Corrosion	Abigail Berube	Nicholas Grumski
4.1.2 Material Life Cycle	Tyler Guertin	Nicholas Grumski
4.1.3 Biofouling	Abigail Berube	Nicholas Grumski
4.1.4 Sediment Disruption in Aquatic Environments	Nicholas Grumski	Zachary Rivernider
4.1.5 Noise Pollution in Aerial & Aquatic Environments	Zachary Rivernider	Nicholas Grumski
4.2 Current Technologies of Oil Detection	Tyler Guertin	Abigail Berube
4.2.1 Main Sources of Oil Pollution in the Baltic Sea	Abigail Berube	Jeremy Trembly
4.2.2 Modern Oil Pollution Identification Methods Universally	Zachary Rivernider	Abigail Berube
4.2.3 Current Limitations in Oil Pollutions Identification	Nicholas Grumski	Zachary Rivernider
4.2.4 Sensors for Navigation & Oil Perception	Nicholas Grumski	Zachary Rivernider
4.3 Physical Design Aspects of AAVs	Tyler Guertin	Zachary Rivernider
4.3.1 Analysis of Propulsion Applicable for Operation in Air & Water	Jeremy Trembly	Abigail Berube
4.3.2 Structural Geometry & Analysis of Materials	Tyler Guertin	Abigail Berube, Zachary Rivernider
4.3.2.1 Fiber-Based Composite Materials	Tyler Guertin	Abigail Berube
4.3.2.2 Metal Materials	Abigail Berube	Tyler Guertin
4.3.2.3 Analytical Comparison of Materials	Tyler Guertin	Nicholas Grumski
4.3.3 Effect of Fluid Dynamics on Structural Design	Tyler Guertin	Zachary Rivernider
4.3.3.1 Methods for Aircraft & Hydrocraft Design	Tyler Guertin	Zachary Rivernider
4.3.3.2 Fixed-Wing Elevator Flap Analysis	Tyler Guertin	Zachary Rivernider
4.3.3.3 Fixed-Wing Angle of Attack Analysis	Tyler Guertin	Zachary Rivernider
4.3.4 Analysis of Sustainable Power Systems for an AAV	Zachary Rivernider	Jeremy Trembly
4.3.5 Analysis of Weight on AAV Operation	Jeremy Trembly	Abigail Berube
4.4 Expert Recommendations & Opinions for AAVs	Jeremy Trembly	Tyler Guertin
4.5 Findings Conclusion: Proposed Conceptual Vehicle Design	All	Nicholas Grumski, Tyler Guertin
5. Discussion & Recommendations	Jeremy Trembley	Nicholas Grumski
5.1 Discussion of Modern Oil Detection Methods	Zachary Rivernider	Nicholas Grumski
5.2 Synthesizing Vehicle Operations & Autonomy	Nicholas Grumski	Jeremy Trembley
5.3 Discussion on Wing Design Methods	Tyler Guertin	Abigail Berube
5.4 Considerations for Overall Structural Design	Tyler Guertin	Abigail Berube
5.5 Application of Materials to AAVs	Abigail Berube	Tyler Guertin
5.6 Justification and Limitations for Batteries	Zachary Rivernider	Abigail Berube

5.7 Considerations for Propulsion Strategies	Tyler Guertin	Jeremy Trembley
5.8 Examination on the Impact of Weight & Buoyancy	Jeremy Trembley	Zachary Rivernider
5.9 Recommendations for Further Development	Nicholas Grumski	All
5.10 Conclusion	Jeremy Trembley	Zachary Rivernider
6. References	Nicholas Grumski	Abigail Berube
7. Appendices		
7.1 Appendix A	Zachary Rivernider	Nicholas Grumski
7.2 Appendix B	Nicholas Grumski	Abigail Berube
7.3 Appendix C		
7.3.1 Objective 1	Abigail Berube	Zachary Rivernider
7.3.2 Objective 2	Jeremy Trembley	Abigail Berube
7.3.3 Objective 3	Drake Hamblin	Abigail Berube
7.4 Appendix D	Zachary Rivernider	Tyler Guertin
7.5 Appendix E		
7.5.1 Michael Lypen – U.S. Coast Guard	Drake Hamblin	Jeremy Trembley
7.5.2 Michael Buckholt – WPI Biology and Biotechnology	Zachary Rivernider	Jeremy Trembley
7.5.3 Olof Lindén – World Maritime University	Zachary Rivernider	Nicholas Grumski
7.5.4 Colt Cotton – U.S. Coast Guard	Drake Hamblin	Jeremy Trembley
7.6 Appendix F	Tyler Guertin	Nicholas Grumski
7.7 Appendix G		
7.7.1 John Bergendahl – WPI Civil Engineering	Nicholas Grumski	Tyler Guertin
7.7.2 Paul Mathisen – WPI Environmental Engineering	Nicholas Grumski	Abigail Berube
7.8 Appendix H		
7.8.1 Anonymous Engineering Expert	Tyler Guertin	Zachary Rivernider
7.8.2 Nicholas Bertozzi – WPI Robotics Engineering	Zachary Rivernider	Abigail Berube
7.8.3 Mark Patterson – Northeastern Robotics Department	Nicholas Grumski	Drake Hamblin
7.9 Appendix I	Abigail Berube	Tyler Guertin
7.10 Appendix J	Zachary Rivernider	Abigail Berube
7.11 Appendix K	Zachary Rivernider	Abigail Berube

TABLE OF CONTENTS

1 INTRODUCTION

The impacts of pollution, originating from a variety of human activities, have resulted in immense and increasing damage to the environment around the globe. Natural ecosystems have lost about half of their original surface area and the biomass of wild mammals have fallen eighty-two percent since the start of recorded history (Watts, 2019). Furthermore, one third of marine species and reef forming coral that exist today are at risk of extinction (Watts, 2019). A prominent source of pollution causing harm is oil-based water pollution. Growth in the oil industry has led to an expansion of oil infrastructure through waterways and has added a heightened risk for oil leakage in the environment as well as major oil spills (Yim & Short, 2017). Spills have been proven to harm organisms in a variety of tidal and subtidal environments (Jackson et al., 1989). Oil-based water pollution has devastating effects on the environment that cannot be ignored.

The Baltic Sea is one of many areas that are at risk to the dire environmental consequences of oil extraction. A combination of oil pipelines bursting, accidental tanker ship collisions, and intentional illegal dumping has caused a constant threat to the marine environment (Krek et al., 2021). There have been 788 detected oil spills through satellite imaging over 17 years since 2004, a conservative estimate due to weather patterns hiding oil pollution and the delay between captured images (Krek et al., 2021). The exact amount of oil that is leaked into the water supply through human actions has not been quantified, but it is large in magnitude. In this area, chronic oil pollution as a result of washing out and dumping fuel tank remnants into the Baltic Sea is the leading cause of water contamination (Krek et al., 2021). It is estimated that 1750-5000 tons per year of pollution comes from this intentional releasing of oil products (Kostianoy, 2020). This pollution of the water supply poses a devastating threat to the Baltic Sea and elicits a need for increased oil pollution detection through increased naval surveillance. Shown in Figure 1 is an example of the detrimental effects of oil-based water pollution. The illustration portrays heavily oiled pelicans found on the coast of Louisiana following an oil spill in the Gulf of Mexico.

Figure 1: Example of Oil Pollution on Pelicans. Note. Gulf-Oiled-Pelicans-June-3-2010 [Photograph], by International Bird Rescue Research Center, 2010, Flickr (https://flickr.com/photos/49788193@N03/4670207222). CC BY 2.0.

Developing capability to survey more frequently in water aids in earlier detection of oil spills and oil leaks related to remote pipelines and rigs which could prevent the exacerbation of already developing pollution issues. The oil industry has been exploring several diverse ways for increased spill detection. One of the main ways of detection is using autonomous underwater vehicles (AUV) that swim through the water towards pipelines and test the water for leaks and pollutants, while mapping the areas in which they are detected (Kato et al., 2017). Other variations of underwater vehicles have been developed, each with their own set of advantages and disadvantages. Specifically, in the Caspian Sea which has similar oil-based issues, a group of students at Worcester Polytechnic Institute assessed an AUV that was purchased by Astrakhan State University and conducted research on its potential applications. It was concluded they would not use the AUV for oil spill detection and instead for shipyard inspection due to the vehicle not having applicable sensors, the cost restraint to implement higher precision instruments, and the cost that came with human supervision (Lombardi et al., 2016). Visual examination of pipelines is another method currently used; however, this method poses significant weaknesses in its overall efficiency and effectiveness because it is more costly than most and requires a much longer amount of time to complete the survey. More crude methods included using helicopters and airplanes, which were less precise as they are mostly visual and do not actually test for oil in the water itself. It is also a method that requires a great deal of petroleum fuel consumption. These methods all have significant limitations and need to be mitigated.

Oil pollution can be identified through physical and visual analysis by either humans or machines, but these methods cannot be seen as equally viable. Oil pipelines are typically examined by humans using boats and less direct methods, such as water sampling, to determine possible leak locations (Zengel et al., 2022). Humans can only examine to a particular extent. Drones in the form of aerial vehicles and amphibious vehicles can be useful for looking at more widespread problems in oil pipelines, especially for underwater applications. Direct data collection from different sensors can provide more specific information pertaining to the locations and source of oil pollution. Likewise, autonomous vehicles provide a further advantage because of their versatility in examining large areas as compared to humans, providing more area coverage (Kato et al., 2017). This allows for oil detection in a variety of locations with both pipelines and natural oil sources, such as that of the Oil Rocks Settlement previously studied by Bayromov and Buchroithner for the development of oil detection algorithms. Likewise with the presence of major pipeline systems within the Baltic Sea, spills in this area need to be detected quickly to reduce widespread damage (Holstein et al., 2018). A system of Autonomous Aerial-Aquatic Vehicles (AAVs) could be capable of detecting oil among a myriad of other pollutants. Consequently, an AAV that can meet the challenge of oil detection by autonomous sensing will make detection quicker, easier, and with less human intervention required. This project will provide future developers with resources and considerations specifically on constructing AAVs, as there was a lack of concise information on these topics. This will allow for AAVs to be developed with more pointed insight.

The goal of this project was to weigh design considerations, provide a concept design, and gauge feasibility for a sustainable AAV that can survey the Baltic Sea and detect oil pollution. This was done through conferring with environmental groups, such as HELCOM, The United States Coast Guard, and environmental professors to assess issues response teams face with current technology for detecting oil. To reveal concerns with materials that would compose an AAV, environmental engineering; sustainability; and material science experts both domestic and abroad were consulted. Their insights set a baseline on design constraints by detailing materials that should be avoided in AAV construction. From here, technical data about ideal sustainable materials, sensors, and mechanical systems was gathered from engineering experts for a complete understanding of desired characteristics that can constitute the system. Our analyses and conclusions have been compiled into this comprehensive document to be referenced when designing sustainable AAVs to survey large bodies of water.

2 BACKGROUND

In this chapter, we begin with a brief overview detailing the issue of oil-based water pollution and its composition, revealing the growing impacts to marine ecosystem on a long- and short-term basis and how the issue relates to the Baltic Sea. Next, we evaluate the strengths and shortcomings of the current technologies being implemented to detect water pollution that are incorporated in modern aerial and underwater uncrewed vehicles. This is followed by a background of the design constraints that exist when developing a vehicle that could traverse more than one environment. We conclude the chapter with an introduction of power sources, outlining important electrical characteristics and the underlying limitations of various renewable power sources.

2.1 Oil Contamination in the Baltic Sea & the Environmental Impact

Oil-based contaminants, such as petroleum, are composed almost exclusively of hydrocarbon compounds. These compounds are composed of hydrogen and carbon molecules and can be in either in chains, cyclic groups, or aromatic groups, as shown in Figure 2 (Rossini, 1960).

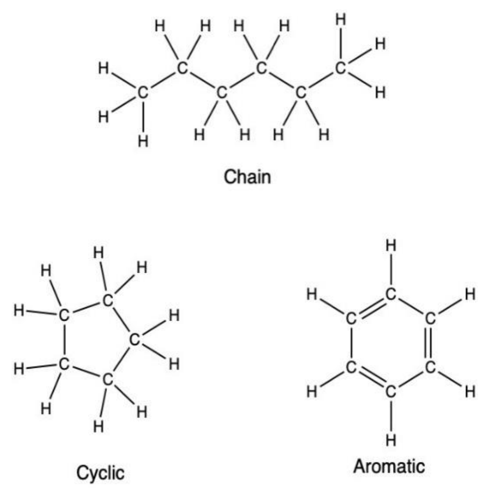

Figure 2: Structural visualization of the hydrocarbons found in petroleum. Note. Author's own work.

In petroleum, along with hydrocarbon you may find naphthenic acid, nitrogen, and sulfur compounds among others which can cause harm to the ecosystem as well (Vandana et al., 2022). What makes hydrocarbons such a messy pollutant in water, is that they have low solubility in water and thus highly hydrophobic (Kronberg, 2016). This means they do not mix with the water they are present in, leaving the contaminants fully intact and difficult to clean up. Therefore, the composition of oil makes it dangerous to the environment if spilt into a body of water during transportation or extraction. Within the last few decades, the oil industry has grown significantly leading to an increase in naval transportation of fossil fuels and a heightened risk of hazardous incidents (Yim & Short, 2017). Whereas an oil spill and tanker ship collision are the common face of oil-based water pollution visible in the media, water contamination also stems from smaller sources. Most of the oil that is discharged into the environment occur through tanker ships "discharging ballast water from oil tanks, leaking pipelines or engine oil disposed of down sewers" (Farmer, 1997). The expansion of the oil industry during the past few decades has chronically increased the concentration of oil in the world's bodies of water and poses an existential ecological threat to the environment.

2.1.1 Environmental Impacts of Oil-Based Water Pollution Through Animal Life

The increased risk of oil related water pollution is detrimental to the environment by creating immediate life-threatening consequences for native animals and catastrophic ecological long-term effects. Demonstrated within natural science studies, directly following an oil spill, the oil in the water creates a thin layer on the surface that smothers seabirds, entraps and kills small sea creatures and poisons larger marine animals through oil inhalation or sticking to an animal's gills (Jernelöv, 2010). The exact extent of the damage depends on the size of the population and migratory habits, but oil can kill seabirds on contact by removing the insulative property of their feathers and by poisoning them through ingestion (Piatt et al., 1990). Oil based water contamination proves deadly to marine life and causes a negative impact on their its ability to survive and flourish.

While the more obvious effects on animal life occur immediately and have some remedies, there are also underlying long term results that severely damage ecosystems. After an oil spill, in areas with rocky and shallow shores, there have been noticeable increase in green algae due to "oil poisoned snails and other algae grazers" that take time to reclaim the environment, preventing native organisms from re-settling (Jernelöv, 2010, p. 356). Green algae, if left to grow uninterrupted, can be harmful to organisms and thus harming the ecosystem. Furthermore, certain animals within the ecosystem were poisoned, offsetting the prey versus predator relationship causing an overabundance of a certain animal. Ecosystems are naturally in static equilibrium; discrete animals exist in balanced proportions that symbiotically create a habitable ecosystem (Withgott & Laposata, 2014). The overpopulation that occurs in the wake of an oil spill creates a long-term effect that requires time for an environment to return to equilibrium.

2.1.2 Chronic Pollution in the Baltic Sea

The Baltic Sea is a mostly enclosed body of water that touches nine European countries including Russia and Germany, shown in Figure 3.

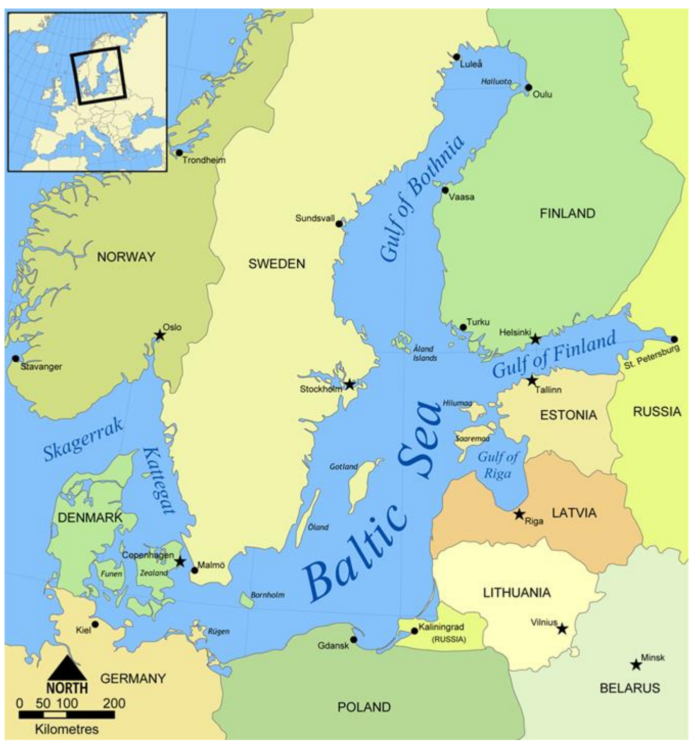

Figure 3: Geographic Map of the Baltic Sea. Note. Map of the Baltic Sea. [Photograph], by NormanEinstein, 2006, Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Baltic_Sea_map.png). CC BY-SA 4.0

It is an incredibly busy body of water that has forty oil terminals and large ports as well as nine percent of the world's trade and eleven percent of the world's oil transportation (Krek et al., 2021) A large contribution of oil that enters the Baltic Sea comes from intentional discharges along the main travel routes in the water. Between June 2004 and December 2020, satellite images were able to detect 788 oil spills in the area (Krek et al., 2021). This illegal dumping of oil is dubbed "operational" discharge and is responsible for chronic oil pollution of the Baltic Sea (Krek et al., 2021, p. 1). These operational discharges are typically from cleaning of fuel tanks and releasing the contents of the wastewater into the sea (Kostianoy, 2020). Continuous pollution from these active ports and naval traffic proves to be a serious threat to the environment. Contamination of seawater, shores, sediments, and beaches in this area stays prevalent from several months to several years after a spillage occurs (Kostianoy, 2020). Repeated intentional oil dispersion in the Baltic Sea represents a substantial portion of oil contamination in this body of water. Since the Baltic Sea is mostly enclosed, there exists irregular stagnant water exchange with the Atlantic Ocean by nature of the channels (Ehlin, 1981). This confined area implies that most of the oil that is spilling into this body of water is staying sedentary in the body of water. There exists a need of further environmental protection strategies to protect this area from further contamination from oil.

2.2 Current Oil-Pollution Detection Technologies with Robotic Vehicles

When detecting oil in the ocean there are two types of locations: dumped out in the open water or leaking from a source, almost always a pipe or duct. Many robotic vehicles today focus their attention on the source of the leak, ignoring scanning open water for slicks. Funded by the Grant-in-Aid for Scientific Research of Japan Society for the Promotion of Science, SOTAB-I was designed. It is an autonomous underwater vehicle (AUV) that swims towards suspected pipeline leaks and tests the water for pollutants, eventually mapping the plume of oil (Kato et al., 2017). With this information, the direction and spread of oil can be known and constantly tracked, which leads to a more informed response. SOTAB-I is equipped with "...tracking, orientation, communication, and surveying sensors; and an acoustic emergency weight drop system" (Kato et al., 2017, p. 389). Shown in Figure 4 is a visual depiction of how the SOTAB-I can detect and track an oil leak.

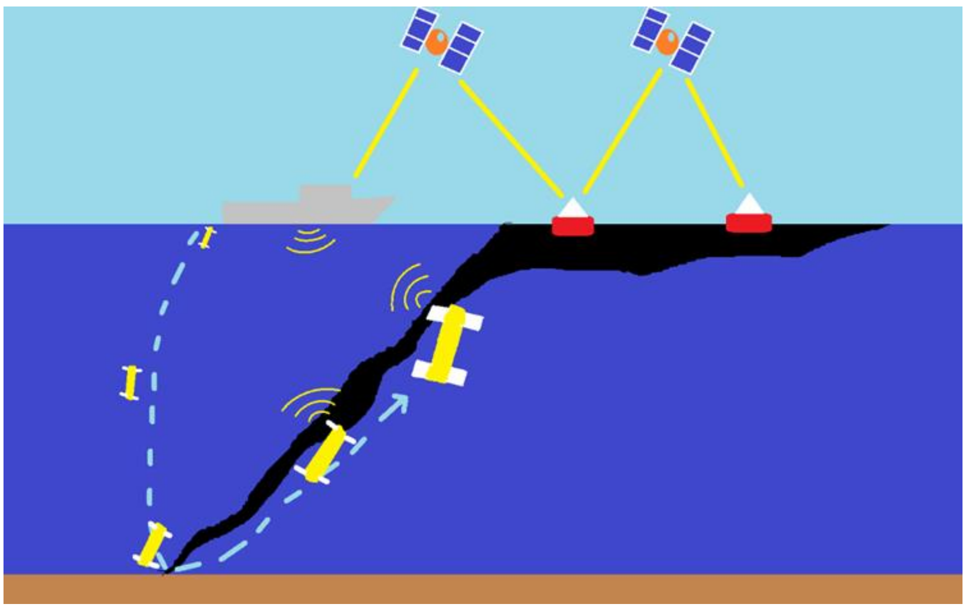

Figure 4: An artist's rendition of the SOTAB multi-robot system detecting and tracking an oil leak. SOTAB-I depicted in yellow on left and SOTAB-II depicted in red on right. Author's own work based on figure 1 from (Kato et al., 2017).

Once the plume of oil reaches the ocean surface it is out of the scope of SOTAB-I. This is where SOTAB-II comes in, an immobile buoy equipped with an oil sensor and communications back to a land base or mothership (Kato et al., 2017). In Kato's design, a fleet of these buoys would be distributed amongst a detected oil slick.

2.2.1 Human Reliance on Current Oil Detecting Robots

While the SOTAB multi-vehicle system allows for the complete tracking of an oil leak, it still requires humans to sail out and sometimes operate robots in targeted areas, meaning that this is not an autonomous system. An attempt by students at Worcester Polytechnic Institute in 2016 aimed to assess the feasibility of using a remotely operated vehicle called GNOM to inspect oil pipelines in the Caspian Sea, but did not find promising results. The training required for humans to detect tiny cracks over kilometers of pipeline is too intensive to be acquired quickly, limiting scalability (Lombardi et al., 2016). The students found that, while operating the robot eight hours a day and assuming perfect conditions, the robot would be able to survey ~50 km/day (Lombardi et al., 2016, p. 14). The survey rate can be improved if the number of hours worked is expanded, but this requires more employees to keep the inspection running while regular inspection already requires massive vessel and team size. (Rumson, 2021, p. 1). A collaborative project between the Brazilian Institute of Robotics and a robotics group at the University of Bremen, Germany made an advanced development towards this goal resulting in FlatFish, a pipeline inspection AUV that exists entirely underwater, recharging in an underwater docking station (Albiez et al., 2015). While FlatFish is still being developed, it is projected to be easily deployable by an oil rig or land station by using the pipeline to guide its autonomous search.

2.2.2 Environmental Monitoring

To make communication a worthwhile endeavor, the aerial aquatic vehicle (AAV) must be able to take sensor readings of the surrounding environmental properties. Developments in machine learning have expanded autonomous aerial vehicles' perception of the environment so that it can quickly detect anomalies. With the AAV's ability to survey the world from a high vantage point, data for several environmental factors can be recorded, such as land and animals. For example, machine learning models have shown the ability to detect the location and type of animal from aerial images with sufficient accuracy (J.-S. Liu & Li, 2021). The data that comes from this model could be used to track animal patterns and alert to changes in wildlife behavior that signal localized changes. Additionally, other models have been able to segment and classify different terrains and land cover within an image (L. Ma et al., 2019). Data from this model can be combined with the previous ones to further build a profile of animal behavior. Collecting data towards animal behavior is important because changes in expected animal behavior often signals a change in the environment, such as a disaster. Machine learning algorithms have also proven able to detect oils on water surfaces from red, green, blue spectrum (RGB) images with over 70% accuracy (Mehdi et al., 2022). This is instrumental in the ability to detect the location of oil spills. Once oil spills are found from the air, a drone can go into the water and search for a cause. These models will prove to be even more useful when combined with diverse types of sensors.

2.2.3 Photographic Techniques

With a myriad of technologies available for implementing controls into environmental surveillance drones, it is helpful to consider specific sensors or sensing techniques that can be applied. Using specific sensors and photographic techniques allows properties to be pinpointed within images and data. This goes beyond the scope of more typical consumer drones, which may implement a camera, but do not provide the capability required to examine pollution in the ocean, due to their poor flight range and communication abilities. Commercial use of cameras is common in military and aerial photography applications, but has also been increasingly used in applications for structural monitoring, such as in the case of bridge supports. Underwater target entities can be examined and observed at close range and photographed to gather some detailed information on structural stability (Noguchi & Maki, 2021). Commercially available cameras have seen use in detecting microscopic surface cracks, which yields valuable information for surveying an oil pipeline, where small cracks and leaks may go unnoticed (Y. Liu et al., 2022). An Infrared camera could also be employed to examine the temperature distribution, which can detect oil in marine environments (Y. Liu et al., 2022). Cameras can be implemented in a variety of methods to detect oil pollutants in bodies of water.

Certain cameras can cause problems underwater since cloudy water cannot be easily detected or avoided. Cloudy water blurs photographs, which would thus be useless if collected. Some devices, such as the water loupe—a device filled with water as an extra "lens"—can help solve this problem (Yang et al., 2016). While these methods are useful, cameras can be aided by varying types of electrical sensors. Sensing capabilities for underwater detection of surfaces and viewing structural impurities should be considered due to their versatility in determining the locations of obstacles and the dynamic properties of the vehicle. Sonar has long been used in watercraft for various applications in object detection. Sonar itself is imperative to underwater vehicles as it can gather data to evade obstacles when incorporated into a control system (Noguchi & Maki, 2021). Some other methods—such as pressure sensors—can determine hydrostatic force and thus, depth. Assuming autonomy, these capabilities would help a vehicle to perform more effectively without human intervention. The selection of materials specific for environmental applications is also an important part of designing for autonomy.

2.3 Multi-Environment Engineering Challenges

Gas and liquid are vastly different mediums and special considerations are needed so that a single vehicle can operate in both effectively. Water is about 800 times denser than air creating a significant impact force when transitioning across domains that requires considerable structural strength and impact resistance (Y. Gao et al., 2021). These design considerations also extend to the propulsion mechanism where Zongcheng Ma (2018) discovered that it is dangerous for high-speed propellers to hit the water. The aerial-aquatic vehicle constructed in this study had separate propulsion systems for each environment. Zongcheng Ma (2018) found that spinning aerial propellers contacting the water or spinning above-water aquatic propellers caused imbalances of power, ultimately leading to failures when transitioning between mediums (Z. Ma et al., 2018). When maneuvering between environments, the change in density require distinctive design considerations so that the vehicle can withstand the additional structural and impact forces.

2.3.1 Geometric Design & Fluid Mechanics in Both Environments

The shape of an air or hydro-craft is especially important to determine the load-carrying and dynamic capabilities of a vehicle. Any vehicle in air must follow the general rule of lift being greater than or equal to the weight, and thrust being greater than or equal to drag to generate enough lift. In water, buoyancy and weight must be considered along with the hydrodynamic properties of the vehicle (Weisler et al., 2018). Hydrodynamics is a matter of density of the craft in comparison to water, “the density of the medium implies that any moving body will experience significant resistance” (Tan & Chen, 2020). Several options are available for a flyable and submersible geometry. For example, a quadcopter may be able to navigate both in water and in air, but the thrust convention must be changed due to buoyancy (Tan & Chen, 2020). Wings may also be used in both air and water scenarios. It can be noted that planes and submarines alike use hydrofoils and airfoils to change course in water and air. However, the convention differs as an aircraft has large wings that maximize lift and minimize drag, whereas, on a submarine, hydrofoils are used to elevate and cause the vehicle to dive. These two terrains exhibit opposing characteristics, where hydrodynamics is referred as the reverse convention of aerodynamics (McGlynn, 2013). These differing uses for each case can introduce inconsistencies between air and water, where the air is considerably less dense than water, meaning that more power is needed to move in water than in air, regardless of geometry.

2.3.2 Aquatic & Aerial Material Applications

Given that an aero-amphibious design is desired to comprehensively survey a body of water for oil pollution, the effects of both air and water on the structure must be considered. These factors include resistance to different failure modes, waterproofing, and corrosion resistance. For lightweight structural applications specific to the aerospace industry, aluminum alloys have been used. Similarly with underwater vehicles, selecting corrosion-resistant, light, and strong materials such as aluminum 6061 for internal and external portions of the body are preferred (Ibrahim & Nor, 2011). It is important to note that such materials are not ideal for the “skin” of the vehicle, as corrosion often occurs on the surface of metals in contact with water and air in succession. Composites can also be used for these applications and can even replace alloy parts in some circumstances (Zhang et al., 2018). Some composites are known for failing under hydrothermal aging because of moisture's effect on the internal structures of the material, leading to catastrophic failure (Mayandi et al., 2020). Failure risk can be reduced if a waterproof coating is applied, which is important to pair with material selection to improve or eliminate moisture retention issues. Some coatings produce a more desirable wetting surface angle, the factor that determines a successful hydrophobic performance. Another implication to be considered of any material entering water is the possibility of biofouling, which has the potential to worsen interactions with the surface due to creation of an artificial bio-surface, causing a change in the fluid-surface interaction of a material. (Xia et al., 2021). This could also have a negative effect on the structural properties of the external surface of a vehicle.

Regarding the more general topic of applied materials, material selection for an AAV application must allow the capability of surviving structural loads in both air and water. An AAV will need to sustain both high pressures underwater, and due to dynamic movement, as well as low pressures high in the atmosphere. Different modeling methods can be used to determine the structural stability of a given material. For example, if an underwater vehicle were to be modeled as a typical cylinder, the pressure of water on the hull would have the ability to cause failures due to the buckling strength of an object (Shen & Pan, 2021). In the case of buckling, hydrostatic pressure forces at a given depth are of the biggest risk, but other stressors such as those from drag and dynamic pressure underwater may also contribute to failure. A given material for an AAV would need to undergo rigorous stress analysis to determine the ability of the AAV to survive the force of drag caused by a dynamic pressure (Koti et al., 2021). Analyses can be done through experimentation with different geometries, which can be a key step in identifying the risk of failure due to structural forces in both mediums.

2.4 Renewable Power Source Characteristics

Due to the advances in technology over time, engineers have discovered various methods of storing energy for mobile applications which have distinctive characteristics that can affect performance. Two critical considerations that will be analyzed across the various power sources are energy density and specific energy. For many batteries, these are the most critical to design performance, where energy density can be defined as the electrical energy that can be stored per unit volume or watt-hours per liter ($\frac{WHr}{l}$) and specific energy is the amount of electrical potential a battery can store per unit mass or watt-hour per kilogram ($\frac{WHr}{kg}$) (Jha, 2016, Chapter 1). These sources define how much weight (specific energy) and volume (energy density) that they consume compared to how much power they hold.

In addition to the specific power and energy density, there are also logistical concerns that can determine the efficacy of each fuel cell. A battery is composed of three fundamental characteristics: energy performance, power performance, and lifespan; where an increase in any one attribute causes a decrease in the other 2 (Jha, 2016, Chapter 1). Hydrogen and oxygen fuel are not limited by these three fundamental characteristics and do not suffer from a lifespan issue, outside of regular maintenance. The perfect power supply does not exist for every application and therefore must be carefully chosen based on the limitations of the system and its environment.

2.5 Conclusion to the Background

We investigated the effects of oil-based water pollution on the Baltic Sea, describing a measurable and dangerous threat to a body of water saturated with oil-related resource extraction operations. This threat to the environment is characterized by the poisoning and subsequent death of many aquatic creatures and the offset of various balanced oceanic ecosystems. Furthermore, these detrimental results have lasting consequences, revealed in endemic populations and oceanic areas that show lasting high toxicity concentrations. Additionally, the current design challenges and technology was analyzed to illustrate how robotic vehicles (such as drones) are being used to aide in the detection of oil contamination. It was also found that the current methods require human intervention, are limited in the environment they operate in, and can only identify a specific contributor of oil pollution.

We also examined the design challenges that exist for a vehicle to maneuver more than one environment on a mechanical and electrical level. Mechanically, the transition between mediums introduces significant structural forces, the salt water corrodes materials, and the vehicle must be analyzed from a hydrodynamic and aerodynamic point of view. Electrically, it was concluded that power sources are categorized based upon the amount of total work they can generate compared to their size and density. Furthermore, sustainable power sources possess diverse traits that demonstrates there is no universal option, but a best fit based on its application.

Based on our research, we identified the problem space that engineers face in designing multi-environment autonomous vehicles and the ecological consequences of water-based oil pollution. We aimed to conquer these challenges by designing a conceptual vehicle that can detect contaminants in the open water and operate in both aerial and marine environments. Additionally, our concept vehicle will be able to construct a 3D map of the pollution to better inform response teams' efforts. Each design consideration discussed will assist others to construct a road map for their vehicle based on our in-depth findings on subsystem functionality. To protect the environment, the vehicle must be sustainably designed and not interfere with endemic populations. Several methods of data collection were implemented to accomplish these underlying goals that drove this project.

3 METHODOLOGY

The goal of this project was to deliver a collection of considerations for the design of an Autonomous Aero-Amphibious Vehicle (AAV) for aiding environmental protection professionals in early detection of oil spills in the Baltic Sea. To accomplish this goal, four objectives were followed:

1. Assess issues with the current technology used by response teams for detecting oil spills.

2. Identify limiting aspects of the AAV design to avoid impacting the surrounding environment during operation.

3. Assess implementation requirements for various subsystems on AAV's in air and water environments.

4. Investigate design considerations for developing an AAV that surveys the Baltic Sea for oil pollution.

Our project concentrated on a comprehensive discussion of subsystem needs that will aid in the future production of an AAV to assist in oil spill detection. We investigated requirements for AAV subsystems, performing our study through a combination of interviews, literature reviews, and engineering analyses. Interviews were a combination of preplanned questions and freeform discussions and were conducted with professionals in the fields of pollutant monitoring, environmental engineering, aeronautical engineering, and robotics engineering. While our work will help develop a solution for the Baltic Sea, it will have broader implications for operationalization in similar environments across the globe.

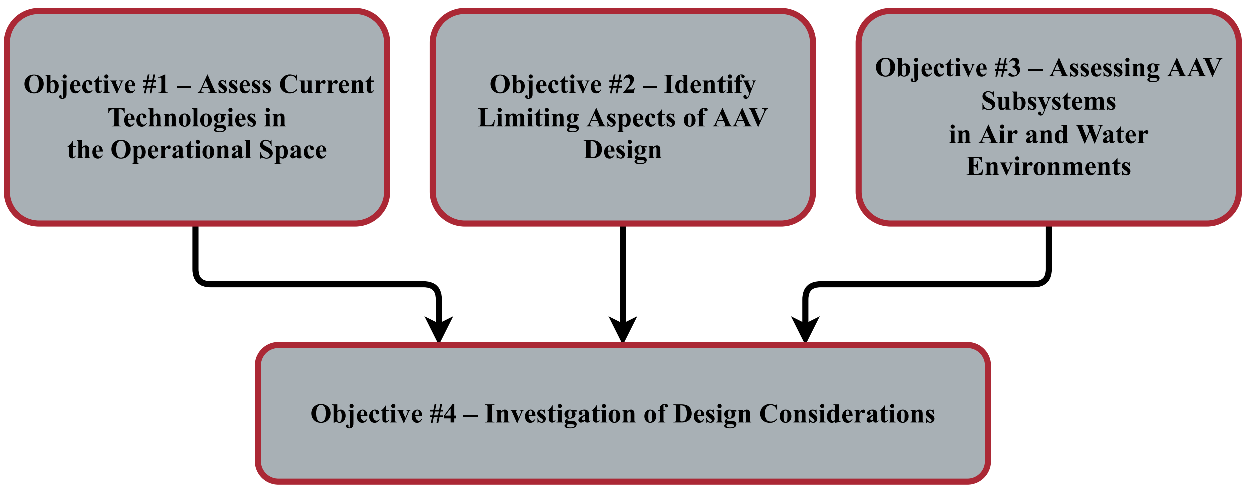

Figure 5: Flow chart showing a visualization of the four objectives fulfilled in this project. All objectives lead to a supplemental investigation of data collected.

We provided interviewees with our main interview questions before we met. We followed the interview ethics guidelines as described in Appendix A. We started the discussion with the interview preamble as in Appendix B and had the interview review and sign a consent form (found in Appendix D). At the end of each interview, we thanked the participants for their time and their participation in our study. The prepared questions we asked can be found in Appendix C.

3.1 Assessing Current Technologies in the Operational Space - Objective #1

Our first objective was focused on assessing the current technologies that are used by response teams for detecting oil spills, particularly focusing on the challenges and limitations of their use. We conducted semi-structured interviews with governmental agencies who specialize in identifying oil contamination in bodies of water and an academic professor with experience with oil spills in the Baltic Sea. A flow chart of this objective is shown below in Figure 6.

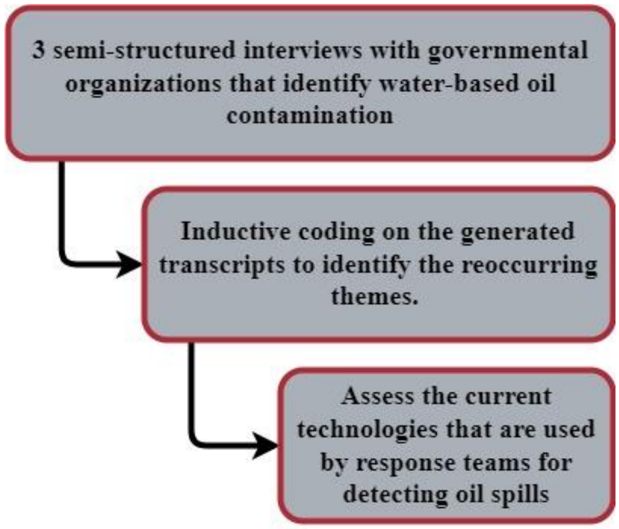

Figure 6: Flow chart showing a visualization of our first objective, going from interviews to analysis to conclusions

The aim of these interviews was to identify the important themes related to the current detection of oil spills and their problems and challenges. Furthermore, we focused on outlining the environmental risk that oil-based water pollution has on bodies of water. The transcripts of these interviews were thematically analyzed to outline the limitations that exist in oil spill detection and the technological issues that plague response teams in identifying oil spills.

3.1.1 Interviews with Experts in the field of Oil Pollution Surveying and Identification

We conducted 3 interviews with experts who specialize in surveying and protecting the ocean. The motivating questions for this objective were:

1. How do experts currently survey the ocean for signs of oil-based water contamination?
2. How do current technologies work to locate these spills?
3. What specific factors exist for experts that impedes the timely detection of oil spills?

Initial communication was through targeted emails to governmental, intergovernmental, and academic organizations with specialization in identifying oil spills in bodies of water. All participants had the option for a recorded interview online or in-person with appropriate safety precautions. For online interviews, a trusted online client like Microsoft Teams, Skype, WebEx, or Zoom was offered based on the interviewee's preferences. For in-person interviews, the interviews took place in the interviewee's office or, if preferred, a more neutral space. The interview party consisted of 3 members of the team. Team responsibilities were split with 1 member serving as the primary interviewer, 1 member as the designated moderator, and the last member as a scribe. The primary interviewer was responsible for asking the structured and follow-up questions. To help the primary interviewer, a moderator focuses solely on forming their own follow-up questions and maintaining the scope of the interview. Scribes focused on drafting notes during the interview to augment our analysis and transcripts were generated by either Otter.ai, Zoom, or Microsoft Word. The interview questions for each interview are found in Appendix E.

3.1.2 Inductive Coding and Development of Codebook

The analysis techniques employed in this method were based on the detailed notes produced by the scribes and the autogenerated transcripts with inductive coding. The manufactured transcripts were coded deductively based upon the several factors that affect oil-based water pollution and the current limitations that exist in their detection. The corresponding codes are noted in the codebook, found in Appendix F. The analysis from this objective was supplemented with related data that was acquired from other objectives. With these coded transcripts and the resultant codebook, the team drew final conclusions on the underlying themes that exist across the interviews.

3.2 Identify Limiting Aspects of AAV Design- Objective #2

Our second objective focused on identifying important limiting aspects of AAV design to mitigate potential harm to the environment. In identifying these aspects, we conducted expert interviews. Specifically, we to investigated how materials, sensors, propulsion systems, and other facets of drone design can affect the environment to gain an understanding of factors to consider when designing an AAV. Interviews were conducted with environmental engineers and sustainability engineers to get their input on environmental issues with drone design. The aim of the interviews was to serve as a basis for a literature review that was completed in a future objective. We compiled all our data from this section using deductive coding to identify design constraints to avoid causing harm to the environment.

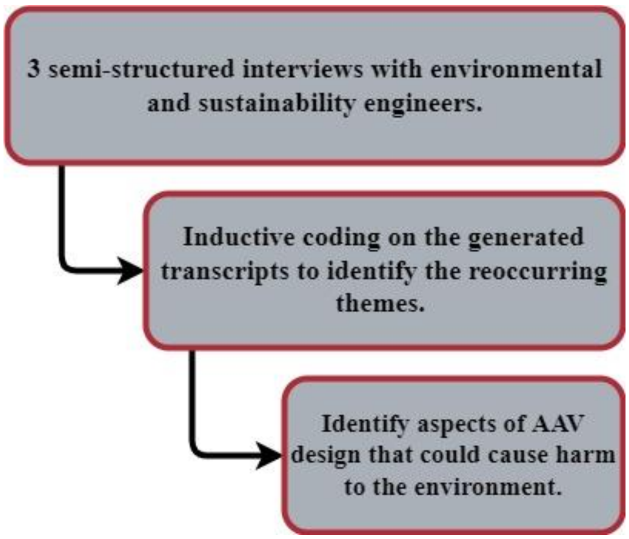

Figure 7: Flow chart showing a visualization of our second objective, going from interviews to analysis to conclusions

A visualization of this objective is shown in the above figure, which details analysis methods and shows the flow of Objective 2.

3.2.1 Interviews with Professionals Familiar with Sustainable Practices

Our team conducted a series of semi-structured interviews with 3 experts within the field of environmental and sustainability engineering to focus on design aspects of an AAV that negatively affect the environment. We focused on these 3 topical areas:

1. What materials cause harm if used in aerial and aquatic environments over time?
2. How do various propulsion systems affect marine and aerial environments?
3. What factors limit the use of material, sensors, and other AAV design features?

Initial contact with interviewees was made over email to schedule a meeting time and method. As mentioned in the previous objective, interviewees had a choice between an in-person interview or over a video conferencing method such as: Microsoft Teams, Skype, WebEx, or Zoom. We had 3 team members participate in interviews: a primary interviewer, a mediator, and a scribe. The primary interviewer asked the prepared questions and the mediator focused on creating follow-up questions. The interview questions for each interview are found in Appendix G. All the while the scribe created a selective transcript, writing down quotes that served to be important, as well as summarized the answers of the interviewee. If our interviewees allowed it, we also recorded the interview to review the conversation later and used an auto-transcribing tool.

3.2.2 Inductive Coding and Development of Codebook

We examined our interview notes to develop themes between the scribe's records and the interview transcript in each individual interview as well as across multiple interviews. We used deductive coding methods to create the themes. Our codebook (found in Appendix F) was created by looking at the themes we noticed in the interviews. From this we developed a knowledge of materials, sensors, and other design aspects that could affect the environment negatively.

3.3 Assessing AAV Subsystems in Air and Water Environments - Objective #3

Our third research objective was to assess requirements for implementing different subsystems of AAVs in air and water environments. Design constraints were identified to enable a vehicle to maneuver in both aerial and naval surveying applications for the specific purpose of oil-based pollution detection. This was primarily executed through interviews with expert engineers who are experienced with aerospace and mechanical system design. A flow chart of this objective is shown below in Figure 8.

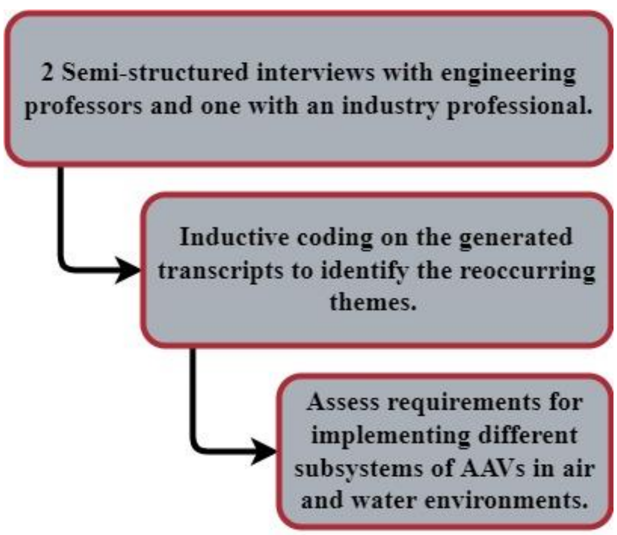

Figure 8: Flow chart showing a visualization of our third objective, going from interviews to analysis to conclusions

Identifying materials, sensors, and propulsion systems are imperative for creating a working drone system specific to the application of detecting oil pollution. Each interview was focused on gathering information on design applications in the previously described areas to show examples of different AAV, UAV, or Unmanned Underwater Vehicle (UUV) designs and systems. Notable properties investigated through this objective were strength, aerodynamics, hydrodynamics, and sensing capabilities for pollutant detection.

3.3.1 Interviews with Engineering Professionals

Interviews were done with aerospace engineering and robotics engineering experts, specifically those with knowledge of autonomous drones that operate sustainably. Interviews were focused on the following topical areas:

1. How can material and sensor integration differ in air and water vehicles?
2. What sensors are recommended for detecting oil in water?
3. What design specifications should the AAV have for multi-environment use?

Experts with research experience in the field of AAV's and UAVs were asked to further elaborate on the technical aspects of their designs, and how several factors may have played into their designs. To integrate previous objectives, the role of sustainability on material and sensor system designs was inquired upon. One industry professional and two academics were interviewed to get different viewpoints. From academic settings, interviews were conducted with Nicholas Bertozzi and Mark Patterson, who have respective backgrounds in robotics engineering and underwater robotics. As for industry professionals, the one interviewee wished to remain anonymous, but has a strong background in the design of rotorcraft and critical systems associated with it. The interview questions for each interview are found in Appendix . These interviews were coded across all the objectives, but information from objective three was targeted in these. Interviews consisted of three team members, one of the three team members was responsible for primary questions, with one moderator, and a scribe. The primary interviewer was focused on asking pre-determined questions and follow-ups. The secondary interviewer served as a moderator and kept questions on track with the desired scope of the interview. Lastly, the scribe kept a detailed note of the technical and informational aspects of the interview.

3.3.2 Inductive Coding and Development of Codebook

When interviewing experts, context on various aspects of power, sensor, and mechanical systems was collected to inform design choices. Analysis began during the interview itself, where follow-up questions were directed to point towards desired topics. Afterward, transcripts were organized and used for data collection. Deductive coding was used to find trends between interviews on material and sensor types in respective expert areas for air and hydro craft design. The coding system used is shown in Appendix F along with definitions. Codes were formulated based on the information gained from interviews, and highlighted important themes that were identified by the team and developed based on professional opinions. Coding each interview consisted of a three-step process of reviewing transcripts, identifying pertinent information, and then coding each block of information. Related data that was presented in previous objectives was also considered to be more intuitive than just a technical perspective. A library of articles compiled from literature reviews was made in Zotero to assist in making concrete conclusions based on the above analyses.

3.4 Investigation into Optimizing Design Considerations - Objective #4

Our fourth and final objective focused on combining the data from previous objectives and pursuing additional analysis to create more concrete results. After the interviews, there were gaps in our knowledge, suggested journal articles, and recommended topics to explore. As a result of this deficit of information, the interview data was combined with various peer-reviewed journal articles and engineering software. Journal articles offered the ability to do pointed in-depth research on data from the interviews and supplement statements made during interviews. Additionally, engineering software offered the ability to model the static and dynamic properties of a system and provide simulated, quantifiable analysis. Continued technical analysis allowed for a supplemented justification of the data gathered from the interviews and as a result, more concrete conclusions.

3.4.1 Literature Analysis of Academic Articles

After completing interviews with experts for each objective, interviewees provided recommendations for both materials and technical systems that they believed would be ideal to be theoretically implemented on an AAV, as well as journal articles to investigate further. These recommendations were then used as a point of reference for in-depth research on the topics and to fill in any gaps of knowledge. Further research was completed with both qualitative and quantitative details being considered to have a complete technical understanding of the subsystems. This additional in-depth research provided us with a more objective conclusion based on proven data from literature sources. The additional research removed any subjectivity that could exist in an interviewee's assertion and relate the statement to peer-reviewed conclusions.

3.4.2 Software for Engineering Analysis

Using various engineering software, we were able to further investigate different subsystems that were considered through literary analysis and previous interviews. Software was used to assist in the evaluation of materials to determine maximum efficiency under both stress and operating temperature. Furthermore, software was used to evaluate the aerodynamic and hydrodynamic coefficients for components of possible AAV geometries. These engineering tasks were accomplished through Computer Aided Design (CAD) in Solidworks, stress and thermal analyses in ANSYS Mechanical, and fluid flow analysis in Solidworks Flow Simulation. By implementing this software, we were able to undergo complex quantitative analysis and supplement the assertions pertaining to these more technical aspects of design.

3.5 Evaluation Justifications & Limitations of Used Methods

The primary methods of data gathering were through interviews with industry experts as well as literature reviews done to analyze previous research on each objective. There are several reasons we believe these methods to be the most efficient as, despite their limitations, much meaningful information could be extrapolated for use in our example designs.

3.5.1 Justification for Semi-Structured Interviews with Professionals

The semi-structured interview method was chosen for its versatility and the ability to ask questions along a common theme. While gathering information, it was imperative that interviews could be more easily compared on a technical basis. The variability of a semi-structured interview provided a larger depiction of the current issues in identifying oil spills that would be limited through other data collection methods, particularly helping us fill in blanks to our knowledge. As well as this, it allowed more technical interviews with engineering professionals to be directed towards their backgrounds. This format encourages focusing on expertise, which is helpful when dealing with several different individuals who may have the same degree but have various levels of competence in more specialized disciplines.

3.5.2 Justification of Literature Review of Engineering and Environmental Topics

Unlike interviews, literature reviews can be completely freeform allowing additional targeted research to supplement the data obtained from the semi-structured interviews. These literature reviews allowed us to delve into specified areas of research that revealed a deeper understanding of any topics suggested from the interviewees. Furthermore, by branching through the references in research articles, more prevalent articles were found that fit our needs more effectively. Lastly, literature reviews allowed for gaps in our research to be filled and helped us to have a deeper understanding of technical concepts that were important to the project.

3.5.3 Discussion of Overall Limitation Within These Methods

Our project was subjected to changing scopes as there was no concrete initial direction. This was in part due to the semi-structured nature of the interviews, however that style of interview was chosen to challenge our preconceived notions. This led to a constantly developing scope of the project which made various details previously researched either irrelevant or of more importance. Our lack of initial knowledge was due to the still developing field of AAVs. As a result, the selection of experts was AAV adjacent, causing many interviewees to question their helpfulness in providing relevant information. Direct information regarding combined aerial-aquatic abilities was not always provided, however broader adjacent information was provided leading to additional interesting avenues of research to be considered. While the freeform nature was intended for semi-structured interviews, it did not always provide desired results.

An unforeseen aspect of conducting interviews was the effect of virtual versus in person format on any given interview. We found that in person interviews were more passionate and personal. This was beneficial because the interviewee became more willing to provide helpful information, though sometimes detrimental as time was wasted on uninformative side tangents. Over virtual means the interviewee was more likely to feel restrained to the questions asked as talking to a screen is less personal. Interview methods were restricted by the location of the interviewee as well, where driving options of more than an hour to get to the interviewee were rejected.

Supplementary to interviews, aspects of literature reviews provided valuable technical detail, but do not qualify as being completely comprehensive. The acquisition of literature was limited to our precognizant biases of what would be important to AAV design. Selected keywords gave us the best representation of the information available, which was employed due to the tight time schedule for collecting literature.

4 FINDINGS

Through four objective goals, data was collected to support the development of design considerations and a full conceptual design of an AAV. Data presented in this section reflects the opinions of field experts and guided further analysis. This section focuses on compiling data gathered on creating the vehicle for the purpose of 3D mapping of oil spills, enabling early detection.

4.1 Sustainability of Vehicle Design Aspects

Sustainable practices allow the vehicle to remain true in its purpose to help the environment, while not causing a detrimental footprint of its own through several types of pollution. Considering factors down to the molecular level is necessary to cover all bases in terms of sustainability. A lot of information was acquired from engineering professionals who have worked closely with environmental and sustainability issues.

4.1.1 Material Degradation & Corrosion

Material degradation and corrosion is an issue in both aquatic and aerial environments. Degradation processes occur naturally over time as a material exists in its environment, and varied materials can have different resistances to these processes. The materials that were recommended for an AAV can be broken into two types: fiber-based composites and metals. During interviews with both an anonymous engineering expert and Professor Nicholas Bertozzi, it was mentioned that carbon fiber composites are great materials to work with in this scope. The anonymous engineering expert mentioned how UV rays can degrade carbon fiber composites, so applying a coating to the material slows down the degradation process. The epoxy matrix portion of the composite that will degrade under UV rays and moisture in an aerial environment, making the material useless over time (Kumar et al., 2002). For marine environments, it has been determined that over a period of time in seawater and at elevated temperatures that the epoxy matrix will delaminate from the carbon fiber (Zhao et al., 2021). Which means in low temperature seawater, it would be long lasting with no corrosion.

For metals, corrosion is also something to be cautious of when choosing to use them on an AAV. In interviews with both Professor Bertozzi and Professor Bergendahl, they made note that a seawater environment can be corrosive when in the water and above. The various components that make up seawater can cause harm to metals if they are not well protected. One example of this is chromium metal. Professor Bertozzi mentioned how using chrome on boat features always need constant upkeep because of corrosion from sea air. With further research, other common metal alloys were investigated. A certain titanium alloy (Ti-6Al-4V) commonly used in aerospace applications, was composed to have high corrosion resistance. This was tested under marine conditions, and it was proven to be stable under low temperature seawater conditions. It was shown that the alloy forms its own corrosion resistant oxide layer, helping the metal be utilized in various environments (Gurrappa, 2003). Aluminum alloys are another metal commonly used in UAV vehicles. One aluminum alloy, created to have high corrosion resistance, is AA6060. Corrosion resistance for this alloy is also through a self-formed oxide film on the material. In marine environments, the chloride ions in solution can form a localized attack on this oxide layer (Allachi et al., 2010). This ion attack weakens and corrodes the oxide layer allowing the alloy to become susceptible to damage.

Corrosion resistance is an important feature to have on a vehicle that is intended to be used in two different environments. Degradation or corrosion of any of the previous materials can put ecosystems in danger. For AA6060 (aluminum alloy), it is stated in the Safety Data Sheet (SDS) that metal powder or dust from this material may cause ecological damage in water environments through sedimentation, reducing habitat for organisms or entering organisms' gills or lungs limiting oxygen uptake, as well as becoming extremely mobile in water (*Aluminum Extrusion Metal, 6060 Series Alloys Safety Data Sheet*, 2015). The SDS for the titanium alloy (Ti-6Al-4V) also has an environmental safety warning for particulates entering waterways through accidental disposal (*Safety Data Sheet: Spherical APA Ti-6Al-4V*

Powder, 2016). As for carbon fiber composites, one instance of releasing harmful substances is in the case of fire where carbon monoxide or carbon dioxide can be released, according to its own SDS (*Carbon Fiber Products: Safety Data Sheet*, 2018). It is also dangerous to cut this material as it releases harmful particulates into the surrounding atmosphere (Nguyen-Dinh et al., 2020). Degradation and corrosion of any of these materials can be potentially dangerous to its surrounding environment, so it is important to ensure the correct materials are being used.

4.1.2 Material Life Cycle

In the field of sustainable engineering, the role of a material lies beyond the scope of its use but encapsulates its entire life span from production to scrap. This is an important consideration based on the ability to use and produce materials in a way that does not expend the resource, release toxic chemicals, or negatively affect the environment when scrapped (Pacheco-Torgal, 2020). Consideration of material life cycles must be made for any material to ensure that sustainable practices are still intact. While it is difficult to control the actions of a material manufacturer directly, particular care can be taken to prevent the vehicle from becoming pollution, such as in the case of a crash. John Bergendahl, an environmental engineering professor at WPI, was concerned by this possibility. If a vehicle were to crash in the water, there would be only a few debris disposed in the ocean. This is less of a problem of sustainability if this happens once but could have massive implications if multiple vehicles were to crash. Likewise, it was said that a vehicle employing organic materials, such as chlorinated solvents, could cause serious problems releasing carcinogens into water environments.

Similarly, inorganic coatings such as cadmium for corrosion resistance were noted as being "particularly nasty" for dealing with possible dispersion into the environment (Bergendahl, 2022). This fact is confirmed by a 1972 study at Caltech, which details the cadmium levels found of plants detrimentally carrying down the food chain to herbivores and further predators (Fleischer et al., 1974). Otherwise known as biomagnification, this is a process in which an increase in the concentration of chemicals and compounds is exhibited when passed down the food chain (Bacaksizlar & Önsel, 2013). This process hinders the sustainability of a life cycle and should be considered for maximum care beyond the operational life of the vehicle.

4.1.3 Biofouling

When constructing an underwater vessel of any type, the idea of biofouling should be taken into consideration when picking materials. Biofouling is "the unwanted deposition and growth of biofilms" on a surface and can occur at solid-liquid interfaces (Flemming, 2002, p. 1). The possibility of this occurring at a solid-liquid interface is a huge factor to take into consideration for a vehicle that would traverse both air and water. Professor Mark Patterson mentioned the point of biofouling and made sure to note that putting most materials in the water unprotected can be susceptible to this process. Professor Patterson also mentioned that if the object has a large biofilm, small sea-life may also start to colonize it, causing harm to the vessel. To ensure biofouling does not result in severe hull corrosion, an appropriate antifouling coating is needed (Xia et al., 2021). In the past, toxic biocides have been employed as an antifouling coating for a hull of a ship, but long-term exposure of these marine ecosystems to these chemicals could cause harm (Xia et al., 2021). Two types of materials for antifouling coatings that have been previously investigated: biomimetic, sustainably mimicking organisms in the environment, and superhydrophobic, elevated resistance to saltwater. To be able to withstand seawater, a combination of the two resulting in super oleophobic and superhydrophobic coatings, can be achieved to have great resistance to potential biofouling (Xia et al., 2021). This component of vehicle construction and design can be sustainably applied to the body of an AAV.

4.1.4 Sediment Disruption in Aquatic Environments

Sediment disruption is defined by the resuspension of sediments into the water column. One of the roles of sediment in an ecosystem is to absorb pollutants while they are suspended and then settling, which removes the pollutants from the water column (Salomons, 1985). After absorption, disruption to the sediment can cause contaminates to leach back into the water (Salomons, 1985). Any system that operates near the sediments can disrupt them, therefore any risks of ecological damage must be minimized. Professor John Bergendahl discussed the possibility of this risk in his interview. He said that if there was a minimal disturbance, it would likely settle quickly and not cause problems. Dr. Bergendahl continued in saying that the magnitude of sediment disturbed is an important attribute, especially in locations where pollution has previously occurred. A statement from Professor Paul Mathisen corroborates this by stating that resuspending contaminated sediments is likely to cause environmental issues. When contaminated sediment is disrupted in copious quantities, it can stay suspended for a longer period and increase the likelihood that contaminated material is spread to other areas (Pracheil et al., 2010). The disruption of the sediment can also cause contaminates to release into the water. In the case of one substance, polychlorinated biphenyl, resuspension causes the contaminate to be desorbed from the sediment twice as fast as compared to undisturbed contaminated sediment (Schneider et al., 2007). The disruption of sediment can cause environmental damage, especially in massive quantities.

4.1.5 Noise Pollution in Aerial & Aquatic Environments

Noise pollution can exist in both aquatic and aerial environments and can stem from sensors and propulsion methods. Noise pollution can be defined as human generated sound through high-intensity impulsive noises like active sonar applications or low frequency stationary noise such as propellers (Chahouri et al., 2022). In aerial environments, there were no referenced instances of impulsive noise causing environmental damage and harming aerial organisms. Conversely, in aquatic scenarios, there is an abundance of information detailing the potential harm to marine life through high powered impulsive sound that is produced by sonars. Professor John Bergendahl emphasized that the size of the AAV is critical to further investigate its effect in aquatic environments. This effect is quantified through marine studies that detail anthropogenic noise pollution. In these studies, it was discovered that sounds induced by humans led to hearing loss, tissue damage, trauma, stress, migratory shifts, and food chain disruptions within marine animals (De Soto et al., 2016; Sultana & Zhi, 2007). This damage is not universal to sonars of all sizes, a study performed by Durban et al. (2022) introduced high-intensity impulsive signals into bodies of water and saw that the probability of a change in migratory habits increases as the signal strength was incremented.

Propulsion methods, like propellers, are another method that can introduce noise pollution into the environment and cause detrimental harm to organisms. Professor Mark Patterson mentioned that in his experience with marine environments, AUV propulsion methods are quiet enough to not disturb most fish and that they see the vehicle as a large animal. In reference to aquatic vehicles, engines introduce a substantial amount of noise to a marine environment, and therefore it is important to reduce the noise produced by the engines (Chahouri et al., 2022). Conversely in aerial vehicles, the propulsion method plays a significant role in the amount of audible noise produced. In the interview with an anonymous engineering professional, they claimed that the noise produced by the propellers is dependent on the speed of the propeller’s tip, where speed and noise positively correlate. In addition to this, it was mentioned that the corresponding solution to a noisy propeller system is to fly higher in the air. Through increased aerial height, the introduced sound waves from the propellers deteriorate before reaching the ground.

4.2 Current Technologies of Oil Detection

Interviews with experts involved with oil pollution identification in bodies of water revealed the current technology and limitations associated with locating contamination in the Baltic Sea and other parts of the world. The data from these interviews are structured to outline how the oil enters the Baltic Sea and modern identification methods, either sensor detection or sampling, and limitations that exist universally. Research focuses on sensor-based detection rather than water sampling as the main source of detection, little information was found on sampling in autonomous vehicles, so it was ruled out.

4.2.1 Main Sources of Oil Pollution in the Baltic Sea

To best detect oil pollution in the Baltic Sea, knowing the main sources of oil pollution can be helpful. The Baltic Sea is home to various oil tanker shipping routes, and at any given moment can have 2000 ships inside of it at once (Rheinheimer, 1998). When interviewing Professor Olof Lindén of the World Maritime University, he mentioned that one of the more prevalent cases of oil contamination in the Baltic Sea is when tanker ships drain sludge into the water. When this occurs, there are tiny amounts of oil within the sludge when it is released. These spills are likely due to human error, something that both Professor Lindén and U.S. Coast Guard member Michael Lypen mentioned when interviewed. The Baltic Sea is also a "Special Area" which means that any discharge or dumping of oil directly into the sea is prohibited (Rheinheimer, 1998, p. 325). Another member of the U.S. Coast Guard, Colt Cotton, also mentioned that during his time as a drone pilot surveying for pollution, intentional discharge of oil has been a prevalent cause of pollution. Being able to identify the most common causes in the Baltic Sea, even if they are not major, is vital for creating a vehicle that can detect oil in this body of water.

4.2.2 Modern Oil Pollution Identification Methods Universally

Many geographical areas surrounding bodies of water implement their own system of oil pollution identification that are similar across the globe. In an interview with Professor Olof Lindén, it was mentioned that continual aerial monitoring was the predominant method implemented by agencies that track oil spills. Professor Lindén also expanded on this idea claiming that countries in the Northeast Atlantic, the North seas, North America (United States and Canada), and the Mediterranean implement some form of aerial technology to track oil spills. Use of aerial monitoring within the United States was confirmed by Michael Lypen of the United States Coast Guard. In the interview with Mr. Lypen, it was found that there are three strike teams that monitor the coasts of the Atlantic Ocean, Gulf Sea, and Pacific Ocean equipped with drones and remotely operated vehicles. Additionally, Mr. Lypen and Professor Lindén outlined external methods that also aide in the detection of oil spills such as oil industries surveying their oil pipelines and established helplines that allow civilians to report evidence of pollution.

With different areas having access to varying resources and dissimilar budgets, aerial surveillance for oil pollution identification changes based on geographic location. In the interview with Professor Olof Lindén, it was found that the aerial surveillance in the Baltic Sea is done only with crewed vehicles. Professor Lindén elaborated on these vehicles, explaining that they implement infrared (IR) imaging to detect oil. Similarly, within pipeline monitoring, the most popular form of oil identification is through the implementation of thermal IR images (Asadzadeh et al., 2022). From a study with UAVs for remote sensing, it was found that with high resolution drone-mounted sensors, it would be possible to "detect even the slightest quantities of oil leaks (Asadzadeh et al., 2022)". Additionally, since the Baltic Sea is surrounded by a multitude of countries, Professor Lindén mentioned an alliance known as the Helsinki Convention that unites the various international powers to fight pollution within the Baltic Sea. The Helsinki Convention focuses on protecting the entire Baltic Sea area with amendments that require international governments to work independently and in unison to combat all forms of pollution that exists or could occur in the Baltic Sea (*The Helsinki Convention – HELCOM*, n.d.). Pollution in the Baltic Sea is carefully monitored by multiple intergovernmental agencies but is hindered by a lack of autonomous system.

4.2.3 Current Limitations in Oil Pollution Identification

Limitations in current detection methods create more time for the oil to disperse and possibly create sustainability issues. First off is the quantity of vehicles searching at once. As mentioned in the previous section, crewed vehicles are often used around the Baltic Sea for the purpose of oil pollution detection. Professor Lindén stated that there are only two to three aircraft surveying the coast every day and he also mentioned that some oil companies only check their pipes when a leak is suspected. More vehicles could provide a more constant surveillance of the coastal region and could expand into areas not as routinely searched, like the open water. Other limitations that Professor Lindén mentioned were the archipelagos and winters in the Baltic Sea. He stated that chains of islands can create calm and wavy sections of water where it may appear that oil is present, or islands may block oil from the view of the aircraft. The additional challenges that winter brings include less hours of sunlight per day, ice, and mist. If oil is under or mixed with ice, it becomes increasingly difficult to detect. Additionally, mist can create low visibility conditions that prevent areas from being thoroughly searched. In other parts of the world, identification methods come with other limitations. For example, United States Coast Guard members Michael Lypen and Colt Cotton both stated that the surveillance of an area is sometimes dependent on citizen reports. The Coast Guard is not able to actively survey all bodies of water and would need timely reports to respond to the pollution in those areas. Without active surveillance, oil pollution is more likely to spread before it is found.

Response time is also a major contributor to oil pollution detection as there is no way to clean up the spill if no response mechanisms can reach it in time. Reduced identification greatly contributes to reduced response time. Traveling to the suspected oil spill location is made difficult by the "hundreds of kilometers," as Professor Olof Lindén puts it, in the Baltic Sea and lack of numerous response headquarters. Professor Lindén has informed us that there are only a few launching points on the east coast and three on the west coast of the Baltic Sea. With so few launching points to cover the entire sea, distance severely limits how quickly a team can be on site for testing or clean-up.

4.2.4 Sensors for Navigation & Oil Perception

Sensors enable the vehicle to perceive the environment. Starting with navigation and control, the anonymous engineering professional recommended that the craft would need an inertial measurement unit (IMU). The IMU is made up of sensors that help the vehicle to know its orientation and position, namely: gyroscopes, magnetometers, accelerometers, and GPS. This sensor serves high importance to the vehicle's autonomy. Without it, the vehicle would not be able to control its movement properly or know that it is surveying the correct areas. In the interview with Professor Bertozzi, he mentioned that a barometer could be used to measure altitude both above and below water using pressure, but it comes with the caveat that it is not extremely accurate, due to atmospheric fluctuations. In addition to the measurements from a barometer, the engineering professional mentioned that it would be helpful that the vehicle is able to detect its height off the water's surface more precisely using a radar. This measurement is done by sending out radio waves and detecting the reflected signals ("Radio Detection and Ranging," 1943). In reference to underwater mapping, Professor Patterson mentioned implementing an analogous sensor for underwater. In his UAV, FETCH!, he used a side scanner sonar. This sensor can be used to map out the ocean floor and detect the craft's height. This measurement is obtained by sending acoustic energy and measuring its reflectance off objects (Degraer et al., 2008). Furthermore, the anonymous engineering professional mentioned an important sensor consideration, referencing the speed of the vehicle compared to the rate of measurement. Sensors have a maximum refresh rate and range, and it is possible for a vehicle to move faster than it can sense. For example, if the sonar can only read 2 meters away and has a refresh rate of 1 Hz, a vehicle moving at 2.5 meters per second would not be able to properly detect obstacles.

Moving towards detecting oil, both Michael Lypen and Professor Patterson supported having a camera on the vehicle for aerial use. As mentioned in the background, machine learning methods exist to detect oil on the water's surface with over 70% accuracy (Mehdi et al., 2022). The interview with Professor Olof Lindén revealed that specifically IR cameras are often used in oil pollution detection. They can detect the infrared from the thermal energy emitted by the oil at 3 to 8 degrees Kelvin above ambient during daylight (Fingas & Brown, 2015). Additionally, Professor Patterson and Professor Mathisen both recommended fluorometers for detecting hydrocarbons. Professor Patterson told us about how FETCH!, his UAV, was used during the 2010 BP oil spill and carried a fluorometer to detect oil. Fluorometers work by exciting a specific wavelength of light onto a target (Walsh et al., 2016). The target then emits light back at a shorter wavelength, the intensity of which is a function of concentration and dispersion (Walsh et al., 2016). Some fluorometers can detect crude oil in concentrations as small as 67 parts per billion (Walsh, 2018). From these sensors, a functional AAV for detecting oil can be realized.

4.3 Physical Design Aspects of AAVs

Different subsystems of a conceptual AAV have been examined through interviews, supplemental research, and engineering analyses. Here, findings are presented on different considerations that can be made based on previous works and expert opinions to determine imperative aspects of the vehicle.

4.3.1 Analysis of Propulsion Applicable for Operation in Air & Water

Not every method of propulsion can operate in aerial and aquatic environments sufficiently. It was found that aerial-based propellers spun by motors can function in both mediums. A study of unmanned aerial and aquatic vehicles found that utilizing common hobby propellers, but at a reduced speed was sufficient for submerged traversal (Palaniappan et al., 2019). Optimization for aerial propellers to perform at an increased efficiency underwater has not been found but is a sector of development that could be explored. The diameter of propeller blades along with the speed of the motor contributes greatly to the operational possibilities of aerial vehicles. The exact blade length will vary with each unique vehicle design and a specific length cannot be suggested. Insight gained from an anonymous engineering expert was that a larger propeller spun at lower revolutions per minute (RPM) will allow for increased loads to be carried. This coincides with a study that tested larger propeller sizes. They concluded that to increase overall efficiency, a lower number of blades and a lower rotational speed is required with a large propeller size (Cruzatty et al., 2022). For lower rpm, a motor with a lower Kv value, which is rpm gained per volt, can be selected for increased efficiency for underwater operation (K. Gao, n.d.; Palaniappan et al., 2019). These considerations will aid in determining specifications regarding propulsion design.

There was no consensus for what orientation or mechanisms should be used to apply thrust through propellers. This decision is best left to the creativity of the designer for the intended scenario. Motors could be fixed or have some mechanism to change their orientation. An interesting prior attempt used a quadrotor-based vehicle that tilts its rotors, allowing for the direction of thrust to be aimed laterally or in the opposite direction without rotating the entire vehicle's body (Tan & Chen, 2020). This design of a rotor that can tilt its orientation after the transition from air to water, provided sufficient propulsion in both environments. With the design of the base designed like a quadrotor, the experimental craft showed an AAV could function underwater without much restriction (Tan & Chen, 2020). Though a complex system is not always required, Professor Bertozzi suggested that all that could be needed was a vehicle with a singular fixed motor and two control surfaces to allow it to move forward, turn, or roll to orient itself anywhere in 3D space.

4.3.2 Structural Geometry & Analysis of Materials

With AAVs being a very specialized application, aeronautic and marine vehicles require specific materials that withstand intense pressure and temperature variances. Strength is important because the material must be tolerant to damage, corrosion, and different operating temperatures. Adding to this, the use of one material in two fluid mediums is an exceedingly perplexing task. Here, findings for different usable materials for AAV design will be outlined.

4.3.2.1 Fiber-based Composite Materials

Functioning aspects of aerospace vehicles could be provided by light weight alloys such as titanium and aluminum (Zhang et al., 2018), but for many aerospace applications, composites are used for their multi-directional properties and high strength. Carbon fiber is a woven material and can be applied in different build orientations, fiber orientations, and stacking sequences for flexural stiffness (Somireddy & Czekanski, 2020). Composites have a density which is much lower than that of metals but provide high durability (strength of 550 MPa, comparable to lightweight metals, such as titanium) and an extensive range of operating temperatures (up to 1400°C, the equivalent of fast-flowing volcanic lava) (Zhang et al., 2018). A large temperature range and high strength allows for use in more diverse settings, as composite materials have often been applied for both structural and thermal applications. As a specific example, a typical airliner uses composites as a structural element on both the body and some portions of the engine of the plane (Zhang et al., 2018). Many interviewees described composites as being especially useful, with several experts noting that composite materials are the best for low-weight applications. Typical aerospace-applied materials can thus be considered for such a vehicle, but with special modifications, mainly waterproofing, due to the change in the fluid viscosity from air to water or vice versa.

4.3.2.2 Metal Materials

One metal that dominated in aircraft production over several decades are aluminum alloys. Aluminum alloys are one third of the density of steel and have a strength of 520 MPa. Because of these properties among others, aluminum alloys have been primarily used as the airframe in these crafts, providing ample structural support (Zhang et al., 2018). Metals are also prevalent when creating the engine for the aircraft. When designing the engine for an aircraft, there are two main components: the cold sections and the hot sections. The two different temperatures require different criteria for material selection. Metals selected typically for the cold section are both titanium and aluminum alloys for their high strength and corrosion resistant properties. For the hot section of the engine, nickel superalloys are typically chosen due to their heat-resistance strength (780 MPa at 950°C) (Zhang et al., 2018). When creating a structure for a vehicle that can traverse both air and water, these aerospace materials may be considered for selection.

4.3.2.3 Analytical Comparison of Materials

As a proof of concept, two identical models of a wing under typical loading were tested with different material properties, to gain insight into the differences between metals and composites. The wing analyzed was a symmetric airfoil, with a skin thickness of 1/100th of an inch, four spars as support structure, and one cross beam that extended the entire 30-inch length of the wing. Aluminum and AS/3501 Carbon Fiber Epoxy Composites were chosen to reflect common examples of the types of metals and composites used for aerospace applications, as noted in sections 4.3.2.1 and 4.3.2.2. Strength data and properties for these materials can be found in Table 1.

This test was conducted using Solidworks simulation tools and was modeled as a beam with one fixed end and one free end. At the free end, a force of 12.8 N was applied, and the boundary condition for a wall was applied at the opposite end. This force was acquired through simulating fluid flow at 20 m/s over the wing geometry and measuring the lift force that would be endured, which will be discussed further in section 4.3.3. Results for this came in the form of color-coded deflection and stress figures, produced by the Solidworks Solver. Material Properties for aluminum and the AS/3502 Carbon Fiber Epoxy composite are shown in Table 1 below, calculated in MATLAB using the Rule of Mixtures for composite materials (Ansari et al., 2016). This rule extrapolates on the multi-material composition of composites.

Table 1: Table of material properties for two wing-shaped beams under structural analysis in Solidworks Simulations.

Material	Properties
AS/3501 Carbon-Fiber Epoxy Composite	Fiber Direction Modulus: 100 GPa Perpendicular Modulus: 20 GPa Poisson's Ratio: 3 Estimated Yield Strength: 2 GPa (Matrix Strength)
6061-T6 Aluminum	Modulus: 69 GPa Poisson's Ratio: 0.33 Yield Strength: 275 MPa

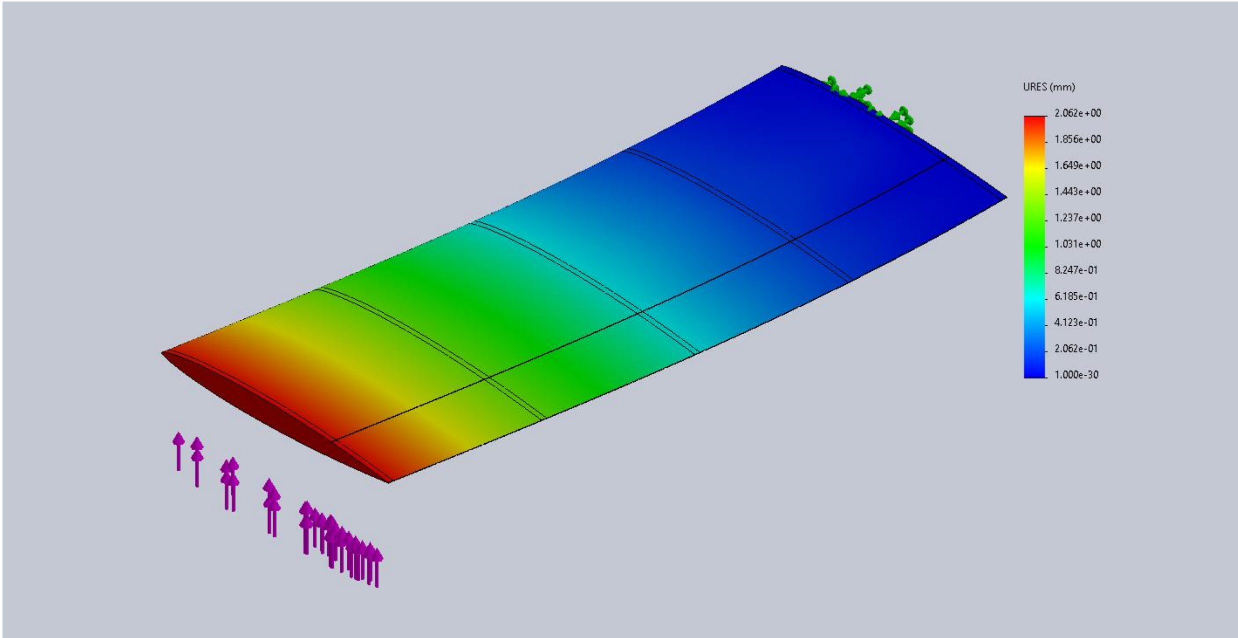

Figure 9: Displacement results for a 30 inch 6061-T6 aluminum wing with internal spars.

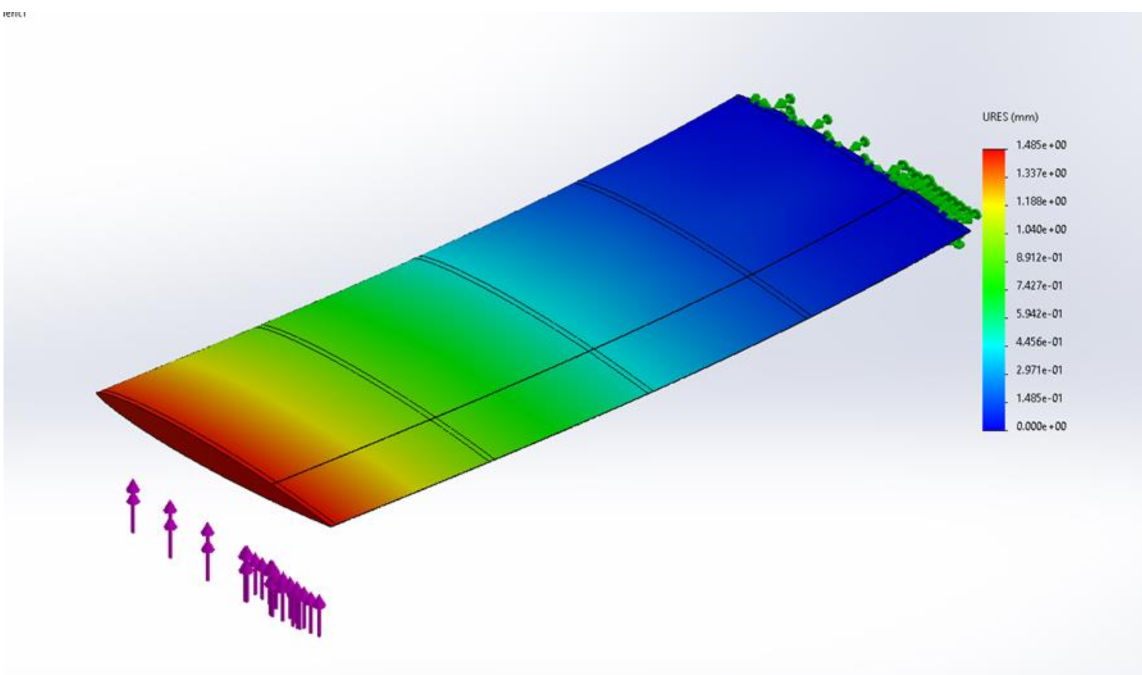

Figure 10: Displacement results for a 30 inch AS/3501 carbon-fiber epoxy- matrix composite wing with internal spars.

In Figure 10 (shown above), deflection of a 30-inch clamped aluminum wing is shown in the Solidworks simulation solver. Zero deflection is occurring at the very edge of the wing where it was fixed, and the maximum deflection, in red, is shown in the color-coded chart to be around 2.06 mm. The second figure shows a composite beam of the same orientation and load bearing setup. Composites are orthotropic, meaning that they have different properties in different directions of stress application

(Schmidt, 2016). Orienting the wingspan along the fiber direction was employed to attempt to maximize the strength of the wing, resulting in a deflection of 1.5 mm.

4.3.3 Effect of Fluid Dynamics on Structural Design

Several experts provided recommendations based on geometry. Models were produced, and run through simulations, to reflect these ideas. Geometry largely contributes to the integration of all other systems utilized by an AAV, and therefore different geometries and methods were meticulously examined. In Appendix I simulation parameters can be found for all fluid dynamics simulations.

4.3.3.1 Methods for Aircraft & Hydrocraft Design

The first suggested approach is the idea of a fixed-wing or glider style geometrical design. In this approach, the vehicle would take the shape of a glider. This design was mentioned by Professor Nicholas Bertozzi, who had noted the high aspect ratio of a glider-type wing could reduce drag and allow for a vehicle to glide down to a water environment without using any extra power, a valuable worry for such a vehicle. Also, given that airfoils on this type of aircraft produce upwards lift, less thrust is needed. The noted problem with this design is in entering the water. In water, a small frontal surface area is desired to reduce drag, as said by an anonymous engineering expert that was interviewed. Drag becomes problematic with water being much denser than air, as even lengthening the span of a vehicle can cause a substantial increase in drag. Branching off this, Professor Bertozzi mentioned that if the airfoil shape could be changed, or the span (length) of the wing could be altered in the transition between each media, then the wing could remain efficient in both terrains. Based on this same idea, a fixed-wing vehicle in air would be able to produce lift easily, as lift is a function of the dynamic pressure, which is a function of density. With density being much greater in water, ships and submarines can only generate lift from hydrofoils when they are in motion and gliding action is attained at a velocity of zero (Sahoo & Pan, 2020). Due to this, hydrofoils are generally used for elevating and changing the course of an in-water vehicle which is already in motion.

Another suggested method is a quadrotor approach, which employs vertical take-off and landing (VTOL). This type of vehicle is dependent on weight, as the thrust to get the vehicle off the ground must be greater than then its own weight. Generally, this type of vehicle is not designed to generate lift as prevalently as a fixed wing. Bertozzi did note that this method is “inherently less efficient than a fixed wing.” Successful testing and production of a small quadrotor was achieved by Tan and Chen in 2020. This was done through thrust-vectoring using a tilting servo to change the direction of thrust in water (Tan & Chen, 2020). This method, as well as the method of using a quadrotor in general, comes with a vastly separate set of dynamical parameters which is more focused on moment of inertia and thrust than that of the fixed wing (Chaturvedi et al., 2019). This is an important consideration as a conceptual design must encapsulate the use of dynamic comparisons as well.

4.3.3.2 Fixed-Wing Elevator Flap Analysis

Based off the favoritism of a fixed-wing geometry from interviews, as well as review of the fixed-wing produced by Weisler et al. (2018), fixed wing systems were chosen to be analyzed. Wing size was based off the AAV made by Weisler et al. and Solidworks Flow Simulation was used to analyze a NACA 0008 airfoil, which is a symmetric thin airfoil, shown in Figure 11. This airfoil was created as a 3D model in Solidworks, implementing a movable flap at the trailing edge of the wing, branching off Prof. Bertozzi who mentioned using a “shape changing airfoil”, a model is shown in Figure 12. Of course, this being an AAV, the properties in air are not the only concern. The main goal of this study was to confirm statements made by Prof. Bertozzi, and to gain a better understanding of the way a fixed wing could be designed.

Figure 11: Side view of NACA 0008 airfoil at zero angle of attack modeled in Solidworks.

Figure 12: Side view of modified NACA 0008 airfoil with deflected elevator at zero angle of attack.

The first set of simulations was conducted based on elevator flap angle, which varied between 0 and 20 degrees and was iterated by 2.5 degrees per each simulation. Each simulation was set to go from a velocity of 0 to 20 m/s in 20 seconds in air, and 0 to 1 m/s in 20 seconds in water. These speed ranges reflected similar ranges to those used in the AAV produced by Weisler et al. (2018). Results were compiled for both water and air, and properties recorded were lift, which is the amount of upward force generated by the wing, drag, which is the amount of horizontal resistance force caused by the wing, and the lift per drag ratio. This ratio was mentioned by Prof. Bertozzi, who noted a high ratio as making a wing more efficient than a quadrotor. Two- and three-dimensional graphs were made in MATLAB to compare the amount of lift and drag found by each simulation, shown in Figure 13 through Figure 16.

Solidworks Flow Simulation data suggests that when a wing with an aileron at 3/4 of the wing chord is used in air, a maximized lift to drag ratio of 9 is achieved at a flap deflection of 7.5 to 10 degrees. A lift to drag ratio of 9 means that a vehicle utilizing the wing at a stable altitude and zero angle of attack would be able to lift 9lbs for every 1 pound of thrust generated by any given propulsion system acting in the facing direction of the leading edge. Lift to drag ratio versus flap deflection can be seen in Figure 17, where the deflections are varying from 0 to 20 degrees, and lift to drag ratio increases logarithmically with velocity. As this test was done at a 0-degree angle of attack with respect to the leading edge of the symmetric airfoil, it is noticed that the frontal area of the wing was increasing with deflection. Since the chord length increases during the deflection change, Lift and Drag both increase, based on Equation 1 below.

$$Lift = C_l * p * V^2 * 0.5 * b * c$$

Equation 1: Equation for lift, expressed in terms of the lift coefficient (Cl), chord length (c), span (b), density (p), and fluid velocity (V).

$$Drag = C_d * p * V^2 * 0.5 * b * c$$

Equation 2: Equation for drag, expressed in terms of the drag coefficient (Cd), chord length (c), span (b), density (p), and fluid velocity (V).

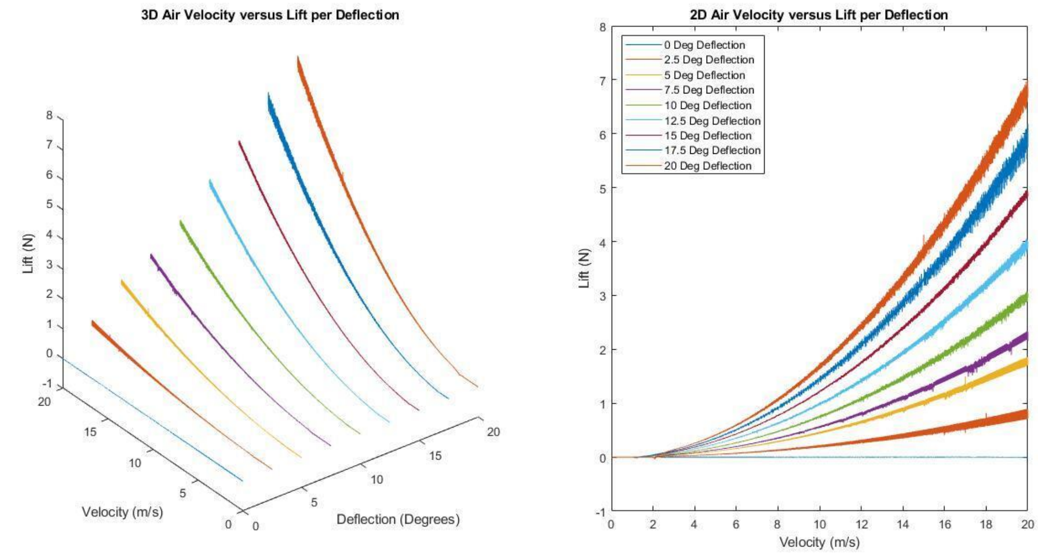

Figure 13: Air velocity versus lift plot at different elevator deflections, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

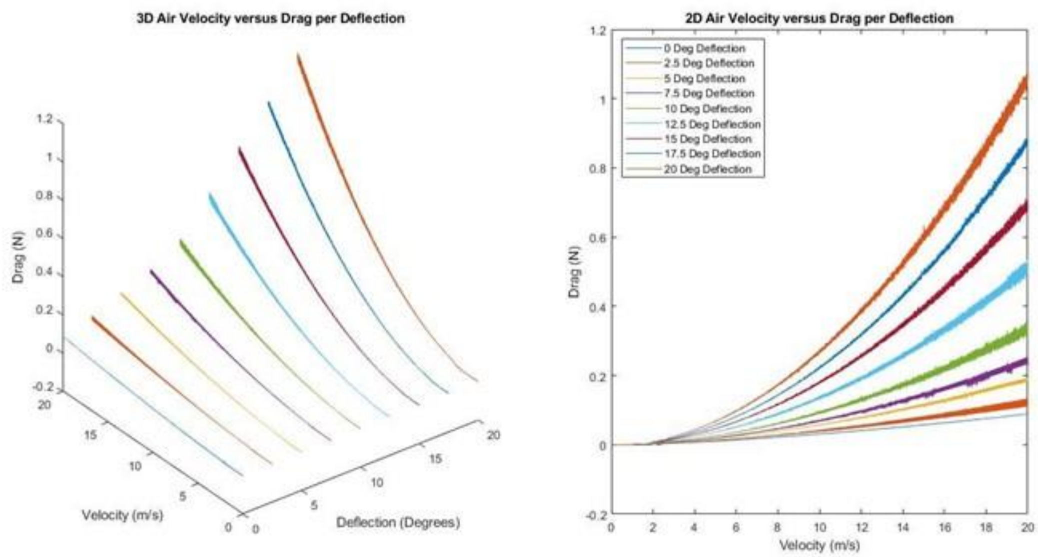

Figure 14: Air velocity versus Drag plot at different elevator deflections, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

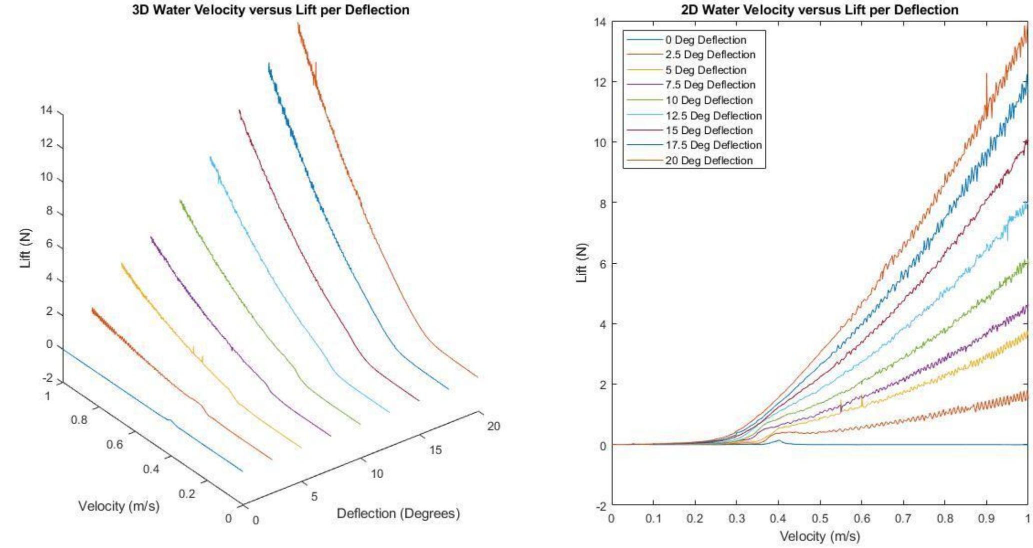

Figure 15: Water velocity versus Lift plot at different elevator deflections, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

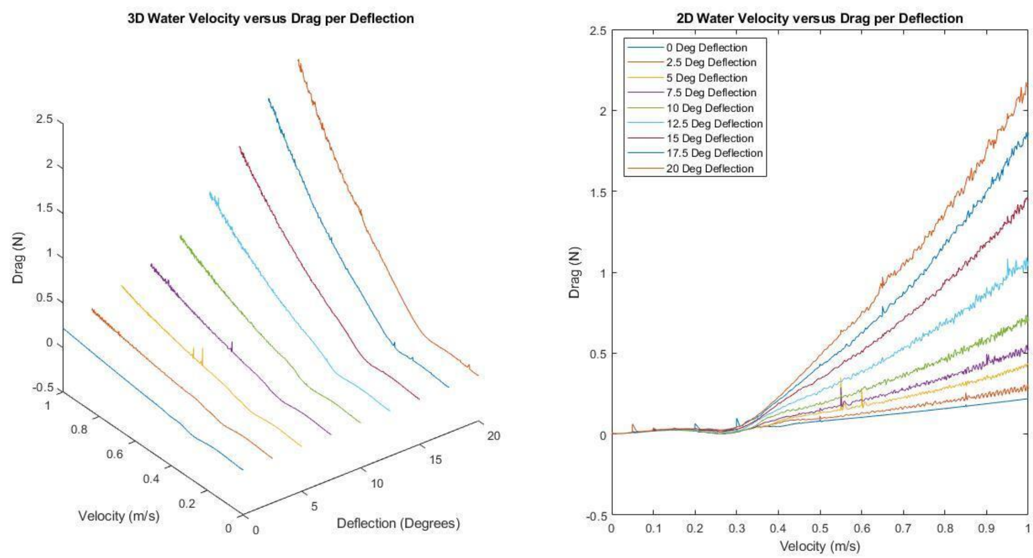

Figure 16: Water velocity versus Drag plot at different elevator deflections, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

Starting with these simulations in air, lift generally increased with fluid velocity over the wing, and with flap deflection. Likewise, drag increased in the same fashion. With this, it is important to note that the prevalence of lift, with respect to velocity, is less than that of deflection. Lift is a direct function of velocity, meaning that it will continue to increase exponentially. Simulations in water proved to be remarkably similar in convention, with both lift and drag showing an exponential increase with respect to velocity and increasing with the flap angle. It should also be noted that these results would be flipped to the negative axis had the flap been moved in orientation in the opposite direction, with this same applying to lift in both air in water. To further elaborate on the relationship between lift and drag, the use of a lift-drag ratio plot can pinpoint the orientation that exhibits the best maximization of lift and minimization of drag. Produced plots for air and water respectively are shown in Figure 17 and Figure 18.

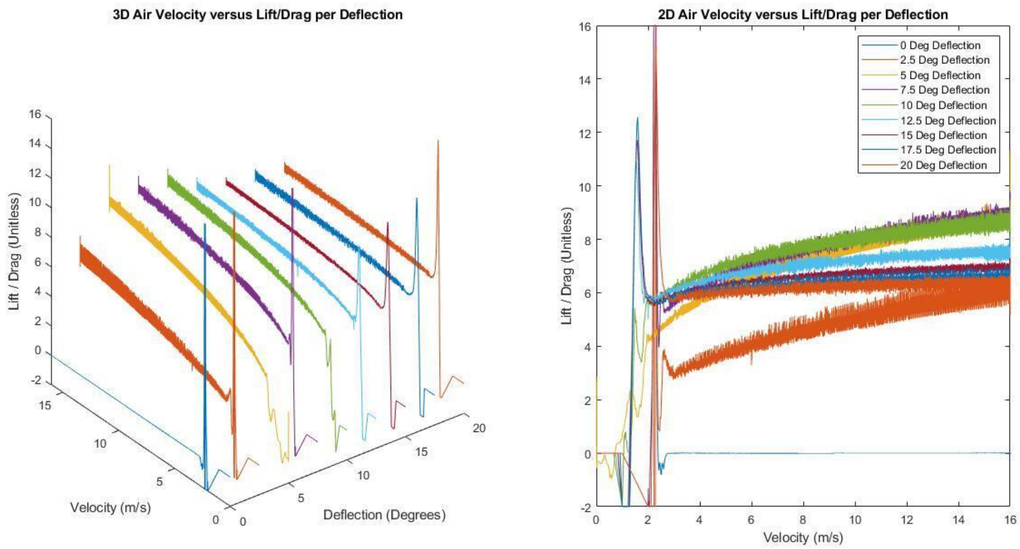

Figure 17:Plot of lift-drag ratios in air at different elevator deflections, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

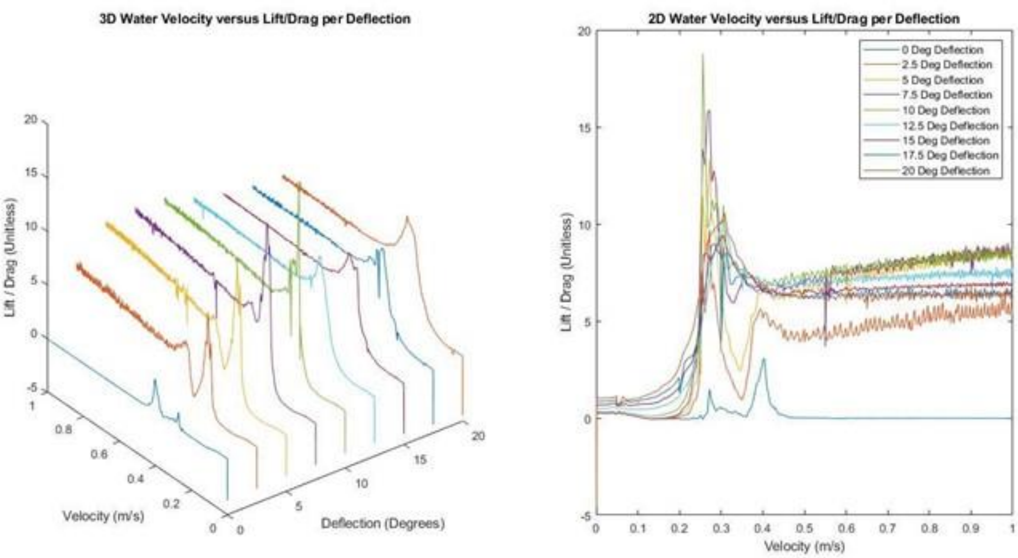

Figure 18: Plot of lift-drag ratios in water at different elevator deflections, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

The produced lift-drag ratio graphs in Figures 17 and 18 have noticeable peaks all in the same general location. In air this spike was seen around a velocity of 1 to 2 m/s, while in water it was localized around 0.2 to 0.3 m/s. The highest lift to drag ratios in air appear to be at 7.5 degrees of flap deflection and 10 degrees of deflection collectively. This ratio seemed to be approaching 10 at max speed in both air and water, like the claim made by professor Bertozzi about a typical ratio for a glider. A similar observation can be made under water, but it is much less clear when viewing the graph. In both air and water, the ratio remains in roughly the same magnitude, which is characteristic of airfoils, and can be scaled to exhibit comparable properties in different mediums.

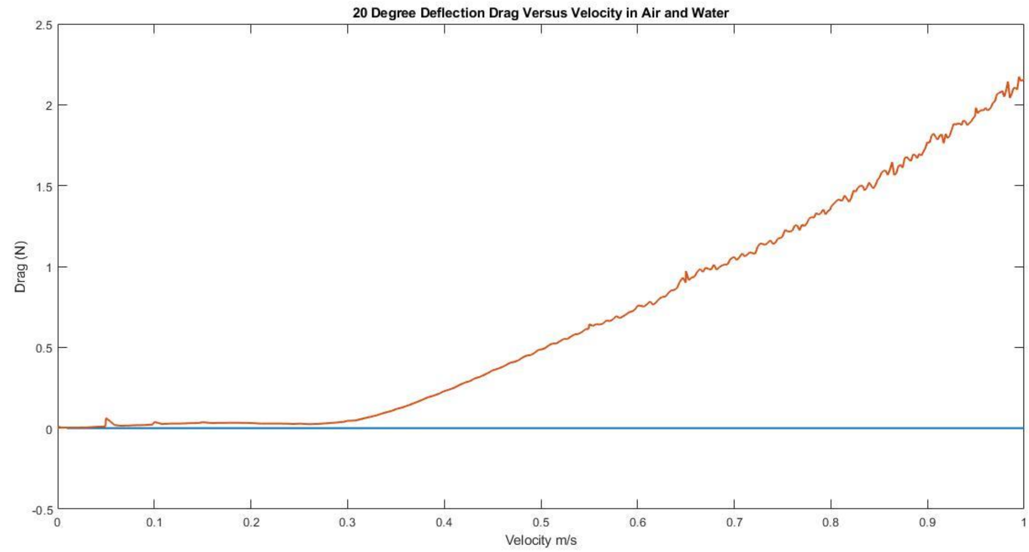

Figure 19: Graph comparing the drag properties of the NACA 0008 airfoil at 20 degrees deflection in water at 1 m/s and in air at 20 m/s.

Another observation is the difference in drag and lift generation from air to water. With water being denser, it produces more drag, which is shown by comparing drag at 20 degrees deflection for water and air, as shown in Figure 19. Water produced about twice the amount of drag that air did with the same flow conditions and elevator deflection. Along with this, water also generated more lift at a lower velocity. Water in this simulation was moving over the airfoil at 1 m/s, while air was moving over it at 20 m/s, which is contrary to the idea that a higher velocity would generate more lift over the same geometry. This relationship is due to the much higher density of water, where the lift increases with an increase in density.

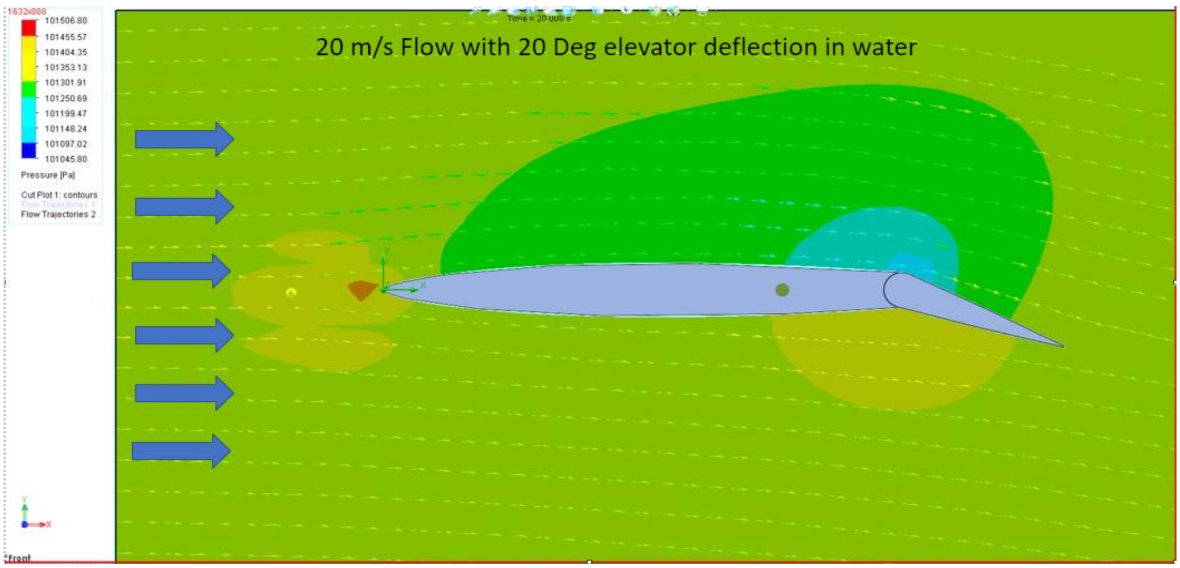

Figure 20: Visualization of the pressure distribution on a NACA 0008 airfoil with an elevator flap deployed at 20 degrees deflection. Flow direction is shown by the blue arrows and green dashed lines.

Results produced from the simulation were also cut plots of pressure distributions around the airfoil. An example of such a plot is shown above in Figure 20. This is a determining factor in the lift characteristics of the wing, as a low-pressure area is generated on top of the wing, and a high-pressure area is formed on the bottom, which creates an imbalance that ultimately causes lift.

4.3.3.3 Fixed-Wing Angle of Attack Analysis

This second aero and hydrodynamic study consisted of changing the angle of attack of an airfoil from -12 to 12 degrees over a 20 second time range. Studies were conducted at 5, 10, 15, and 20 m/s in air, and 0.25, 0.5, 0.75, and 1 m/s in water. These velocity ranges were based on the ranges from the previous study of elevator deflection. Once again, Lift and Drag were compiled into 3-dimensional graphs. It is important to note that for this simulation, the main goal was to view the effects of angle of attack on aerodynamic forces. This can be seen as an alternative method to moving an elevator to increase lift generation.

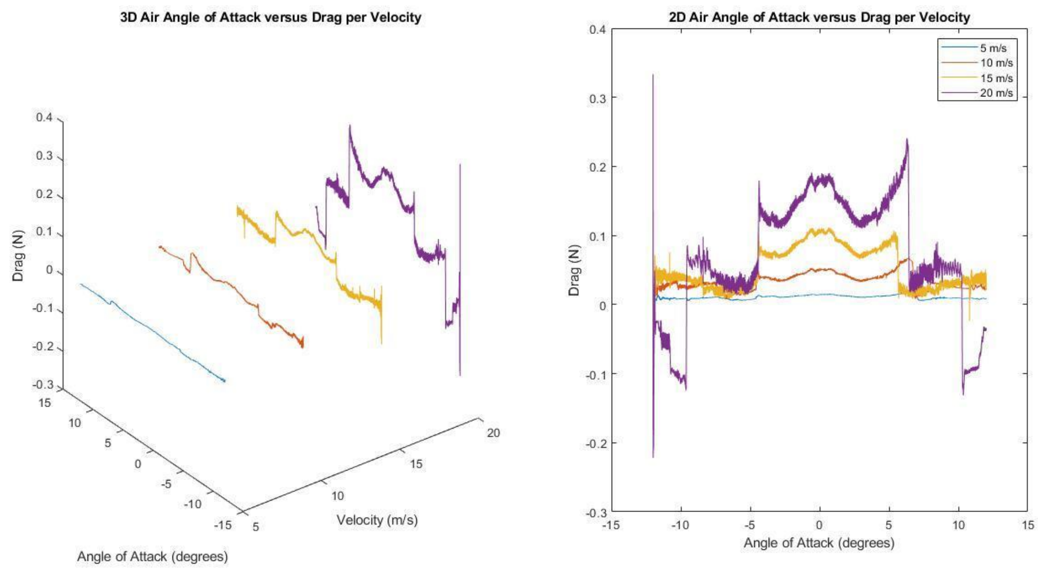

Figure 21: Angle of attack versus Drag plot in air at four different velocities, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

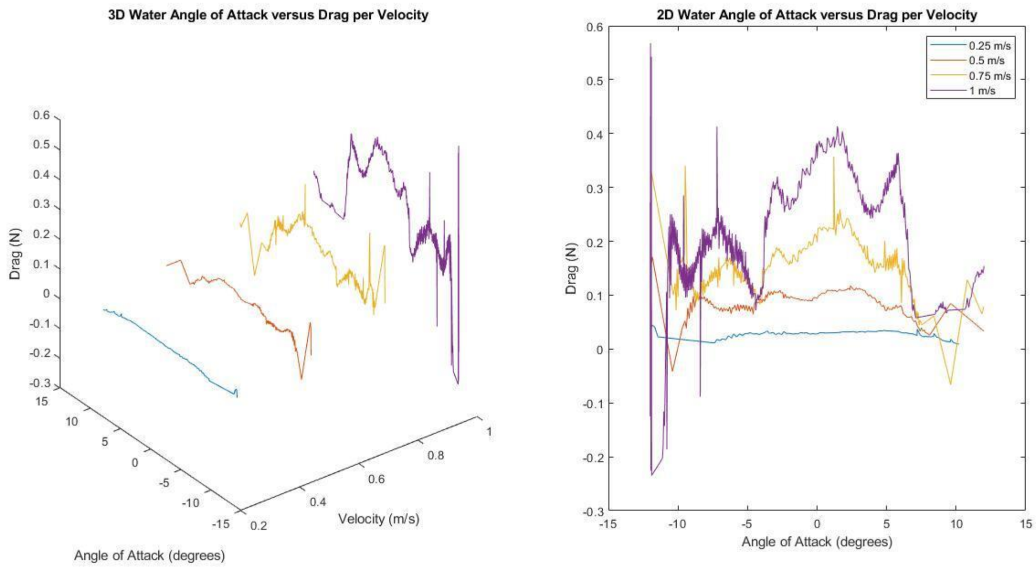

Figure 22: Angle of attack versus Drag plot in water at four different velocities, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

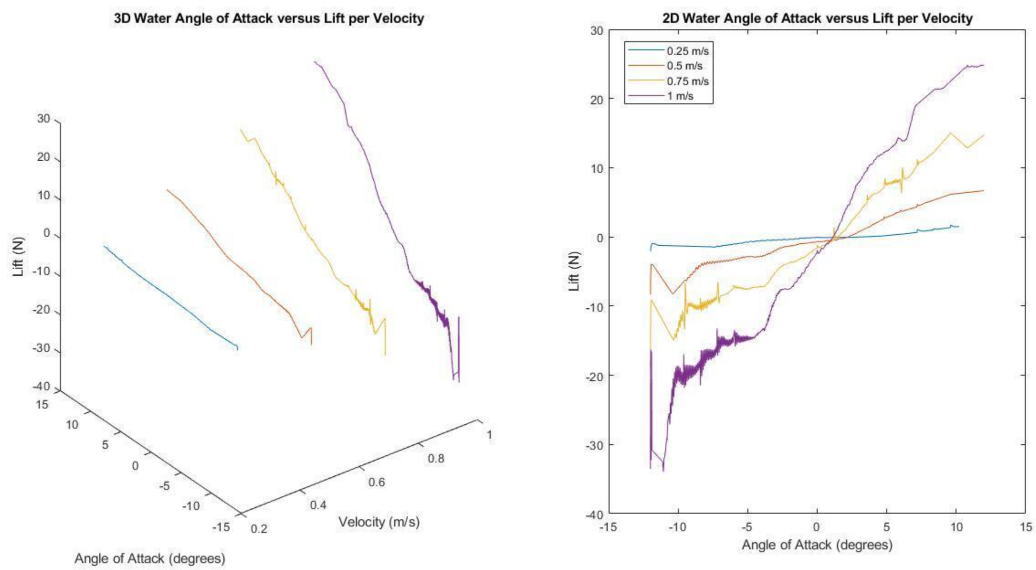

Figure 23: Angle of attack versus Lift plot in water at four different velocities, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

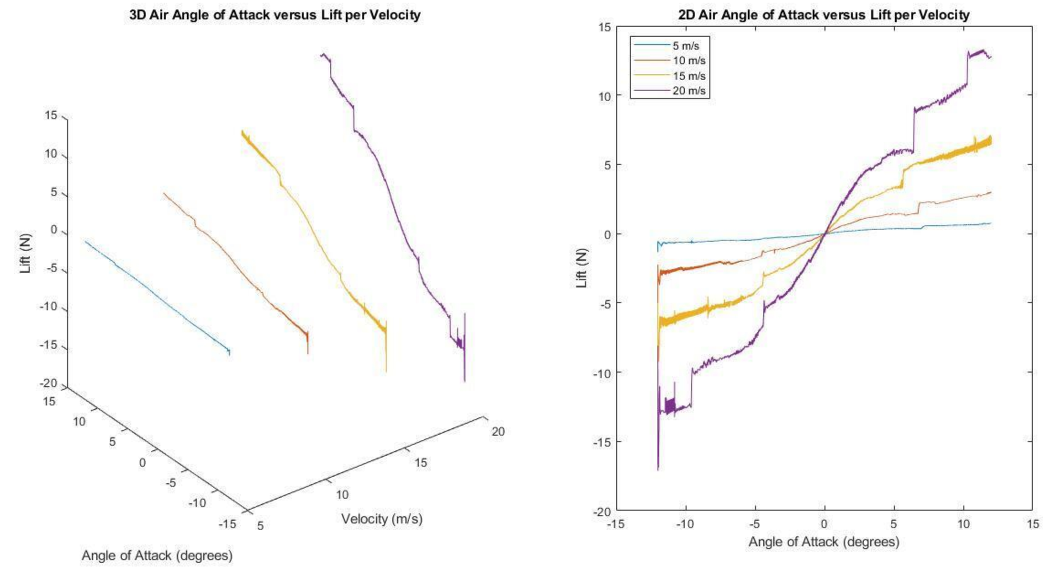

Figure 24: Angle of attack versus Lift plot in air at four different velocities, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

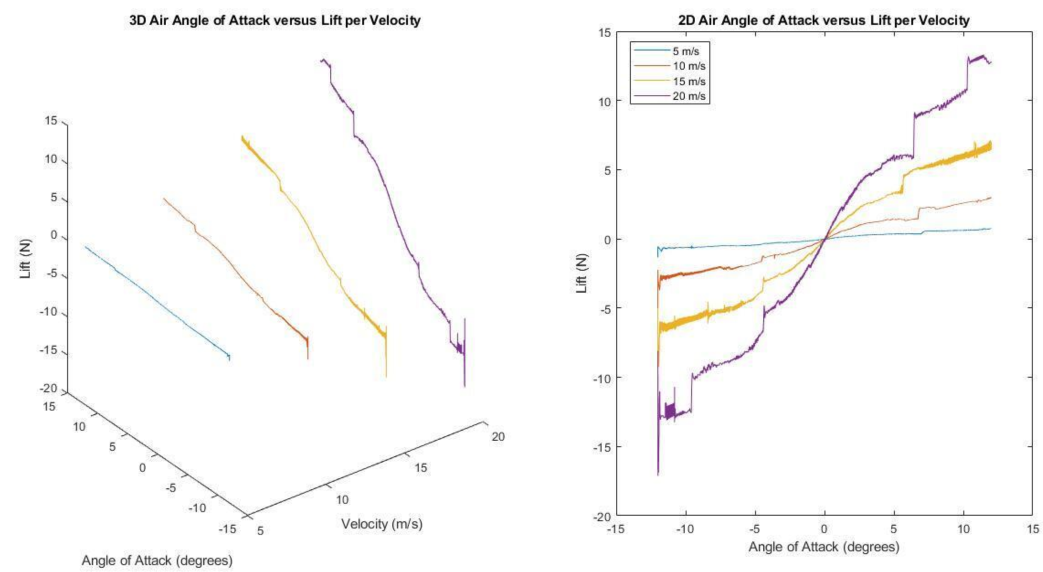

Figure 25: Angle of attack versus Lift plot in air at four different velocities, shown in both 2D and 3D. Extrapolated from Solidworks Flow Simulation data for a modified NACA 0008 airfoil. Made in MATLAB software.

For the air-based simulations, it is apparent that the lift graph has a linear profile when viewing lift versus angle of attack, drag seems to be rather jumbled and messy. For the lift graph, it is apparent that as angle of attack goes up, so does the generation of lift, and the convention seems to be the same on both sides going down to -12 degrees and going up to 12 degrees. At 20 m/s, the Lift is maximized at 10 degrees angle of attack. This makes sense when considering that this would enable the craft to climb in air. Likewise, the minimum amount of lift is at -12 degrees at 20 m/s. Reflection of this same convention is also seen in the angle of attack study in water. At maximum velocity of 1 m/s in water, a 12-degree angle of attack produces maximum lift of around 25 newtons. This force compares to the deflection calculations, where the maximum lift in water was close to 15 Newtons, demonstrating that the max lift in this situation increased by 10 Newtons.

As discussed in section 4.3.3.2 about elevator deflection findings, pressure above and below the wing can be viewed on cut plots. Cut plots show different pressure regions on the wing, with high pressure denoted in red, orange, or yellow, and low-pressure regions shown in blue or green, as shown in the example cut plots in Figure 26 and Figure 27. The intensity of these cut plots is based on the angle at which air is hitting a surface. For example, in Figure 26, where angle of attack is 20, air is creating a high pressure region below the wing since that is where most of the air is hitting. This is shown further by the low pressure region above it, which is at lower pressure, meaning less air is pressuring that portion of the surface.

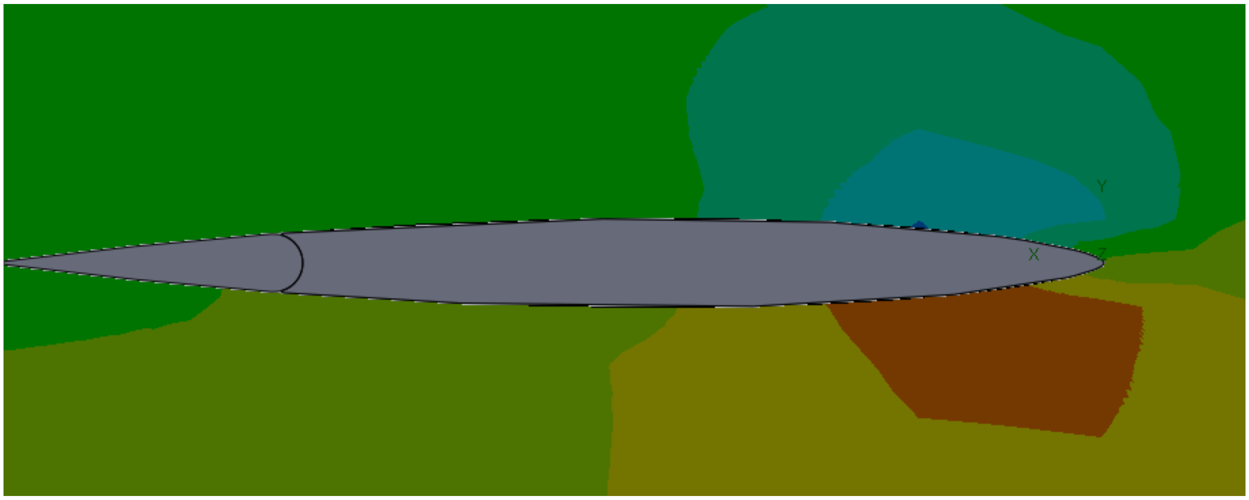

Figure 26: Pressure cut plot showing high pressure below the leading edge and low pressure above the leading edge at 20 m/s and an angle of attack of +20 degrees

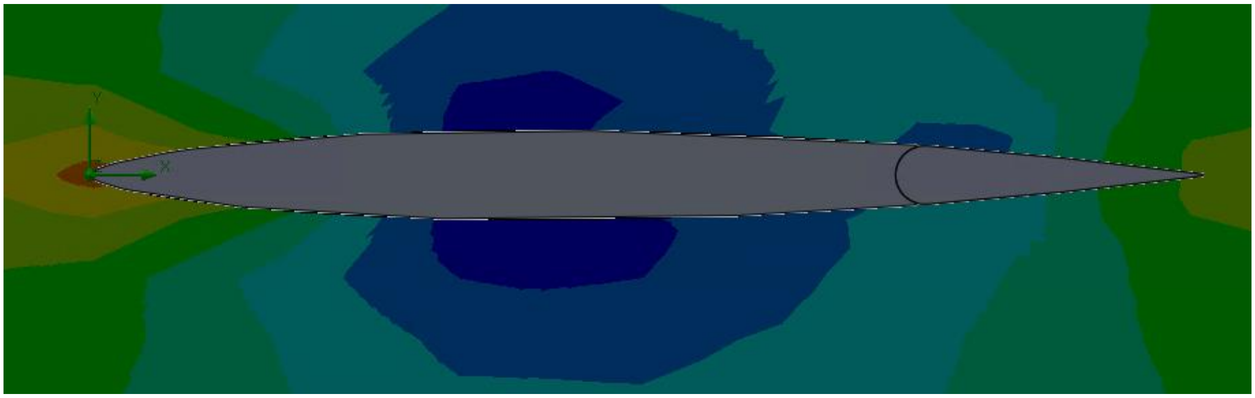

Figure 27: Pressure cut plot showing equal pressure above and below the leading edge at 20 m/s and an angle of attack of 0 degrees.

As seen by comparing Figure 24 and Figure 25 with data in figures ranging from Figure 20 to Figure 24, it was observed that higher lift corresponds to a wing with areas of high pressure on the underside of the wing. On the opposing side, it was found that lower lift corresponds with an angle of attack that is approaching zero, with lift being zero as shown by the symmetric pressure profile in Figure 25.

4.3.4 Analysis of Sustainable Power Systems for an AAV

The selected power system plays a vital role in the operation time of the vehicle, where various systems offer their own set of advantages and limitations. During the interview with the anonymous engineering expert, it was mentioned that, in their experience and with the current technology that exists, there is a lower flight operation time with green energy systems like batteries or hydrogen fuel cells compared to non-sustainable fuels. The corresponding energy densities and specific energy for various sustainable power sources can be found in Figure 28. An important note regarding this graph is that the batteries have an energy density and specific energy quantified at a fixed electrical state, whereas the oxygen and hydrogen fuels are based on the theoretical maximum that they can produce. Additionally, this graph is a log-log plot meaning a relationship that seems linear is indicating a power relationship.

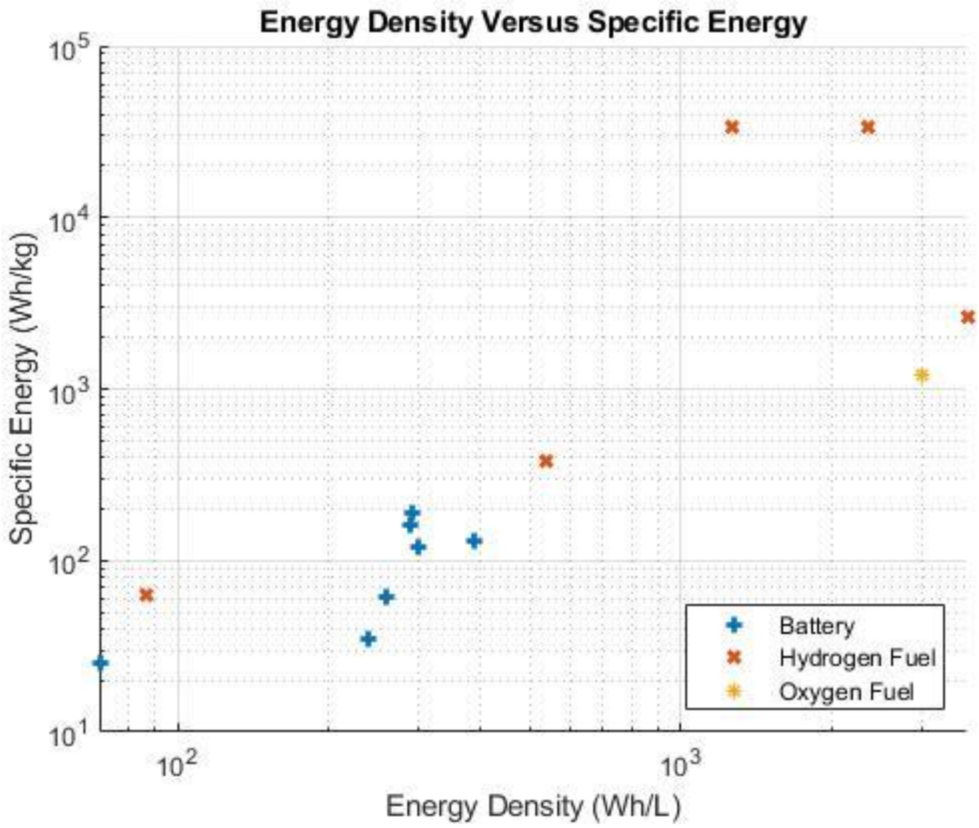

Figure 28: Energy Density versus Specific Energy for a variety of power sources. Note. Authors own work based on data from various sources (Hahn et al., 2015; Jha, 2016; Lu et al., 2020; Luo et al., 2019; Peng et al., 2018).

The characteristics of fuel sources, like oxygen and hydrogen, create unique benefits and challenges that dictate where it can be implemented. These fuel sources require supplemental infrastructure to facilitate a chemical reaction to convert its energy into a usable form, congruous with how gasoline requires an engine to transform its combustion into mechanical energy. The specific infrastructure plays a factor in the complexity and output power, with a compression system being the simplest option (Dutczak, 2018; Lu et al., 2020). A more complex system implements these fuels in a liquid state. Since oxygen has a boiling point of -183°C and hydrogen has a boiling point of -253°C, a liquid fuel cell requires cryogenic tanks. As shown in Figure 28, both fuel cells are extremely potent and can produce a lot of work for the space and weight they consume.

Contrary to refillable fuel sources, batteries can be composed of various materials and exhibit a wide array of characteristics, but all batteries face the same universal benefits and limitations. An advantage of batteries was outlined in the Interview with Professor Nicholas Bertozzi. It was mentioned that solar collectors can be implemented to recharge batteries, an important consideration if the vehicle must travel long distances. Solar panels, in respect to aerial vehicles, must be carefully selected so that they are highly efficient and can be fit onto the vehicle's wing because these vehicles are sensitive to additional weight (Carmo et al., 2021; Karabetsky, 2016). In a study outlining the effectiveness of solar panels for UAV flight, it was found that in ideal conditions a 40-minute flight was able to be extended by 7.5 % and saw a range of 1.5% - 5.8% in non-ideal circumstances (Carmo et al., 2021). A disadvantage to these types of power sources is their perpetual implementation. All batteries face a lifecycle where they can only be recharged a set amount of time before they begin to fail (Jha, 2016). From a sustainable engineering point of view, this periodic battery waste can be detrimental to the environment. In the interview with Professor John Bergendahl, it was emphasized that the effect of every chemical must be analyzed along with how it is synthesized. In respect to batteries, it is important that the battery can be recycled, and the corresponding materials are not gathered in environmentally unsafe methods, like mining. In addition to these sustainable engineering concerns and the desired electrical characteristics, another factor that dictates the optimal battery composition is the operating temperature. All commercially available batteries have listed operating temperatures. For example, batteries composed of nickel metal-hydride cannot operate in freezing temperatures, but nickel-cadmium batteries can produce a large amount of power at 41 degrees Celsius below freezing (Jha, 2016). With the ability to choose a variety of compositions and combine several types of batteries, batteries can be specially selected for their application.

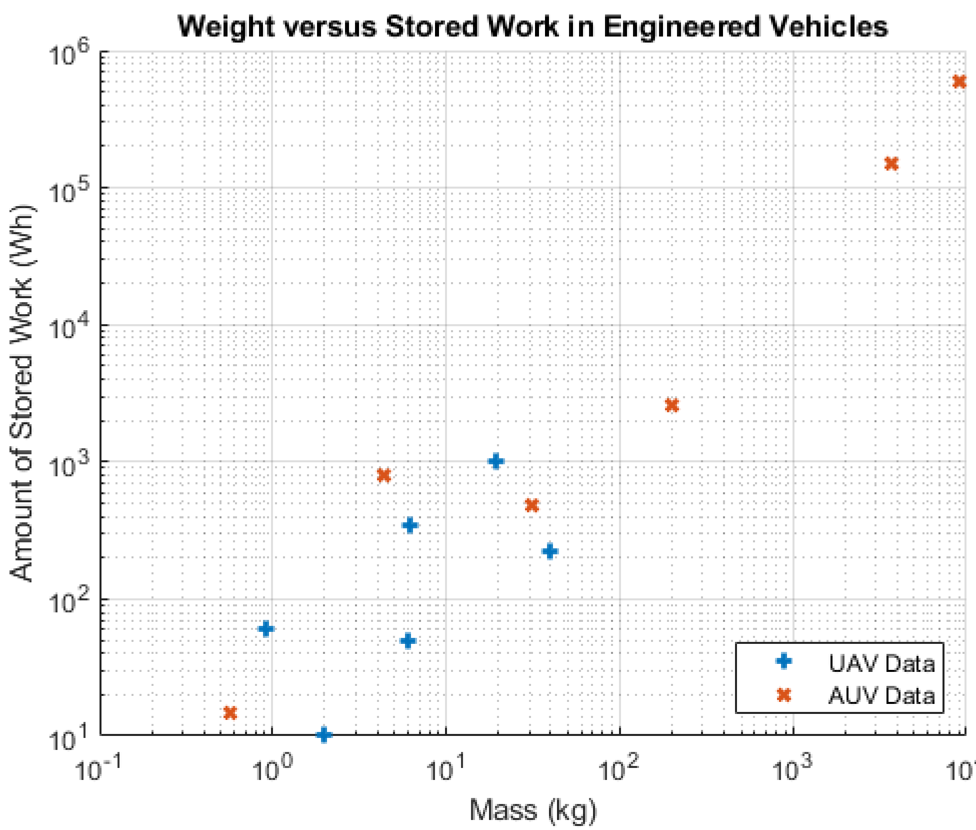

Figure 29: Weight versus stored work in engineered vehicles. Note. Author's own work based on data from various sources (Allen et al., 1997; Chao et al., 2017; Elipse VTOL - Shop with BAAM.Tech, 2021; Mavic 2 - Product Information - DJI, n.d.; Vertek | Fixed-Wing VTOL UAV | C-16 Condor, n.d.; Fabrique, n.d.; Gornak et al., 2006; Hyakudome et al., 2018; Pyle et al., 2012; Technologies, n.d.; Woolsey et al., 2017).

With all power sources, it is important to consider the weight of the vehicle to assure there is enough internal stored work to perform adequately. Shown in Figure 29 is a compilation of various unmanned aerial vehicles (UAV)'s and AUV's, many of which are commercially available, and the distribution of the amount of stored work per a given weight. The amount of stored energy that can be held within a power source can be quantified in watt-hours (Wh). This unit of measurement quantifies the amount of work that can be performed or generated within a power source. Additionally, the unit of measurement for weight is quantified in kilograms. Whereas there is no correct answer in the amount of stored work a power source must produce, modern engineered vehicles highlight how current engineers consider the relationship between weight and stored work.

4.3.5 Analysis of Weight on AAV Operation

The weight of any aerial vehicle is of utmost importance as it will heavily dictate operation capabilities. It was emphasized by an anonymous engineering expert that a vehicle must hold all necessary components used to survey, support detection devices, and to propel the vehicle. Professor Bertozzi mentioned that the amount of thrust required to stay airborne is connected to the lift generated and the weight of the vehicle. He provided a notable example of a 100lbs vehicle that utilizes VTOL for lift, the propellers need to generate at least 100lbs of thrust to maintain upward momentum at the bare minimum. In contrast, Professor Bertozzi mentioned if a vehicle utilized airfoils with a lift to drag ratio of 10 to generate lift, a 100lbs vehicle would only need 10lbs of thrust to stay airborne. No matter what method of propulsion is used, less weight requires less thrust to keep the vehicle airborne. The anonymous engineering expert implored to always keep in mind that an overweight vehicle cannot fly.

Likewise, each component and structural support adds weight which cannot be overlooked. The anonymous engineering expert explained that the expected operation time should be determined early on to help define the target weight for the vehicle. This target weight will help calculate how much energy needs to be stored by the fuel cell. The weight budget aims to aid in guiding the discussion of which tradeoffs to make during the design process. A study based around designing and building a cost-effective surveying drone developed plans for a hexacopter to weigh 6kg on its own with extra connectors and wires adding unexpected weight (Kauhanen et al., 2020). The planned flight time had a simulated minimum of 8.8 minutes and maximum of 12.0 minutes if there was no payload. While the drone can support a payload of up to 11kg, supporting this payload "would require full throttle and cripple the flight time to less than 3 minutes" (Kauhanen et al., 2020, p. 170). This example outlines the importance of considering how weight is necessary and how extra weight compromises the effectiveness of the vehicle.

It is important to understand that there are governmental agencies that could impose considerations during the design process. The Federal Aviation Administration (FAA) is a transportation agency in the United States that regulates, among other things, unmanned aerial vehicles. The anonymous engineering expert explained that Part 107 regulates unmanned vehicles up to 55lbs and any additional weight does not have any current regulations. Once an unmanned vehicle exceeds 55lbs, it is up to the designer to collaborate with the FAA to ensure governmental agencies will allow the vehicle to be legally operated. There were no identified regulations within the Baltic Sea, but it is important to keep in mind that regulations for drones are based on their weight. As the weight budget of the vehicle will impact operating time and legality, it is a major consideration for designers.

4.4 Expert Recommendations & Opinions for AAVs

Two conceptual methods of organizing the robotic system and various recommendations were gathered from experts in industry and academia. The first concept was from an anonymous engineering expert who suggested that it might be more feasible to split one vehicle up into a system of vehicles where each component specializes in either air or water, but specifically not both. An example of a multi-vehicle systems would consist of an aerial vehicle that deploys payloads of aquatic vehicles or sensing pods that would detect and relay information. The idea was based on current technology not being supportive of AAV operation. The second concept was from Professor Bertozzi, who suggested implementing an aerial vehicle that could land on the surface of the water and float, then lower a tethered probe into the sea. This style of vehicle would not completely submerge. The idea was based on using energy efficient gliding techniques that planes provide.

Interviewees also recommended that current technology may not support the style of AAV outlined by this report. There was a consensus within the interviews that the decrease in overall efficiency for one medium would be too much from having to accommodate the requirements of another terrain. Referencing hobby vehicles is an easy method to understand what is financially and technologically feasible because these designs incorporate aspects that can support healthy businesses. Professor Patterson mentioned that a viable option for completing the mission is to use commercially available vehicles that can incorporate payloads, such as oil detecting devices. While AAVs are not commercially available, a hobby aerial or aquatic vehicle could be implemented to complete their respective portion of the mission. Another aspect of using what is commercially available is that easily accessed replaceable parts allow for ease of repair.

Likewise, a crucial aspect of the design process was highlighted by the anonymous engineering expert who recommended that a designer should first determine the requirements to complete the mission, this clarifies aerial and aquatic necessities. The same expert also stated that complete functionality of the vehicle is essential for practical viability.

4.5 Findings Conclusion: Proposed Conceptual Vehicle Design

A multi-terrain vehicle that can traverse both air and water for oil pollution detection contains fundamental design considerations that must be examined. Through identifying the underlying themes that existed throughout the conducted interviews, literature reviews, and computer simulations, a set of proposed design considerations were concluded.

The first critical design constraint that was analyzed was the strategy for which the vehicle will identify pollutants within the Baltic Sea. In the air, the vehicle will fly above the sea with a thermal IR camera and implement machine learning algorithms to interpret the captured images. For further analysis, the AAV will land in the water, submerge to a shallow depth, and implement fluorometers to detect hydrocarbons such as petroleum and other oil-based contaminants. In the case of detected oil pollutants, environmental protection agencies, like the Helsinki Convention (HELCOM), will be notified by the AAV. The AAV will then begin to continually monitor the body of water until it detects another section of pollution. Whether the AAV is in the air or the water, in both cases the vehicle requires additional sensors that allow it to operate in a controlled manner. The vehicle will contain an IMU (Gyroscope, Accelerometer, Magnetometer, and GPS), side scanning sonar, barometer, and radar. The IMU plays a fundamental role in the location, orientation, and speed of the vehicle and allow it to understand its position in the Baltic Sea. The side scanning sonar will allow the vehicle to map its surrounding environment underwater. This sonar will need to be low power to reduce its environmental impact and not harm the surrounding ecosystem. The barometer will measure the air or water pressure to estimate the height or depth of the vehicle. With the inconsistencies from the barometer, a radar will be implemented for aerial maneuvering for an accurate elevation. Through the fusion of these sensors, the vehicle will be able to reliably operate in both terrains.

For the overall geometry of the vehicle, data heavily supported a fixed wing design with a single propeller. This design will provide better aerial efficiency over options like multi-rotors. The wing will be centered on the body vertically and be made up of a symmetrical airfoil. The airfoil will have a large aileron to dynamically camber the wing in air and will be on an actuated pivot to change its angle of attack underwater. The body of the craft will be kept slender to reduce drag in water. With a fixed wing design and the desired application, it is most sensible to go with a single aerial propeller on the craft. This is because aerial propellers can also work sufficiently in water, although the rotational speed will need to be reduced. A large propeller with a small number of blades will be engineered to aid in efficiency.

Given the geometry considerations, the most plausible material chosen is carbon fiber composite. This material is inherently lightweight which is great for aerial and aquatic use and has a high durability making it great for structural components. Carbon fiber is also a woven material that has infinitely many stacking sequences that can maximize flexural stiffness. These attributes make this material optimal for use between air and the water on a vehicle used for oil detection.

With many unknown parameters for a high-level conceptual vehicle like exact weight and operating power consumption, the most ideal power source that was identified was batteries. With various internal compositions, batteries were found to be the most versatile option for an AAV and can be carefully selected to be sustainable, resilient to its environment, and capable of electrically maintaining the system. Even though batteries can accompany rechargeable apparatuses such as solar cells, it was decided that the proposed vehicle would not contain these cells due to their instability in various environments. Across various weather conditions, there was a large variability in the effectiveness of solar panels, meaning assistance to the battery may not be feasible. Whereas it is possible that technology could evolve, based on current data solar cells are too unreliable to be a source of power.

Excess power used to carry unnecessary weight in the air or provide downward thrust underwater cannot be spared. As such, minimizing the weight of the vehicle will be crucial for extending operating time. In addition, it is intended for the vehicle to be neutrally buoyant in the Baltic Sea to reduce the power needed to dive. A passive system was chosen as opposed to an active one with the aim of reducing the complexity and weight of the vehicle. Regardless of variable buoyancy, an active system will consume power (Zavislak et al., 2021). Since the Baltic Sea has been recorded to have varying salinity and temperature, which affect density, true neutral buoyancy is unlikely (Millero & Kremling, 1976). The simplifications made to the vehicle will outweigh the mobility complications prevalent in slight positive or negative buoyancy.

With the conclusions of different subsystems, the mission design for the vehicle can also be described based on sustainability, purpose, and vehicle design aspects. Below in Figure 30, is shown a mockup of the stages of the mission the vehicle will go through.

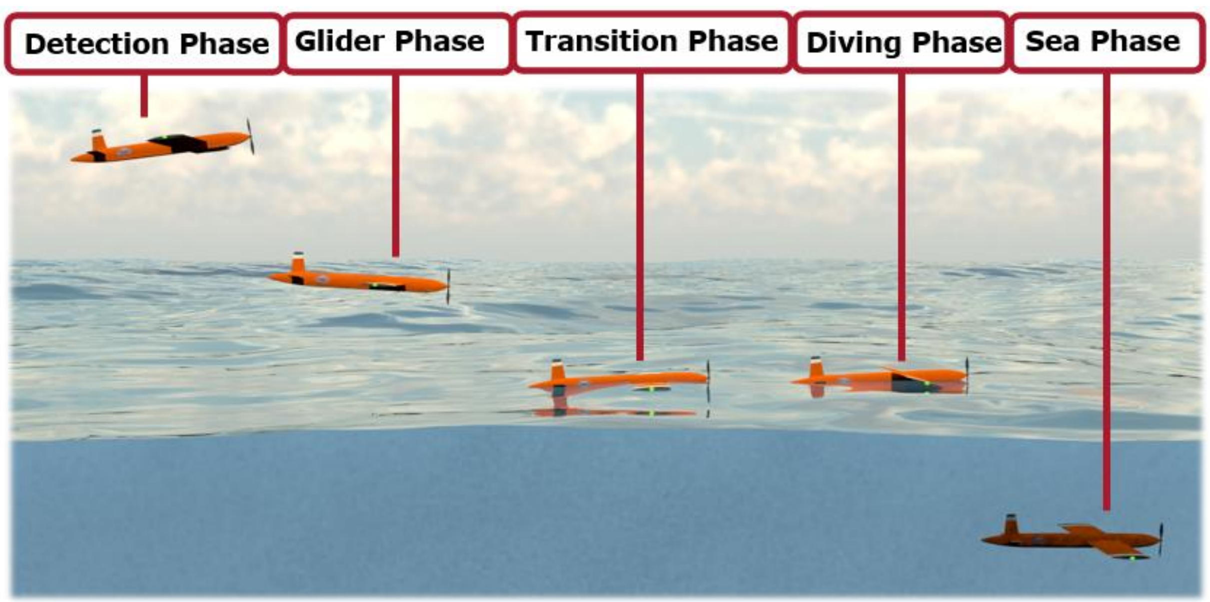

Figure 30: Five phase mission design of an AAV with a fixed wing for combined aero-amphibious oil detection

The first phase the vehicle will go through is the detection phase. During this phase, the vehicle will maintain a cruise speed between 15 and 20 m/s (from flow simulations) and will fly in a pattern specified by its user while utilizing an IR camera to seek oil slicks. When a slick is found, the GPS location will be recorded, and the vehicle will enter the glide phase. The glide phase is characterized by the initial action of turning off the propeller, turning the AAV into a glider. Aileron deflection will also be deployed at 7.5 degrees to achieve max lift at this point. GPS, accelerometers, and gyroscopes will allow the glider to glide down to the water at the same location. Once the AAV hits the water, the vehicle enters the transition phase, where it is essentially acting as a boat. At this point the vehicle's wing will be at zero angle of attack with zero deflection. The diving phase is initiated when the wing is brought to a negative angle of attack, which will cause a negative amount of lift. This negative amount of lift, combined with the neutral buoyancy of the vehicle, will allow the vehicle to dive down into the water. Diving will be complete when the vehicle reaches the user-defined depth. Lastly, during the Sea phase, the vehicle will move at 1 m/s, at which speed oil data will be collected and stored. Storing and collecting this data will allow for 3D mapping of the area where oil was detected.

5 DISCUSSION & RECOMMENDATIONS

In many engineering challenges there are no universal solutions that perfectly fits the desired need. Typically, tradeoffs are made to fit the precise application. After discovering that a serious contributor to oil-based water pollution in the Baltic Sea is the intentional dumping of oil from ships, we decided to base the concept vehicle around detecting this style of pollution. With this in mind, we narrowed the requirements down to a vehicle that could cover swathes of the sea on its own for extended periods of time. Once oil is found, the vehicle would glide down to the water to collect data on concentration and position to create a map of the spill for clean-up teams to use. Many, if not all, of our design choices contribute to supporting this goal, optimizing to receive the best results. While there are many possible vehicles that could have been conceptualized, our theorized vehicle was based on available technology and was guided by expert opinions and literary research.

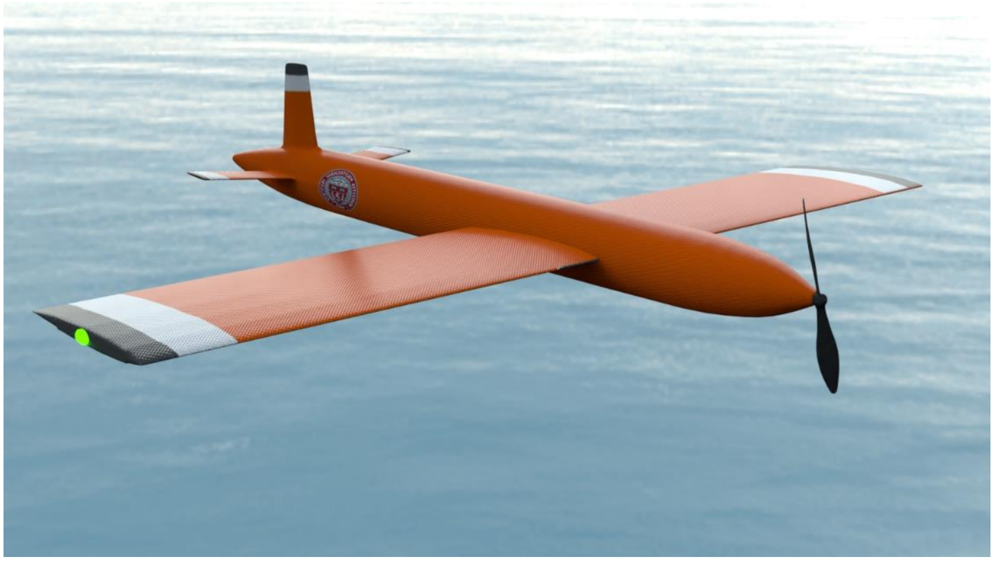

Figure 31: A rendering of our concept AAV. This illustration is a compilation of all gathered data and is heavily influenced by recommendations made by experts.

Shown in Figure 31 is a rendered image of the designed concept vehicle that encompasses all the data we have gathered during this project. This vehicle will be able to survey the Baltic Sea for signs of oil pollution, map oil spills, and operate in both aerial and aquatic environments.

5.1 Discussion of Modern Oil Detection Methods

It was through interview data that we were able to discover that IR thermal imaging is implemented in the Baltic Sea to detect oil pollutants. Additional literature research demonstrated that IR thermal imaging is the modern approach for detecting oil contamination and can successfully identify signs of pollution with machine learning algorithms. With little research on the comparison between manual and autonomous oil detection, it is possible for the proposed solution to be inferior to human performance. While it is also plausible that the contrary is true, it is worth noting that there was no identified evidence of an autonomous system performing better than a human in oil pollution identification.

To bolster the effectiveness of the system, the vehicle can traverse the water and measure the concentration of hydrocarbons using a fluorometer. This measurement allows the system to immediately evaluate the hazard and can cause rapid deployment of oil response teams. With the system of IR imaging and fluorometers, there also exists the reality of biofouling skewing oil pollution identification. We were unable to identify the effect of biofouling on these methods and still exists as an additional point of concern that could limit the effectiveness of the vehicle.

During the interview process with environmental protection experts, it was discovered that the environmental risk of oil-based water pollution stems from the current methods that exist for cleaning the water. The larger underlying issue is not in discovering contamination but getting the necessary materials to the site to extract the oil from the water. Elements such as traffic cause a large delay in cleaning the oil. Furthermore, weather conditions like high waves can diminish the effectiveness of the current oil cleaning strategies and thus increasing the harm of the oil spill. With the findings from this project, the autonomy of the vehicle in the Baltic Sea will theoretically allow the governing agencies to divert manpower from oil pollution detection to be more focused on oil spill clean-up. This project revealed that there may not be a technological limitation in the detection of oil spills, but a secondary benefit of increased technologies that will allow environmental protection agencies to redistribute manpower.

The outlined oil pollution system evaluated here is a counterpoint to the current commercial vehicles that exist for oil pollution due to the variance in targeted consumer. Many of the vehicles that exist today seem geared for the oil industry to help them survey their pipelines, whereas this project aims to assist governmental agencies in examining the Baltic Sea for pollution. Perhaps due to the difference in potential income, there were few available vehicles that can discover instances of chronic pollution in bodies of water.

5.2 Synthesizing Vehicle Operations & Autonomy

From interviews with three of our interviewed engineering experts, it was identified that certain sensors would be crucial in AAV operation. An IMU, consisting of a gyroscope, accelerometer, magnetometer, and GPS, was chosen to detect the orientation and position of the vehicle. We also selected a barometer for altitude measurements along with a radar to increase accuracy when the craft is approaching the water’s surface. From those main sensors, we believe the vehicle will be able to attain controlled motion by measuring movement in all translational and rotational axes. To complement the current suite of sensors, we elected a low power side scanning sonar to be added to detect and map the sea’s floor. In Section 4.2.5 (Sediment Disruption in Aquatic Environments), we identified sediment disruption as a possible issue that could be caused by our AAV. By detecting the sediment floor, we can throttle down the propulsion system or avoid the ocean floor to avoid sediment disruption. We reached these conclusions by asking comprehensive sensor questions for either aerial or aquatic vehicles. Due to this collection of data, there may be aspects to the operation of an AAV that are shared by neither type of vehicle. We have tried to consider all the operational scenarios for an AAV, but until there is more research into the creation of physical AAVs, it remains difficult to tell what additional sensors could be needed.

5.3 Discussion on Wing Design Methods

With the desired scope of this vehicle being within the remote areas of the Baltic Sea, it is apparent that surveying from the air would be the most efficient for detecting oil pollution over long distances. In this area, there are two typical options for geometry that must be synthesized, fixed wing aircraft and VTOL vehicles. It is apparent from interviews that fixed-wing aircrafts are inherently more efficient than VTOL. For this reason, the decision was made to view different methods of orienting wings on an aircraft. The geometry of the wing that will base our analysis is shown in Figure 32.

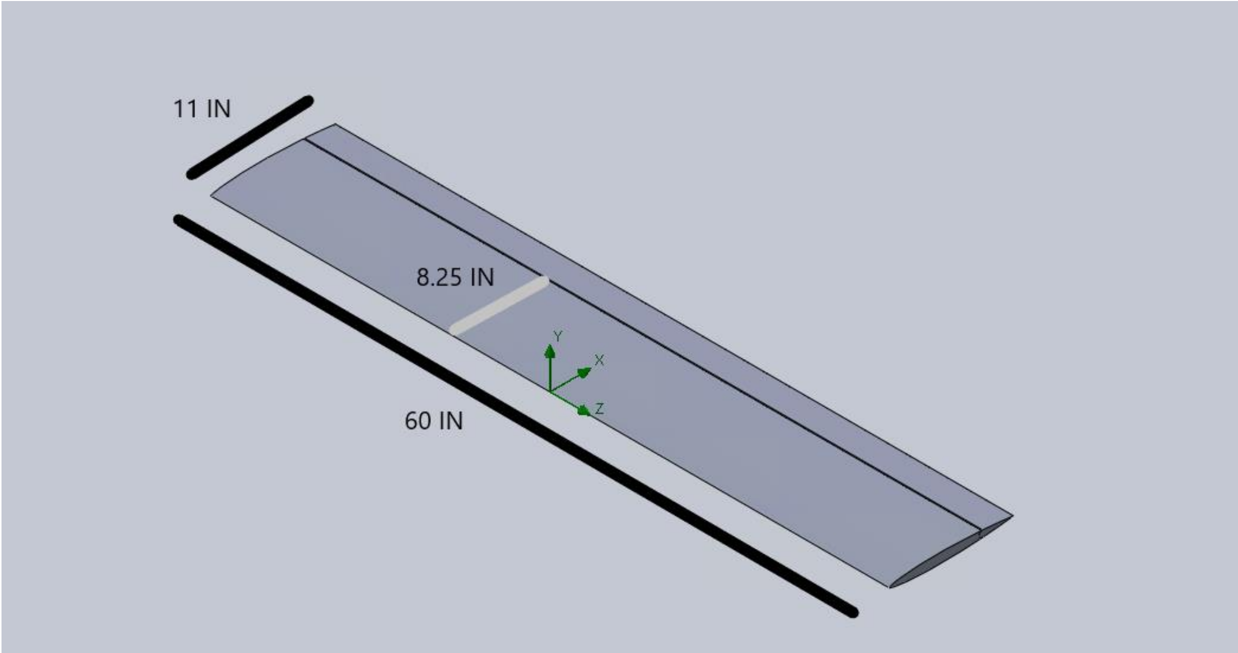

Figure 32: Symmetric with made from a NACA 0008 airfoil with a span of 60 inches and chord of 11 inches, designed with internal spars. An aileron is present at 8.25 inches from the leading edge.

Within this single design choice, it is also important to compare different orientations for these geometries based on the flow simulation analyses. The first was a wing with a deflecting flap at ¾ of the wing chord (aileron), and the second was actuating the wing entirely by turning it on its longitudinal axis (change in angle of attack). Each of these accounts for a single degree of freedom, meaning that a combined system with both actuation methods would have two degrees of freedom. Examination into both scenarios will provide insight into design differences that could optimize the fluid dynamics of the wing in air and water environments, respectively. This allows for a full integration of features to make the vehicle as efficient as possible.

In air, when viewing the action of an aileron for improved aerodynamics, an optimal range of deflections will generate a maximum lift-drag ratio. In the chart shown in Figure 17, Lift-drag ratio consistently goes up from 0 to 7.5 degrees of aileron deflection, exhibiting the peak between 7.5 and 10 degrees, proving to be the most lift-efficient orientation. At this ratio, the air velocity was 20 m/s, and lift generated was approximately 2.1 Newtons. Comparing the 20 m/s flow here to the same during the angle of attack-based simulations, maximum lift is generated at an angle of attack of 12 degrees for the symmetric airfoil, with a value of 15 Newtons. Taken at face value, it may be assumed that the best way to generate the most amount of lift is to increase the angle of attack, but this is not the case. When comparing range of travel of each actuation method, it is apparent that actuating the entire wing 360 degrees would require much more power as compared to actuating an aileron over a 15-degree range. Furthermore, comparing the actions of the wing at 20 m/s in both simulations, a change in angle of attack of as little as 1 degree due to disturbances could cause a loss in lift generation of 1 Newton, shown by the slope of the graph in Figure 25. This disturbance has the potential to cause unstable behavior of the aircraft if it needs to adjust quickly. For all these reasons, when a fixed-wing approach is used, the best method of actuation for lift generation in air, to both preserve power and stability was seen to be the elevator placed at 3/4 of the chord length on a NACA 0008 airfoil.

Since this is a multi-environment vehicle, the use of the fixed wing in water must also be further discussed. Comparing similar simulations to those done in air reveals a lot about the properties of both an airfoil with an aileron, and a symmetric airfoil with changing angle of attack. With water being much denser than air, the property of drag will be more extensively discussed. Looking at the top-speed of 1 m/s, minimum drag attained during the angle of attack study remained on the order of 0 to 0.5 Newtons. This is similar to the minimum drag of 0.25 Newtons at 0 degrees of aileron deflection. Drag is increased to around 2 Newtons at highest elevator deflection of 20 degrees, but at the highest angle of attack (12 degrees), that is decreased tenfold to 0.2 Newtons, which favors the use of full wing actuation. Looking into the lift characteristics in each of the same instances, lift is much greater at a high angle of attack, with a maximum lift of around 25 Newtons (at 12 degrees angle of attack). This lift generation is twice the amount achieved by the elevator being deflected 20 degrees at the same 1 m/s velocity. Unlike in air, stability is much less of a concern since the higher density causes pressure around the foil to be greater. In this case, angle of attack actuation appears to be better design choice since more lift will allow for diving into water to occur more naturally, where the wing can be turned completely vertical to allow for the vehicle to dive. Furthermore, reflecting analogies to submarines in the findings, the wing can be used at 0 angle of attack to maintain depth. It is also apparent that drag is greatly reduced with this method, with an outlying max still being around 0.6 Newtons, which is about 4 times smaller than the drag produced by the highest elevator deflection, shown in Figure 22. As a result, to the comparison between angle of attack and deflection in both mediums, we chose a wing that can actuate in two degrees of freedom. An elevator for deployment in air and an angle of attack actuation for water. The elevator will have a range of freedom of -10 to 10 degrees of deflection and the angle of attack actuation will move freely 360 degrees.

Both water and air simulations were conducted in 2D based on the fully symmetric nature of the 60-inch-long wing. This is important to note as the solver found lift and drag per unit span, and then applied that to the geometry. Chosen velocities for these simulations were chosen based off the approximate top speeds from the AAV created by Weisler et al.. Ranges for angle of attack were chosen based on typical aircraft stall ranges. Deflection was purely an experimentally chosen range.

5.4 Considerations for Overall Structural Design

As mentioned in Section 4 (Findings), the wing design takes the shape of a symmetric wing, using the NACA 0008 airfoil. Equally important to this is the general structural composition of the vehicle. To minimize weight and maximize strength, it was decided that a set of spars with one cross brace would be employed to hollow out the wing. For fluid mechanics testing, the shape of a wing is all that is considered, but in real world applications it is important to utilize light-weighting which preserves strength by cutting away unneeded material. On the interior of the wing, five spars were used, with two on the outside edge of the wing, and three on the inside of the wing, all equally spaced. A cross brace was placed at the halfway point between the leading edge and the deflecting flap, spanning the wing. Based on discussions with interviewees it was decided that the body would take the shape of a submarine. As this vehicle is purely conceptual, the exact shape and dimensions of the wings and body were chosen to convey findings and may not be optimal. The detailed analysis of sparring was intended for conveying a practical method to demonstrate the strength of varied materials. The full wing and internal spars, as well as a mock-up of the submarine shaped fuselage are presented below in Figure 33 and Figure 34.

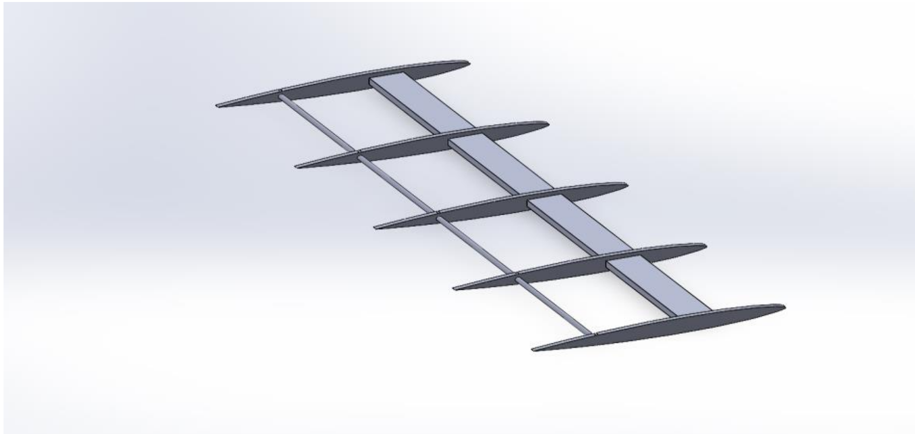

Figure 33: NACA 0008 airfoil wing skeleton, with 5 spars equal distance apart.

Figure 34: Submarine style hull design, inspired by several modern submarine and UUV designs

It should be noted that simulation of this wing was done for two dissimilar materials in SolidWorks. The structure withstood the highest load applied to it regardless of material and only deflected by a matter of millimeters at the free end. It is important to also observe that the wing did not exhibit any fracture or high-stress areas in these simulations, proving its structural stability for the purpose. Modeling this wing with the load at the free end being the highest lift value does assume that there is no load change across the wing surface, which is not fully accurate. A full theoretical model for this simulation would require the known pressure distribution in air and water on the wing. Given that the lift is extrapolated from this parameter, this approximation was sufficient for estimating the load bearing capabilities of the wing, and a valid proof of concept for both the sparring and varied materials.

5.5 Application of Materials to AAVs

When it comes to materials, it has been noted that carbon fiber composites would be the optimal choice for a vehicle made to traverse air and water in the Baltic Sea. When compared to other common aerial materials, carbon fiber is the better choice. This material was suggested through interviews with experts which prompted further research on the material. During further research, an aluminum alloy (AA6060) was another possible material that could be used, often found in aerospace applications. Carbon fiber composite materials are lightweight and durable, making it great for the body and structure of a vehicle that can swim and fly. The woven nature of the material makes it so it can be stacked or arranged in different orientations to maximize the flexural stiffness. It also has a wide range of thermal resistance. Aluminum alloy is often used for its high corrosion resistance, being lighter than steel, and high strength, and because of these properties, it is often found in the airframe or the engine of an aircraft. The strengths of the materials were compared and confirmed using SolidWorks. During these structural simulations, a carbon fiber-based wing and an aluminum alloy-based wing were tested under applied forces at the tip, with a length of 30 inches. It was observed that the aluminum alloy wing tip deformed around 2.06 mm and the carbon fiber composite wing deformed 1.50 mm. This is because carbon fiber has less density and more strength making it 33% more resistant to deformation than aluminum alloy, confirming that the carbon fiber is the better choice of material.

The high resistance to corrosion that aluminum alloy has is due to a self-formed oxide layer on the alloy's surface. Despite the high corrosion resistance, it was found that it is susceptible to chloride ions in sea water solutions, as the ions can destroy the oxide layer. This degradation releases particles of this aluminum alloy into the ecosystem, harming organisms and contaminating water ways and sediments. On the environmental side, a carbon fiber body would need a protective layer to ensure UV and moisture in the air would not degrade the material over time. It is a highly stable material in both aquatic and aerial environmental conditions, unlike aluminum alloys. These traits suggest carbon fiber composite materials were the best choice, of the investigated materials, for an AAV in the Baltic Sea.

5.6 Justification and Limitations for Batteries

Through all the proposed power sources, batteries were chosen due to their simplicity and customizability to produce sustainable energy for an AAV. The fuel cells (hydrogen and oxygen) require additional infrastructure to convert the fuel to electrical energy that can be readily harnessed. With weight being a prevalent concern, it was concluded that any fuel cell would add an additional weight that would be consequential to the performance of the vehicle.

Additionally, the customizability of a battery allows various internal configurations that can be specially selected for a variety of situations. Due to the theoretical nature of the project, there are underlying electrical characteristics that are unknown that prevent a more detailed analysis. For our considerations, analysis for the power supply was based upon interview data accompanied with market research of power sources and power storage in contemporary vehicles. These considerations do not extend to various electrical attributes such as the operating voltage, nominal current draw, and the absolute maximum current draw of the vehicle. Additionally, there are external characteristics that prevent a more comprehensive conclusion. Required amount of energy storage, temperature, and the operating time of the vehicle do not exist in a conceptual design and play a significant factor in the chosen battery composition.

The power source is vital to the operation of an AAV, for it will directly determine the operating time of the vehicle. The more energy stored in a power source relates to the operational time of the vehicle. Where there is no set time limit that the vehicle must be able to achieve, it is imperative that the vehicle can survive long enough to adequately survey a portion of the Baltic Sea. With no testing, it is unknown what constitutes an adequate portion of the Baltic Sea. Due to this subjectivity, it is important that the selected power source has a high specific energy and energy density that allows it to store a lot of potential energy while not incurring an excessive weight.

5.7 Considerations for Propulsion Strategies

Green energy systems, such as batteries, leave a small amount of available propulsion strategies. An aerial propeller was found to be the best option for its versatility and simplicity in design, where the size, propeller speed, and selected motor allow for a wide range of usability in a relatively small vehicle. Due to this small size, hobby parts that are designed for remote controlled aircraft could be applied to our conceptual vehicle to navigate both environments. With the use of commercially popular parts, hobby components would be easily acquired and therefore making it easier to repair and construct the AAV. These points influenced our decision to use a single hobby propeller spun by a low Kv electric motor. This system would be sufficient for our aquatic aspect because rotating the propeller at lower speeds will allow for efficient aquatic travel. Having two propellers, one specialized for air while the other for water, was also considered. After deliberation, we decided a large-surface-area propeller, which is more suited for water, in conjunction with the main aerial propeller would create unnecessary drag in air and thus require the propulsion system to consume more energy. Similarly, having the air propeller inactive in water would once again cause more energy than necessary to be exerted to move around. We felt that the additional drag in both environments will make the system less efficient. With our design, one propeller would be in continuous operation for both terrains, reducing the amount of wasted weight or energy.

The propulsion method is also largely dependent on the chosen geometry of the aircraft. Given that this is a fixed-wing aircraft, a single propeller mounted at the front of the vehicle was desired. This is an uncomplicated way to propel the vehicle while taking advantage of lift generation from the wings. Conversely, using a VTOL would not utilize the benefits of an aircraft's wings as well as increase the complexity as it requires four degrees of freedom to change direction. The complex control required from a rotorcraft also reflects the earlier discussion on the inherently less thrust-efficient nature of these vehicles. We found that our AAV could maneuver just as well with using one propeller and changing the angle of attack, opposed to a multi-rotor system, while also being simpler and more efficient.

5.8 Examination on the Impact of Weight & Buoyancy

Since the proposed AAV will be operating primarily in the air, we decided weight and buoyancy aspects should be optimized for improved flight characteristics. We chose to reduce weight as much as possible to optimize the operating time and reduce the burden on the propulsion system. This can be demonstrated in Figure 29 where the amount of power required in an engineered vehicles has a power relationship with weight. This can be demonstrated by the near linear nature of the AUV data points on a log-log plot. Since this report is developing a conceptual vehicle and not specific design plans, it is difficult to specify an exact weight. Since the vehicle will be traversing remote portions of the Baltic Sea, maximizing the flight time by reducing weight is crucial so the vehicle can cover as much area as possible.

Building on limiting weight and aquatic traversal, we decided to not include a variable buoyancy mechanism in the vehicle. Near the end of Section 4.5 (Findings Conclusion: Proposed Conceptual Vehicle Design), it was discussed that unnecessary energy could not be spared. An active buoyancy mechanism will consume precious energy for a portion of the mission, so we elected to avoid variable buoyancy. This led us to decide that a static density will allow the AAV to dive and hold its depth while exerting little to no energy. We think this is sufficient as the vehicle only needs to submerge to a shallow depth. In addition to the power constraints, we believe a variable buoyancy mechanism will contribute extra complexity to the design and additional unnecessary weight. It should be noted that information regarding buoyancy was not prevalent in our interviews which could be a result of our interview questions lacking the topic. To compensate the lack of information, we investigated existing aerial-aquatic vehicles and observed their buoyancy conclusions. The AAV will still be able to operate aquatically, but at a reduced efficiency.

5.9 Recommendations for Further Development

By using the considerations laid out here with additional research, future developers could design and construct a physical AAV for the purpose of detecting oil. For example, one would need to select components for the sensors and propulsion systems as well as develop control algorithms for the movement of the vehicle in the air and water. In addition, algorithms for data collection and analysis can be written and implemented. This would include taking the data collected and mapping a three-dimensional graph of the oil pollution. Collecting data is important but discovering a way for it to be useful is what makes the difficult development valuable. Other areas of future inquiry include extending our single vehicle into a multi-vehicle system to cover a large area of sea very quickly. Finally, AAVs may not be the most suitable vehicle in its current form. Some of the interviewees commented that much of the technology used to create AAVs needs further refinement and development. They recommended different forms the vehicle could take including separate aquatic and aerial vehicles or an aerial vehicle that releases a small tethered underwater vehicle. The analysis of these multi-vehicle systems, as compared to our conceptual design, will help to find an even more capable method of detecting oil spills. We hope that future research will further aid the in swift detection of oil pollution.

5.10 Conclusion

The work completed in this report will provide beneficial progress towards creating autonomous aero-amphibious vehicles designed to operate in the open waters of the Baltic Sea, particularly pertaining to keeping sustainable practices intact. Information compiled on the factors that affect different environments can be easily applied beyond our vehicle. Assisting in this initiative is the selection of a renewable energy source, and examination of others that are equally safe for the environment. This is imperative in a world where gas engines are becoming outdated. Our AAV also employs several systems contributing to the field of autonomous surveying drones. Some notable achievements are the combination of previously used IR imaging for detection in air and combining that capability with the use of underwater sensing for mapping. Having a way to map oil spills and identify them through a mission plan, as shown in Figure 30, combines the typical processes of identification and tracking. This could also go even farther in providing a way to see how oil may carry in different currents or still bodies of water. Likewise, structural considerations of the drone allow for lots of leeway with the development of future drones for similar purposes in aerial-aquatic fixed-wing vehicles. Our findings will enable future developers, such as later IQP teams guided by Worcester Polytechnic Institute or protection agencies such as many Baltic Sea coast guards, to contributed towards improved detection of oil-based water pollution. By being able to understand the magnitude and location of oil pollution, response teams can coordinate their actions and mitigate the ecological effects of contamination.

6 REFERENCES

Albiez, J., Joyeux, S., Gaudig, C., Hilljegerdes, J., Kroffke, S., Schoo, C., Arnold, S., Mimoso, G., Alcantara, P., Saback, R., Britto, J., Cesar, D., Neves, G., Watanabe, T., Merz Paranhos, P., Reis, M., & Kirchner, F. (2015). FlatFish—A compact subsea-resident inspection AUV. *OCEANS 2015 - MTS/IEEE Washington*, 1–8. https://doi.org/10.23919/OCEANS.2015.7404442

Allachi, H., Chaouket, F., & Draoui, K. (2010). Protection against corrosion in marine environments of AA6060 aluminium alloy by cerium chlorides. *Journal of Alloys and Compounds*, *491*(1), 223–229. https://doi.org/10.1016/j.jallcom.2009.11.042

Allen, B., Stokey, R., Austin, T., Forrester, N., Goldsborough, R., Purcell, M., & von Alt, C. (1997). REMUS: A small, low cost AUV; system description, field trials and performance results. Oceans '97. MTS/IEEE Conference Proceedings, 2, 994–1000 vol.2. https://doi.org/10.1109/OCEANS.1997.624126

Aluminum extrusion metal, 6060 series alloys safety data sheet. (2015). Sierra Aluminum. https://www.samuel.com/globalassets/our-businesses/sierra-aluminum/pdfs/sds_6060_alloys.pdf

Ansari, M., Chakrabarti, A., & Iqbal, M. (2016). Effects of impactor and other geometric parameters on impact behavior of FRP laminated composite plate. *Modelling, Measurement and Control A*, *89*, 25–44.

Asadzadeh, S., Oliveira, W. J. de, & Souza Filho, C. R. de. (2022). UAV-based remote sensing for the petroleum industry and environmental monitoring: State-of-the-art and perspectives. *Journal of Petroleum Science and Engineering*, *208*, 109633. https://doi.org/10.1016/j.petrol.2021.109633

Bacaksizlar, N. G., & Önsel, N. (2013). *Modeling the dynamics of methylmercury biomagnification*. 12.

Carbon fiber products: Safety data sheet. (2018). Finite Fiber. https://www.finitefiber.com/images/pdf/Carbon%20SDS.pdf

Carmo, J. E., Torres, J. P. N., Cruz, G., & Marques Lameirinhas, R. A. (2021). Effect of the inclusion of photovoltaic solar panels in the autonomy of uav time of flight. *Energies*, *14*(4). https://doi.org/10.3390/en14040876

Chahouri, A., Elouahmani, N., & Ouchene, H. (2022). Recent progress in marine noise pollution: A thorough review. *Chemosphere*, *291*. https://doi.org/10.1016/j.chemosphere.2021.132983

Chaturvedi, S. K., Vishwath, N. C. A., Verma, H., & Manchanda, T. (2019). Unmanned aero-amphibious vehicle: Preliminary study on conceptual design. *INCAS Bulletin*, *11*(3), 41–53. https://doi.org/doi.org/10.13111/2066-8201.2019.11.3.4

Chao, S., Guan, G., & Hong, G.-S. (2017). Design of a finless torpedo shaped micro AUV with high maneuverability. OCEANS 2017 - Anchorage, September 18, 2017 - September 21, 2017, 2017-January, 1–6.

Cruzatty, C., Sarmiento, E., Valencia, E., & Cando, E. (2022). *Design methodology of a UAV propeller implemented in monitoring activities*. *49*, 115–121. Scopus. https://doi.org/10.1016/j.matpr.2021.07.481

De Soto, N. A., Gkikopoulou, K., Hooker, S., Isojunno, S., Johnson, M., Miller, P., Tyack, P., Wensveen, P., Donovan, C., Harris, C. M., Harris, D., Marshall, L., Oedekoven, C., Prieto, R., & Thomas, L. (2016). From physiology to policy: A review of physiological noise effects on marine fauna with implications for mitigation. *4th International Conference on the Effects of Noise on Aquatic Life 2016, July 10, 2016 - July 16, 2016*, *27*(1). https://doi.org/10.1121/2.0000299

Degraer, S., Moerkerke, G., Rabaut, M., Van Hoey, G., Du Four, I., Vincx, M., Henriet, J.-P., & Van Lancker, V. (2008). Very-high resolution side-scan sonar mapping of biogenic reefs of the tube-worm Lanice conchilega. *Remote Sensing of Environment*, *112*(8), 3323–3328. https://doi.org/10.1016/j.rse.2007.12.012

Durban, J. W., Southall, B. L., Calambokidis, J., Casey, C., Fearnbach, H., Joyce, T. W., Fahlbusch, J. A., Oudejans, M. G., Fregosi, S., Friedlaender, A. S., Kellar, N. M., & Visser, F. (2022). Integrating remote sensing methods during controlled exposure experiments to quantify group responses of dolphins to navy sonar. *Marine Pollution Bulletin*, *174*. https://doi.org/10.1016/j.marpolbul.2021.113194

Dutczak, J. (2018). Issues related to fuel cells application to small drones propulsion. *Scientific Conference on Automotive Vehicles and Combustion Engines, KONMOT 2018, September 13,*

2018 - September 14, 2018, *421*(4), Development and Research Centre BOSMAL; EC Engineering; FEV Poland; Horus-Energia; Polish Scientific Society of Combustion Engines (PTNSS). https://doi.org/10.1088/1757-899X/421/4/042014
Ehlin, U. (1981). Chapter 2 Hydrology of the Baltic Sea. In *Elsevier Oceanography Series* (Vol. 30, pp. 123–134). Elsevier. https://doi.org/10.1016/S0422-9894(08)70139-9
Elipse VTOL - Shop with BAAM.Tech. (2021, May 7). https://baam.tech/design/product/elipse/
Fabrique. (n.d.). Avy Aera 3—Avy—Drones for good. Retrieved March 29, 2022, from https://avy.eu/our-integrated-solution/new-aera/
Farmer, A. (1997). Pollution of the marine environment. In *Managing Environmental Pollution*. Routledge.
Fingas, M., & Brown, C. E. (2015). *Oil Spill remote sensing*. 311–356. https://doi.org/10.1002/9781118989982.ch12
Fleischer, M., Sarofim, A. F., Fassett, D. W., Hammond, P., Shacklette, H. T., Nisbet, I. C., & Epstein, S. (1974). Environmental impact of cadmium: A review by the Panel on Hazardous Trace Substances. *Environmental Health Perspectives*, *7*, 253–323. https://doi.org/10.1289/ehp.747253
Flemming, H.-C. (2002). Biofouling in water systems – cases, causes and countermeasures. *Applied Microbiology and Biotechnology*, *59*(6), 629–640. https://doi.org/10.1007/s00253-002-1066-9
Gao, K. (n.d.). *RC Basics: Motor Turns & Kv Rating*. AsiaTees.Com. Retrieved April 15, 2022, from https://www.asiatees.com/article?id=2200
Gao, Y., Zhang, H., Yang, H., Tan, S., Gulliver, T. A., & Lu, T. (2021). Trans-Domain amphibious unmanned platform based on coaxial counter-propellers: Design and experimental validation. *IEEE Access*, *9*, 149433–149446. https://doi.org/10.1109/ACCESS.2021.3125138
Gornak, V. E., Inzartsev, A. V., Lvov, O. Yu., Matvienko, Y. V., & Scherbatyuk, A. Ph. (2006). MMT 3000—Small AUV of new series of IMTP n FEB RAS. OCEANS 2006, September 18, 2006 - September 21, 2006. https://doi.org/10.1109/OCEANS.2006.306803
Gurrappa, I. (2003). Characterization of titanium alloy Ti-6Al-4V for chemical, marine and industrial applications. *Materials Characterization*, *51*(2), 131–139. https://doi.org/10.1016/j.matchar.2003.10.006
Hahn, R., Mainert, J., Glaw, F., & Lang, K.-D. (2015). Sea water magnesium fuel cell power supply. Journal of Power Sources, 288, 26–35. https://doi.org/10.1016/j.jpowsour.2015.04.119
Holstein, A., Kappas, M., Propastin, P., & Renchin, T. (2018). Oil spill detection in the Kazakhstan sector of the Caspian Sea with the help of ENVISAT ASAR data. *Environmental Earth Sciences*, *77*(5). https://doi.org/10.1007/s12665-018-7347-0
Hyakudome, T., Tani, T., Ito, H., & Sugihara, K. (2018). Concept of Long Cruising Range Autonomous Underwater Vehicle Powered by Fuel Cell. 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO), 1–5. https://doi.org/10.1109/OCEANSKOBE.2018.8559227
Ibrahim, F., & Nor, M. F. M. (2011). Finite element analysis (fea) of a tear-drop shaped unmanned underwater vehicle (uuv). *Defence S&T Technical Bulletin*, *4*(2), 144–152.
International Bird Rescue Research Center. (2010). Gulf Oiled Pelicans [Digital]. https://flickr.com/photos/49788193@N03/4670207222
Jackson, J. B. C., Cubit, J. D., Keller, B. D., Batista, V., & Burns, K. (1989). Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science*, *243*(4887), 37. https://doi.org/10.1126/science.243.4887.37
Jernelöv, A. (2010). The threats from oil spills: Now, then, and in the future. *Ambio*, *39*(5/6), 353–366.
Jha, A. R. (2016). *Next-generation batteries and fuel cells for commercial, military, and space applications* (p. 368). CRC Press.
Karabetsky, D. (2016). Solar rechargeable airplane: Power system optimization. *2016 4th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC)*, 218–220. https://doi.org/10.1109/MSNMC.2016.7783146
Kato, N., Choyekh, M., Dewantara, R., Senga, H., Chiba, H., Kobayashi, E., Yoshie, M., Tanaka, T., & Short, T. (2017). An autonomous underwater robot for tracking and monitoring of subsea plumes after oil spills and gas leaks from seafloor. *Journal of Loss Prevention in the Process Industries*, *50*, 386–396. https://doi.org/10.1016/j.jlp.2017.03.006

Kauhanen, H., Rönnholm, P., Vaaja, M., & Hyyppä, H. (2020). *Designing and building a cost-efficient survey drone*. *43*(B1), 165–172. Scopus. https://doi.org/10.5194/isprs-archives-XLIII-B1-2020-165-2020

Kostianoy, A. G. (2020). Oil pollution: The Baltic Sea. In *Managing Water Resources and Hydrological Systems* (2nd ed.). CRC Press.

Koti, V., ArunaKumara, P. C., Sindhoora, V., Peddada, K., Upadhyaya, G. S., Gaonkar, S., & Chandragowda, M. (2021). Development of fin propelled unmanned underwater drone. *International Journal of Vehicle Structures & Systems*, *13*(3), 357–360. https://doi.org/doi.org.ezpv7-web-p-u01.wpi.edu/10.4273/ijvss.13.3.23

Krek, E. V., Krek, A. V., & Kostianoy, A. G. (2021). Chronic oil pollution from vessels and its role in background pollution in the southeastern Baltic Sea. *Remote Sensing*, *13*(21), 4307. http://dx.doi.org/10.3390/rs13214307

Kronberg, B. (2016). The hydrophobic effect. *Current Opinion in Colloid & Interface Science*, *22*, 14–22. https://doi.org/10.1016/j.cocis.2016.02.001

Kumar, B. G., Singh, R. P., & Nakamura, T. (2002). Degradation of carbon fiber-reinforced epoxy composites by ultraviolet radiation and condensation. *Journal of Composite Materials*, *36*(24), 2713–2733. https://doi.org/10.1177/002199802761675511

Liu, J.-S., & Li, D.-W. (2021). A drone patrol system for target object counting and geolocalization. *2021 18th International Conference on Ubiquitous Robots (UR)*, 357–362. https://doi.org/10.1109/UR52253.2021.9494676

Liu, Y., Hajj, M., & Bao, Y. (2022). Review of robot-based damage assessment for offshore wind turbines. *Renewable and Sustainable Energy Reviews*, *158*, 112187. https://doi.org/10.1016/j.rser.2022.112187

Lombardi, J. P., Haydon, T. C., Gallati, W. G., & Trant, P. M. (2016, October 17). *Applications of GNOM robot*. Worcester Polytechnic Institute.

Lu, J., Tang, T., Bai, C., Gao, H., Wang, J., Li, C., Gao, Y., Guo, Z., & Zong, X. (2020). *Reviews of fuel cells and energy storage systems for unmanned undersea vehicles*. https://doi.org/10.1080/15567036.2020.1795313

Luo, Q., Li, J., Li, B., Liu, B., Shao, H., & Li, Q. (2019). Kinetics in Mg-based hydrogen storage materials: Enhancement and mechanism. Journal of Magnesium and Alloys, 7(1), 58–71. https://doi.org/10.1016/j.jma.2018.12.001

Ma, L., Liu, Y., Zhang, X., Ye, Y., Yin, G., & Johnson, B. A. (2019). Deep learning in remote sensing applications: A meta-analysis and review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *152*, 166–177. https://doi.org/10.1016/j.isprsjprs.2019.04.015

Ma, Z., Feng, J., & Yang, J. (2018). Research on vertical air-water transmedia control of hybrid unmanned aerial underwater vehicles based on adaptive sliding mode dynamical surface control. *International Journal of Advanced Robotic Systems*, *15*(2). https://doi.org/10.1177/1729881418770531

Mavic 2—Product Information—DJI. (n.d.). DJI Official. Retrieved March 29, 2022, from https://www.dji.com/mavic-2/info

Mayandi, K., Rajini, N., Ayrilmis, N., Indira Devi, M. P., Siengchin, S., Mohammad, F., & Al-Lohedan, H. A. (2020). An overview of endurance and ageing performance under various environmental conditions of hybrid polymer composites. *Journal of Materials Research and Technology*, *9*(6), 15962–15988. https://doi.org/10.1016/j.jmrt.2020.11.031

McGlynn, D. (2013, November 1). Diving to the edge of darkness. *Berkeley Engineer Magazine*, *Fall*. https://engineering.berkeley.edu/news/2013/11/diving-to-the-edge-of-darkness/

Mehdi, S. R., Raza, K., Huang, H., Naqvi, R. A., Ali, A., & Song, H. (2022). Combining deep learning with single-spectrum UV imaging for rapid detection of HNSs spills. *Remote Sensing*, *14*(3). Scopus. https://doi.org/10.3390/rs14030576

Millero, F. J., & Kremling, K. (1976). The densities of Baltic Sea waters. *Deep-Sea Research and Oceanographic Abstracts*, *23*(12), 1129–1138. Scopus. https://doi.org/10.1016/0011-7471(76)90889-5

Nguyen-Dinh, N., Hejjaji, A., Zitoune, R., Bouvet, C., & Salem, M. (2020). New tool for reduction of harmful particulate dispersion and to improve machining quality when trimming carbon/epoxy composites. *Composites Part A: Applied Science and Manufacturing*, *131*, 105806. https://doi.org/10.1016/j.compositesa.2020.105806
Noguchi, Y., & Maki, T. (2021). Tracking omnidirectional surfaces using a low-cost autonomous underwater vehicle. *IEEE Journal of Oceanic Engineering*, *46*(1), 11–23. https://doi.org/10.1109/JOE.2020.2972046
NormanEinstein. (2006). Map of the Baltic Sea. Own work (Created by NormanEinstein). https://commons.wikimedia.org/wiki/File:Baltic_Sea_map.png
Pacheco-Torgal, F. (2020). Introduction to advances in construction and demolition waste. In F. Pacheco-Torgal, Y. Ding, F. Colangelo, R. Tuladhar, & A. Koutamanis (Eds.), *Advances in Construction and Demolition Waste Recycling* (pp. 1–10). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-819055-5.00001-2
Palaniappan, A., Ganesh, P., Pranesh, S. B., Sathianarayanan, D., & Ramadass, G. A. (2019). Design and development of unmanned underwater and aerial vehicle. *Lecture Notes in Civil Engineering*, *22*, 479–489. Scopus. https://doi.org/10.1007/978-981-13-3119-0_28
Peng, C., Guan, C., Lin, J., Zhang, S., Bao, H., Wang, Y., Xiao, G., Chen, G. Z., & Wang, J.-Q. (2018). A Rechargeable High-Temperature Molten Salt IronOxygen Battery. ChemSusChem, 11(11), 1880–1886. https://doi.org/10.1002/cssc.201800237
Piatt, J. F., Lensink, C. J., Butler, W., Kendziorek, M., & Nysewander, D. R. (1990). Immediate Impact of the “Exxon Valdez” Oil Spill on Marine Birds. *The Auk*, *107*(2), 387–397. https://doi.org/10.2307/4087623
Pracheil, B. M., Snow, D. D., & Pegg, M. A. (2010). Distribution of Selenium, Mercury, and Methylmercury in Surficial Missouri River Sediments. *Bulletin of Environmental Contamination and Toxicology*, *84*(3), 331–335. http://dx.doi.org.ezpv7-web-p-u01.wpi.edu/10.1007/s00128-009-9932-0
Pyle, D., Granger, R., Geoghegan, B., Lindman, R., & Smith, J. (2012). Leveraging a large UUV platform with a docking station to enable forward basing and persistence for light weight AUVs. 2012 Oceans, 1–8. https://doi.org/10.1109/OCEANS.2012.6404932
Radio Detection and Ranging. (1943). *Nature*, *152*(3857), 391–392. https://doi.org/10.1038/152391b0
Rheinheimer, G. (1998). *Pollution in the Baltic Sea*. https://link.springer.com/article/10.1007/s001140050508
Rossini, F. D. (1960). Hydrocarbons in petroleum. *ACS Publications: Division of Chemical Education*. https://doi.org/10.1021/ed037p554
Rumson, A. G. (2021). The application of fully unmanned robotic systems for inspection of subsea pipelines. *Ocean Engineering*, *235*. Scopus. https://doi.org/10.1016/j.oceaneng.2021.109214
Safety Data Sheet: Spherical APA Ti-6Al-4V Powder. (2016). Advanced Powders & Coatings. https://www.ge.com/additive/sites/default/files/2018-04/SDS-Ti-6Al-4V-Coarse-English-16-04-15.pdf
Sahoo, P., & Pan, Y. (2020). *Preliminary Study Of Transformable Submersible Hydrofoil Trimaran*. OMAE 2020, Fort Lauderdale, FL. https://bt.e-ditionsbyfry.com/article/Preliminary+Study+Of+Transformable+Submersible+Hydrofoil+Trimaran/3907071/694411/article.html
Salomons, W. (1985). Sediments and water quality. *Environmental Technology Letters*, *6*(1–11), 315–326. https://doi.org/10.1080/09593338509384349
Schmidt, N. (2016). *Experimental Procedures and Data Analysis of Orthotropic Composites*. 119.
Schneider, A., Porter, E., & Baker, J. (2007). Polychlorinated Biphenyl release from resuspended Hudson River sediment. *Environmental Science & Technology*, *41*(4), 1097–1103.
Shen, K.-C., & Pan, G. (2021). Buckling and strain response of filament winding composite cylindrical shell subjected to hydrostatic pressure: Numerical solution and experiment. *Composite Structures*, *276*, 114534. https://doi.org/10.1016/j.compstruct.2021.114534

Somireddy, M., & Czekanski, A. (2020). Anisotropic material behavior of 3D printed composite structures – Material extrusion additive manufacturing. *Materials & Design*, *195*, 108953. https://doi.org/10.1016/j.matdes.2020.108953

Sultana, S., & Zhi, C. (2007). *A review of noise impacts from offshore oil-gas production activities on the marine biota*. *35*(3), 174–176.

Tan, Y. H., & Chen, B. M. (2020). A morphable aerial-aquatic quadrotor with coupled symmetric thrust vectoring. *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2223–2229. https://doi.org/10.1109/ICRA40945.2020.9196687

Technical Specifications. (n.d.). DeltaQuad VTOL UAV. Retrieved March 29, 2022, from https://www.deltaquad.com/resources/technical-specifications/

The Helsinki Convention – HELCOM. (n.d.). Retrieved April 12, 2022, from https://helcom.fi/about-us/convention/

Vandana, M. P., Mahto, U., & Das, S. (2022). *Chapter 2. Mechanism of toxicity and adverse health effects of environmental pollutants | Elsevier Enhanced Reader*. https://doi.org/10.1016/B978-0-323-85455-9.00024-2

Vertek | Fixed-Wing VTOL UAV | C-16 Condor. (n.d.). Vertek. Retrieved March 29, 2022, from https://www.vertek.io/c-16-condor

Walsh, I. (2018). *Identifying oil in water with the SeaOWL UV-A fluorescence and backscattering instrument*. Sea-Bird Scientific. https://www.seabird.com/technical-papers/SeaOWL-case-study

Walsh, I., Robinson, B., Koegler, J., & Conmy, R. (2016). *Oil in water fluorescence and backscattering relationships*. https://www.seabird.com/asset-get.download.jsa?id=54627861907

Watts, J. (2019, May 6). Human society under urgent threat from loss of Earth's natural life. *The Guardian*. https://www.theguardian.com/environment/2019/may/06/human-society-under-urgent-threat-loss-earth-natural-life-un-report

Weisler, W., Stewart, W., Anderson, M. B., Peters, K. J., Gopalarathnam, A., & Bryant, M. (2018). Testing and characterization of a fixed wing cross-domain unmanned vehicle operating in aerial and underwater environments. *IEEE Journal of Oceanic Engineering*, *43*(4), 969–982. https://doi.org/10.1109/JOE.2017.2742798

WikiImages. (2013). Scandinavia, Norway, Winter, Icy [Digital]. https://pixabay.com/photos/scandinavia-norway-winter-icy-67676/

Withgott, J. H., & Laposata, M. (2014). *Essential Environment: The Science behind the Stories*. Pearson Education.

Woolsey, M., Adams, L. D., & Jarnagin, R. (2017). Integration of pressure-tolerant lithium ion battery modules within the Mola AUV. OCEANS 2017 - Anchorage, 1–7.

Xia, X. C., Cao, X. K., Cai, G. Y., Jiang, D., Zhang, F., & Dong, Z. H. (2021). Underwater superoleophobic composite coating characteristic of durable antifouling and anticorrosion properties in marine environment. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *628*, 127323. https://doi.org/10.1016/j.colsurfa.2021.127323

Yang, Y., Hirose, S., Debenest, P., Guarnieri, M., Izumi, N., & Suzumori, K. (2016). Development of a stable localized visual inspection system for underwater structures. *Advanced Robotics*, *30*(21), 1415–1429. https://doi.org/10.1080/01691864.2016.1218794

Yim, U. H., & Short, J. (2017). Marine environmental emergencies in the North Pacific Ocean: Lessons learned from recent oil spills. *Archives of Environmental Contamination and Toxicology*, *73*(1), 1–4. http://dx.doi.org/10.1007/s00244-017-0416-7

Zavislak, C., Keow, A., Chen, Z., & Ghorbel, F. (2021). AUV tool manipulation with hard and soft actuators. *IEEE Robotics and Automation Letters*, *6*(4), 8553–8560. Scopus. https://doi.org/10.1109/LRA.2021.3110537

Zengel, S., Weaver, J., Mendelssohn, I. A., Graham, S. A., Lin, Q., Hester, M. W., Willis, J. M., Silliman, B. R., Fleeger, J. W., McClenachan, G., Rabalais, N. N., Turner, R. E., Hughes, A. R., Cebrian, J., Deis, D. R., Rutherford, N., & Roberts, B. J. (2022). Meta-analysis of salt marsh vegetation impacts and recovery: A synthesis following the Deepwater Horizon oil spill. *Ecological Applications*, *32*(1). Scopus. https://doi.org/10.1002/eap.2489

Zhang, X., Chen, Y., & Hu, J. (2018). Recent advances in the development of aerospace materials. *Progress in Aerospace Sciences*, *97*, 22–34. https://doi.org/10.1016/j.paerosci.2018.01.001
Zhao, Q., Zhang, D., Zhao, X.-L., & Sharma, S. (2021). Modelling damage evolution of carbon fiber-reinforced epoxy polymer composites in seawater sea sand concrete environment. *Composites Science and Technology*, *215*, 108961. https://doi.org/10.1016/j.compscitech.2021.108961

7 APPENDICES

7.1 Appendix A

Ethical Standards

Prior to the formal start of each meeting, explicit verbal and written communication will be acquired from the interviewee to allow for their recording. In addition to this, prior to the publication of the project, the interviewee will be allowed to review the material produced because of their interview and be allowed to revoke their consent to be studied at any point in time prior to project's publication.

7.2 Appendix B

Interview Preamble

We are students from Worcester Polytechnic Institute. We are conducting research into the design requirements of an Autonomous Aerial-aquatic Vehicle or AAV that can detect oil pollutants in bodies of water. We wish to interview you for your expertise in one of our subject areas of interest. Your participation is completely voluntary, and you may choose to withdraw and end your participation at any time. Do you agree to be interviewed? If so, may we record our interview for the purpose of data retention? Additionally, do we have your permission to quote you for our final report or would you prefer to stay anonymous?

7.3 Appendix C

Preliminary Interview Questions

7.3.1 Objective 1

Below is a series of preliminary focus areas and sample questions we used to create questions to ask in our interviews with individuals who are involved with the survey of bodies of water for pollution and those who survey for oil in bodies of water.

Table 2: An outline of possible questions to be asked during interviews with two types of interviewees

Focus Area	Questions for interviewees that survey bodies of water for pollution	Questions for interviewees that survey bodies of water for oil
Introduction	How long have you been involved in surveying bodies of water for pollution in general and how did you find yourself here?	How long have you been involved in oil detection in general and how did you find yourself here?
Current methods and technologies	What are the current methods or technologies that you rely on for surveillance of bodies of water?	What are the current methods or technologies that you rely on for oil detection?
Causes	What do you find to cause the most amount of pollution in a certain body of water?	What do you find to cause the most amount of oil pollution in a certain body of water?
Response time	What factors cause a delay in response time for pollution clean-up?	What factors cause a delay in response time for an oil spill?
Factors to look for	What are some indicators that pollution is a major issue in a body of water?	What are some indicators to look for that an oil spill has occurred?
How to determine where AAVs will be needed	How do you determine if a body of water needs surveillance for pollution?	How do you determine if a body of water needs surveillance for oil pollution?

7.3.2 Objective 2

Below is a preliminary series of questions we plan to ask in our interviews with experts who are involved with environmental engineering and knowledge of materials, sensors, propulsion systems, and other facets of AAV design that could negatively impact the environment. We will follow-up as needed.

- How long have you been involved in environmental engineering?
    - Do you have any interests or specializations?
- What aspects of materials and/or sensors could cause harm to aquatic environments?
    - What are the ways a material can harm the environment?
    - How can materials affect animals?
    - How can materials affect plants?
    - How can materials affect water?
- What is an example of a material that breaks down in its environment overtime?
- How important is noise pollution caused by actuators and designs like propellers?
    - Are there any benefits to noise pollution? (Such as keeping animals away from dangerous propellers)
    - Are there any other side effects the propulsion system could have on the environment?
- Do you know any aspects of the environment that could affect sensors?
    - How could sensors be damaged?
    - Could air or water block operation?
    - Are there any sensors that work well in both environments?
- What fluctuation in temperature could exist transitioning from an aerial environment to a marine environment?
    - Going from mild temperatures in the air to cold temperatures by plunging deep into the ocean
    - Would there be any notable effect on any materials?
- How would temperature change affect with recommended materials and sensors?
- How does depth pressure affect materials?

7.3.3 Objective 3

Below is a preliminary series of questions we plan to ask in our interviews with experts who are involved in the development of air and water UAV and AUV materials and sensors. We will follow-up as needed.

- What are your specific areas of research/work?
- How can material integration differ in air and water?
    - What materials are already being used?
    - What atmospheric factors should we be taking into consideration when evaluating various materials?
- How can sensor integration differ in air and water?
    - What sensors are already being used?
    - What atmospheric factors should we be taking into consideration when evaluating various materials?
- What current methods of detecting pollutants are being used?
- What sensors would you recommend for detecting pollutants?
    - What are the recommended sensors capabilities and limitations?
    - What would be the advantages and disadvantages of using the sensors being recommended?
- Are there any design specifications that the AAV should have for multi-environment use?
    - What kind of propulsion systems can operate in both air and water?
- How would temperature change affect with recommended materials and sensors?

7.4 Appendix D

Example Consent Form

Below you will find a blank consent form that was given to our interviewees prior to interviewing.

WORCESTER POLYTECHNIC INSTITUTE

IQP Informed Consent Contract

Introduction:
You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study. This form presents information about the study so that you may make a fully informed decision regarding your participation. Please read and note your preferences on the form.

Purpose of the Study:
We are an Interactive Qualifying Project group from Worcester Polytechnic Institute (WPI) in the United States conducting interviews to produce design recommendations for an autonomous aero-amphibious vehicle (AAV) for the detection of oil spills in the Baltic Sea. This is split among three objectives:

1. Current methods for detection oil pollutants in bodies of water and the environmental consequences.
2. The factors that must be considered for a sustainably built system.
3. The material, sensor, and mechanical system requirements for a vehicle to traverse air and water.

Procedures to be followed:
This is a seven-week study starting from March 14, 2022, and ending April 29, 2022. Prior to the start of the interview, an interview preamble will be vocally dictated to all participants.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: The team alias at gr-teamdrone-d22@wpi.edu. In addition, WPI's IRB Manager Ruth McKeogh, Tel. 508 831-6699, Email: irb@wpi.edu or the Human Protection Administrator: Gabriel Johnson, Tel. 508-831-4989, Email: gjohnson@wpi.edu.

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this

☐ Do we have your permission to audio record your interview?

☐ Will you allow us to use your words in our final published article?

☐ Do we have permission to quote you in our paper? Not checking the box, you will remain anonymous

___________________________ Date: ___________________

Study Participant Signature

____

Study Participant Name (Please print)

____________________________________ Date: ___________________

Signature of Person who explained this study

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

7.5 Appendix E

Objective 1 Interview Questions by Interviewee

Below you will find each individual that was interviewed for based on involvement with the survey of bodies of water for pollution and those who survey for oil in bodies of water and what questions were prepared for their respective interview.

7.5.1 Michael Lypen – U.S. Coast Guard

- How long have you been involved in surveying bodies of water for pollution in general and how did you find yourself here?
- What are the current methods or technologies that you rely on for pollution detection in bodies of water?
    - Does the method change based on geographic location and varying resources?
- What factors cause a delay in response time for pollution clean-up?
    - Is it a technological limitation?
- Based on your experience, what factors are the leading causes of pollution?
    - Do you believe that this factor is universal to other bodies of water?
- How do you determine if a body of water needs surveillance for pollution?
    - Are all bodies of water monitored?
- Do bodies of water have indicators that pollution is a major issue?
    - Have you witnessed any examples of long-term environmental damage?

7.5.2 Michael Buckholt – WPI Biology and Biotechnology

- Can you tell us a little about your background?
- In your opinion, is oil-based water pollution an environmental concern?
    - What makes it an environmental concern?
    - If there is a concern, is this a short term or long-term concern?
- What environmental consequences exist with oil-based water pollution?
    - Do different environments pose different environmental consequences?
- Do you know any methods that are used to survey bodies of water for oil pollution?
    - Do these methods change in different bodies of water?
- Are there indicators that pollution is a major issue in a body of water?
    - Are these indicators universal to all bodies of water?
- When thinking of oil-based water pollution, what bodies of water do you feel are at the most risk?
    - Do you know of any oil-based water pollution in the Baltic Sea

7.5.3 Olof Lindén – World Maritime University

- Can you give us a little background about your work?
- What are the current methods or technologies that are relied on for pollution detection in bodies of water?
    - Does the method change based on geographic location and varying resources?
    - Are there any unique aspects of the Baltic Sea that contribute to pollution detection?
- Are there any limitations in the current methods or technologies that are relied on for pollution detection in the Baltic Sea?
    - How could an autonomous options strengthen or weaken detection capabilities?
- What factors cause a delay in response time for pollution clean-up?
    - How long after a leak or spill comes into existence is detection possible?
    - Is it a technological limitation?
- Based on your experience, what factors are the leading causes of pollution?
    - Do you believe that this factor is universal to other bodies of water?

- How do you determine if a body of water needs surveillance for pollution?
    - Are all bodies of water monitored?
- Do bodies of water have indicators that pollution is a major issue?
- Have you witnessed any examples of long-term environmental damage?

7.5.4 Colt Cotton – U.S. Coast Guard

- How long have you been involved in surveying bodies of water for pollution in general and how did you find yourself here?
- What are the current methods or technologies that you rely on for pollution detection in bodies of water?
    - Does the method change based on geographic location and varying resources?
    - How long after a leak or spill comes into existence is detection possible from the drone you pilot?
- As a drone pilot, are there any limitations in what your vehicle can accomplish?
    - Contrary to this, are there any advantages within your vehicle that makes your job easier?
    - How could an autonomous option strengthen or weaken the purpose of your drone?
- What factors cause a delay in response time for pollution clean-up?
    - Is it a technological limitation?
- Based on your experience, what factors are the leading causes of pollution?
    - Do you believe that this factor is universal to other bodies of water?
- How do you determine if a body of water needs surveillance for pollution?
    - Are all bodies of water monitored?
- Do bodies of water have indicators that pollution is a major issue?
- Have you witnessed any examples of long-term environmental damage?

7.6 Appendix F

Codebook

Objective 1	
Code	**Definitions**
HUM	Human limitations in current surveying methods
TEC	Technical limitations of current methods
CUR	Current methods of oil pollution detection
TIM	Effects of response time on oil spill detection and mitigation
CAU	Discussion of probable causes for oil pollution
UNM	Discussion of currently used unmanned vehicles
VIS	Visual cues for surveying bodies of water for pollution

Objective 2	
Code	**Definitions**
SUS	Sustainable engineering practices
ENV	Environmental Impact of drones or vehicles
EVDAM	Environmental damage done to the vehicle (I.e. degradation and crashes)
ECOEF	Ecological effects of the vehicle on the surrounding area
DREF	Effects of the environment on the physical dynamics of a vehicle
SENSEF	Effect of the environment on the sensing capabilities of a vehicle
COR	Discussion of corrosion of materials and/or its effects on the environment
LOC	Mention of physical location (I.e. Baltic Sea
MON	Monitoring pollution
TPOL	Discussion of types of pollution

Objective 3	
Code	**Definitions**
MED	Discussion of fluid dynamics in different viscous mediums
FLY	Specific to flying vehicles
UND	Specifically swimming or underwater vehicles
WGH	Considerations based on weight or buoyancy
POW	Power/Wattage considerations for vehicles
SENS	Sensing techniques for drones and autonomous vehicles
MAT	Specifications of materials or discussions of viable materials
IDEA	Direct design ideas from professionals/interviewees
PROP	Discussion of propulsion and propulsion systems
PURP	Probing on the purpose of AAVs or drones in general for different applications
REG	Discussion of governmental agency regulation of drones
SYS	Discussion of the possibility of using a system of vehicles to complete this task
COST	Economic cost of the vehicle due to design aspects
AERO	Discussion of general aerodynamic principles
HYD	Discussion of general hydrodynamic principles
GEO	Vehicle geometry considerations
NUM	Numerical values or direct technical insight for analysis of the vehicles systems
TIME	Flight time and operation time concerns
COM	Discussion of communications methods for an autonomous vehicle

7.7 Appendix G

Objective 2 Interview Questions by Interviewee

Below you will find each individual that was interviewed for based on being experts who are involved with environmental engineering and knowledge of materials, sensors, propulsion systems, and other facets of AAV design that could negatively impact the environment and what questions were prepared for their respective interview.

7.7.1 John Bergendahl – WPI Civil Engineering

- Could you tell us a little about your background?
- Could you tell us a little about your work related to water pollution?
- Are there any certain types of materials tend to cause problems in water?
  - Are there any ways to prevent/mitigate this harm?
  - How long does it take for these issues to arise?
  - Do you have recommendations to what materials should be used for the design of the drone?
- What kinds of harm can you see a propulsion system doing to a marine environment?
  - Is there harm in disturbing sediment or causing turbulence underwater?
  - Do you see noise pollution as a problem in marine environments?
- Are there any pollution detection methods that you are familiar with for bodies of water?
  - Any specifically for oil-based pollution?
  - Do you think any of them would be effective employed by a small drone?
- How do you think pollution prevention methods can be improved?
  - Do you think better pollution surveillance will help in preventing pollution?

7.7.2 Paul Mathisen – WPI Environmental Engineering

- Could you tell us a little about your background?
- What types of materials tend to cause problems in water?
  - Are there any ways to prevent/mitigate this harm?
  - Over what time scale do these issues arise?
  - Do you have recommendations to what materials should be used?
- What kinds of harm can you see a propulsion system doing to a marine environment?
  - Is there harm in disturbing sediment or causing turbulence underwater?
- Are there any pollution detection methods that you are familiar with for bodies of water?
  - Any specifically for oil-based pollution?
  - Do you think any of them would be effective employed by a small drone?

7.8 Appendix H

Objective 3 Interview Questions by Interviewee

Below you will find questions asked to interviewees who are familiar with identifying important limiting aspects of AAV design to mitigate potential harm to the environment and can assess requirements for implementing materials, sensors, and mechanical systems in air and water environments.

7.8.1 Anonymous Engineering Expert

- Could you tell us a little about your background?
- Can you give us a brief introduction of your work with _______?
- What is your background in sustainable engineering?
  - Do you have any interests or specializations?
  - How is sustainable design achieved?
- What type of environmental sensing does your vehicle employ?
  - Have there been any scenarios where environmental factors have blocked sensor operation?
    - How was this overcome?
  - Have there been any circumstances where environmental factors have damaged or destroyed a sensor?
- Do you factor in noise pollution caused by actuators and designs like propellers?
  - Are there any benefits to noise pollution? (Such as keeping animals away from dangerous propellers)
  - Are there any other side effects the propulsion system could have on the environment?
- What do you think could limit effectiveness of a multi-environment drone?

7.8.2 Nicholas Bertozzi – WPI Robotics Engineering

- Could you tell us a little about your background?
- What do you think could limit effectiveness of a multi-environment drone?
- How could material integration differ in air and water?
- What are important aerodynamic considerations for an aerial vehicle?
  - Do these considerations restrict performance in a marine environment?
- What sensors, in your opinion, are critical for the performance of an AAV?
  - What sensors could aid in detecting pollutants?
- In your opinion, what would be important aspects in a material that would be used for an aerial vehicle?
  - How about an aquatic vehicle?
- Moving from the different environments, would you expect a significant change in temperature?
  - Would this temperature change be detrimental to the structure of materials?

7.8.3 Mark Patterson – Northeastern Robotics Department

- Could you tell us a little about your background?
- Could you tell us a little about your most recent publication about underwater robots?
  - Do you have any interests or specializations?
  - How is sustainable design achieved?
- What type of environmental sensing does your vehicle employ?
  - Have there been any scenarios where environmental factors have blocked sensor operation?
    - How was this overcome?

  - Have there been any circumstances where environmental factors have damaged or destroyed a sensor?
- Do you factor in noise pollution caused by actuators and designs like propellers?
  - Are there any benefits to noise pollution? (Such as keeping animals away from dangerous propellers)
  - Are there any other side effects the propulsion system could have on the environment?
- What do you think could limit the effectiveness of a multi-environment drone?
- What aspects do you consider when assessing material for use in use in aquatic environments?

7.9 Appendix I

Simulation Parameters

Fluid Dynamics						
Simulation	Range of Angles	Velocity Range ($\frac{m}{s}$)	Iterating By	Density (kg/m^3)	Turbulence Parameter (%)	Type Of Simulation
Water AOA	-12 to 12	0 to 1	Velocity	1000	0.1	2D
Air AOA	-12 to 12	0 to 20	Velocity	1.225		
Water Deflection	-20 to 0	0 to 1	Deflection	1000		
Air Deflection	-20 to 0	0 to 20	Deflection	1.225		

Structural Simulations			
Material	Load (N)	Load Location (in)	Fixed End Location (in)
Carbon Fiber Epoxy AS/3501	12.5	30	0
6061-T6 Aluminium	12.5	30	0

7.10 Appendix J

List of Figures

7.11 Appendix K

List of Tables