December 2012

A Study of the Feasibility of Autonomous Surface Vehicles

Christopher Michael Byrne
Worcester Polytechnic Institute

Dylan Tabare Rodriguez
Worcester Polytechnic Institute

Matthew James Franklin
Worcester Polytechnic Institute

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Interactive Qualifying Project

Submitted by:

Dylan Rodriguez

Matthew Franklin

Christopher Byrne

Project Advisor:
Ingrid Shockey

Submitted December 12, 2012

Abstract

As climate change is continuing to negatively impact our environment, it is important for society to take a closer look at our oceans. Oceans are a significant part of our environment and contain telltale information about the systems that allow society to function. However, there are many difficulties and limitations in current ocean observation systems. In this report, we examine the use of autonomous surface vehicles to collect data and perform tasks in a variety of environmental areas.

Executive Summary

Climate change, now more than ever, is hard to ignore. A trend in increasing global temperatures has brought us to 2012, the hottest year recorded so far. This increase in temperature has many negative environmental impacts, only one of which is increased storm severity. Recently, Hurricane Sandy struck residents of the East coast of the United States; taking lives, destroying homes, and crippling local economies. Such recent phenomena and environmental abnormalities are forcing scientists to look at our oceans for explanation and for preventative measures that can be used to mitigate damage created by these disasters. The ocean contains incredible amounts of valuable data, but the large area and constantly changing conditions of our oceans can make them difficult to study. While there are many ocean monitoring systems currently in place, this report will research the feasibility and areas of application for an Autonomous Surface Vehicle (ASV), an oceangoing vessel capable of navigating and performing tasks without control or assistance of a human user. We highlight weaknesses of current ocean monitoring systems, areas of application for ASVs, obstacles for ASV development, and recommendations for future development of ASVs. We also feature an ASV, SCOUT, that was built by a team that includes two of the authors of this report. This vessel will make a transatlantic attempt in 2013.

Background

ASVs can range in complexity but must include four main elements: a body (hull), a propulsion system, a navigation system, and a data collection and transmission system. There is no standard that regulates autonomous surface vehicles and these vessels differ greatly in appearance and functionality depending on the production of the unit and its intended function.

ASVs are a relatively new technology and have a brief history. Early ASVs were designed mostly for educational use. Further advancement of ASVs has been due to the rapid progression of technology. For example, Global Positioning System Receivers (GPSR) have become more compact, affordable, and easily available. Today, most ASVs exist as prototypes being developed by private interest groups and are not being applied to perform routine or standardized tasks. There exists at least one company, *Liquid Robotics,* which markets its ASVs to the commercial market.

Liquid Robotics' Wave Glider (left) and SCOUT, another long range ASV (right).

There is a great amount of potential in using ASVs to benefit our environment. ASVs can be applied to environmental monitoring tasks, which encompass many different types of data collection and observation. There are other data collection methods such as satellite systems and networks of stationary and floating buoys used today by scientists and researchers; however there are limitations to these systems, which include the range of buoy networks and the accuracy and cost of satellite systems. In both areas, ASVs can offer a solution or contribute as an additional resource to collecting ocean data. Many more aspects of environmental monitoring, such as mapping oil spills, have been explored to show how ASV technology can help the environment.

ASVs can also perform tasks in the ocean, such as gathering and delivering water samples or cleaning up ocean contaminants. Current methods of sample collection and cleaning hazardous spills are costly, time consuming, and require a lot of manpower. A simple water sample can cost thousands of dollars to collect today because a manned ship must be hired to drive to the site of collection and take the sample manually. While ASVs cannot solve all of these problems, they certainly can be fitted with sample collection equipment and may have the potential to be equipped with oil removing devices and contribute to the clean-up effort. A fleet of ASVs may be able to save time and money in future oil clean-up efforts.

The application of ASVs in environmental monitoring and task performance areas has the ability to lower human and animal vulnerability to certain environmental issues. In the area of weather, for example, an ASV might be able to collect new ocean data that could contribute to forecasting storm systems. As more accurate data is fed into weather models, those models produce more accurate outputs. By contributing data to these models, ASVs can improve the accuracy of storm predictions. This improved accuracy may be able to help areas at higher risk of damage from these environmental events receive more attention, and would allow for staging directors to more effectively plan the movement and distribution of supplies and resources during and after the disaster.

ASVs also show promise in helping efforts to study current climate change. ASVs can collect oceanic data to help produce models of important currents that transfer warmth around the globe. Critical to understanding climate change is understanding how the environment can impact us and how we impact our environment. In all cases, new oceanographic data can inform actions that can be taken to mitigate some of the threats feared by environmental scientists worldwide.

Methodology

The goal of our project was to determine the feasibility of autonomous surface vehicle application in regards to environmental monitoring and task performance. In order to achieve this goal we completed the following objectives:

- Determine the weaknesses of existing systems for environmental monitoring and task performance.
- Identify application demand for environmental monitoring and task performance systems.
- Identify potential clients for ASV's and assess interest.
- Develop a set of feasible recommendations for ASV deployment and implementation.

To complete these objectives it was necessary to gather information from scientists and researchers in a variety of different environmental fields. We first established an initial list of experts drawn from our background research and from local contacts. These experts were familiar with current methods of environmental monitoring, these methods' impacts on society, and in some cases the use of autonomous vehicles. Overall, our team used a combination of background research, semi-standardized interviews, and surveys to gather information on our first three objectives. We then analyzed this information and were able to develop a list of recommendations to further the advancement and use of ASV technology in improving responses to social and environmental issues.

Findings

Using our background research, interviews, and surveys, we compiled a set of findings pertaining to our objectives as outlined above.

Weaknesses of Existing Systems for Environmental Monitoring and Task Performance

In speaking with a range of environmental researchers, we found many common limitations in current environmental monitoring and ocean task performance systems. For environmental monitoring, we interviewed two groups of researchers: those who *collect* ocean data and those who *use* the collected ocean data. Limitations in current environmental monitoring systems became apparent in our findings when we interviewed Dr. Thomas Webler, a founder and researcher at the Social and Environmental Research Institute (SERI) who is also a user of ocean data collected by outside organizations. In an interview he highlighted a popular weakness in environmental monitoring– he discussed the great value in continuous and long term data collection but expressed that factors such as cost, dangerous conditions, and the endurance of current systems are limiting the amount and location of data points collected today.

For oceanic task performance, we interviewed Marco Kaltofen, a researcher at Boston Chemical Data Corporation. Mr. Kaltofen has worked a great deal in mapping and cleaning oil spills, specifically in the Deepwater Horizon spill of 2011. Current methods of mapping oil spills that he uses include manned boats and aircraft. The first notable weakness is the expense involved with the usage of those systems. Secondly, since oil spills are constantly changing due to wind and current, there is a need for continuous oil mapping systems that can update information frequently. These issues of cost and frequency of data collection and transmission appear often in other systems.

We also interviewed Ken Pryor who is directly involved in the use and development of NOAA's Geostationary Operational Environmental Satellites (GOES) system. This system is capable of collecting a wide range of data that meteorologists rely on heavily to predict weather patterns. The satellites need ocean surface data to both verify GOES data and also to calibrate the sensors on board the satellites. While NOAA currently uses a system of buoys to collect this surface data, Mr. Pryor believes there would be great value in a dynamic platform to collect and send data from a variety of different locations.

The Woods Hole Oceanographic Institute (WHOI) is one of the leading organizations in oceanic observation and studies. One of their main methods of data collection is through the use of a fleet of autonomous underwater vehicles (AUVs). The problem with AUV technology is that these units need to be accompanied by a manned research vessel that can deploy, refuel, remission and track the AUV. Again, the weakness here is in the cost associated with a manned vessel. This cost limits the time span and location of data points that can be effectively collected by AUVs.

Application Demand for Environmental Monitoring and Task Performance

We had learned from our interview with Dr. Webler that accurate and reliable ocean salinity data is in demand due to potential effects of reduced salinity in the oceans. A decrease in water salinity can be damaging to many sea creatures and can lead to endangerment of entire species. Both Dr. Webler and Marco Kaltofen agreed that there would be great value in continuous and long term ocean salinity data, and both agree that this data could be recorded by an ASV. This continuous data could then be analyzed so that scientists could better understand what corrective action could be taken to mitigate environmental damage.

We spoke with Mr. Kaltofen about the application of ASVs in mapping or cleaning oil spills. In referring back to his work in the Deepwater Horizon spill and knowledge of current mapping methods, he believes ASVs could be outfitted with low cost fluorometry sensors to detect and measure oil and send that data back to a central station. If this could be effectively implemented, ASVs have the potential to be much less costly than current mapping methods and would offer the ability to continuously collect data, both of which cannot be said for current mapping systems.

WHOI has proposed one major application area for ASVs- assisting in the coordination and endurance of their AUVs. ASVs can eliminate the need for a manned vessel to follow AUVs and therefore lower the cost of research undertaken by these systems. This reduction in cost will allow for longer periods of data collection with a larger covered area. Since many outside organizations use the data collected by WHOI, the use of an ASV would benefit many different environmental groups and help them achieve their respective goals.

Potential Client Bases for ASV Technology

Our findings in applications for ASVs revealed many potential clients for such a platform. In locations where decreasing ocean salinity is a rising concern, coastal communities and economies depend greatly on the sea for food and economic stimulus. Their use of ASVs to continuously collect data could provide them with valuable information regarding the resources that their local economies depend on.

A major client base for ASV technology may include coastal resorts and businesses that could be affected by an oil spill. Such a disaster can put a halt to income for coastal businesses, and preparation is necessary for the survival of these businesses. Oil mapping data is also valuable to businesses so that they can get reimbursed from the responsible oil company for damage caused by the spill.

Obstacles for the advancement of ASV deployment

One major obstacle for the advancement of ASV deployment is maritime law that governs territorial and international waters. We interviewed Jill Taft, a maritime regulatory compliance manager and attorney based in Miami, Florida, to gain more information on ASV legality. Jill states that the law clearly lags behind the growth in technology, and this applies directly to the autonomous vehicle sector. ASVs are new technology and there is currently no law directly governing their deployment.

Another obstacle for ASV deployment is in collision avoidance. ASVs have the potential to be very small, difficult to detect, and could create navigational hazards. Although some prototypes have been built with collision avoidance systems, no methods of collision avoidance have been proven and a collision with an ASV could potentially damage vessels. ASVs could also collide with lobster traps, buoys, fishing nets and other sea debris that could ensnare or disable the vehicle.

Recommendations and Conclusion

After some background research and gathering information from a variety of environmental experts we propose the following recommendations for the advancement of ASV application:

Developing legal standards for ASVs and regulations for their deployment

Without the capacity to adhere to regulations, companies will not want to enter the ASV market because the current legal gray area that ASVs are being deployed under makes investing in these technologies risky. Legal guidelines for ASVs would reduce the risk of investing in these systems and would bring stability to a developing market.

Investigating and developing system standards

Creating system standards would reduce the number of proprietary ASV systems. System standards would lead to accurate and directly comparable data for all organizations using ASV technology, and would help to maximize the number of organizations that could benefit from access to that data.

Exploring a system to share ASV data between organizations

Exploring a system to share data between organizations would enable data collected by any participating organization to be used by the others to further their research. Allowing collected data to be shared between organizations would mean that in some cases multiple surveys of the same area could be avoided, which would reduce cost to participating parties and enable more unique surveys and data points to be collected.

Conclusion

While autonomous surface vehicles are in their infancy, we believe that tremendous opportunity exists for modular and customized ASVs if some hurdles can be overcome. In addition to saving money over existing systems, ASVs also offer benefits that are currently unmatched by existing systems that include endurance missions, collection of data in hazardous environments, and swarm behavior that can use multiple units to gather data more quickly. The capacity of autonomous surface vehicles to be used for environmental monitoring and ocean task performance will serve to improve our understanding of the oceans, which will in turn benefit the interaction between society and the environment.

Acknowledgements

We would like to thank the following individuals for their support and contribution to the research and success of this Interactive Qualifying Project.

- Ken Pryor, of NOAA's Satellite Climatology and Meteorology Division, who was extremely helpful and encouraging in our research.
- Professor Ingrid Shockey, of Worcester Polytechnic Institute, for her generous guidance and support throughout the completion of this project.
- Thomas Webler and Seth Tuler, of the Social and Environmental Research Institute, for their knowledge between social and environmental interactions.
- The Applied Ocean Physics and Engineering Department at Woods Hole Oceanographic Institute for their quick responses and knowledge of Autonomous Surface Vehicle applications.

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List of Acronyms

Automatic Identification System	(AIS)
Autonomous Coastal Exploration System	(ACES)
Autonomous Surface Vehicle	(ASV)
Autonomous Underwater Vehicles	(AUV)
Defense Advanced Research Projects Agency	(DARPA)
Environmental Protection Agency	(EPA)
Essential Fish Habitat	(EFH)
Geostationary Operational Environmental Satellites	(GOES)
Global Positioning System Receivers	(GPSR)
Massachusetts Institute of Technology	(MIT)
National Oceanic and Atmospheric Administration	(NOAA)
Naval Underwater Warfare Center	(NUWC)
Shallow Water Influence Minesweeping System	(SWIMS)
Social and Environmental Research Institute	(SERI)
Unmanned Surface Vehicle	(USV)
University of Rhode Island	(URI)
Very High Frequency	(VHF)
Weather Forecast Offices	(WFO)
Woods Hole Oceanographic Institute	(WHOI)
Worcester Polytechnic Institute	(WPI)

Chapter 1: Introduction

The year 2012 is on track to be the hottest year ever recorded (Arnndt, 2012). Records show global temperatures rising dramatically over the past 15 years and society is starting to see the negative impacts of such climate change. Increased storm severity, as was witnessed with hurricane Sandy, is only one of the negative environmental issues that are forcing scientist to take a closer look at our oceans. The world's oceans hold a great amount of data that is valuable in understanding environmental conditions; yet difficulties such as cost, time, safety, and range of current data collection methods are limiting our the amount of data that we can collect from the environment. We believe the use of Autonomous Surface Vehicles (ASVs) can help to overcome some of these challenges and assist scientists and researchers in their efforts to understand and mitigate the impacts of a rapidly changing environment.

For a vehicle to be autonomous, it must be able to navigate and perform functions independently, without outside help or control. Existing prototypes and working ASVs have different parameters and vary widely by design. A typical unit includes a hull, a propulsion system, a navigation system, and a data collection and transmission system. An important distinction is that an ASV is different from an Unmanned Surface Vehicle (USV), which relies on a user to remotely operate the vehicle. After deployment, ASVs are able to perform tasks, collect data, and either transmit the data to a home base or store that data onboard for analysis once the vessel is retrieved.

Despite the potential of these systems, ASVs have a fairly brief history and we are just starting to see the introduction of different prototypes and developed systems into the market. This is partly due to the growth of technologies that support the development and implementation of these vessels. For example, Global Positioning System Receivers (GPSR) are improving in their accuracy, size, and affordability. Some of the earliest ASV research using GPS can be credited to the MIT Sea Grant college program in 1993. The first prototype developed by this program was a kick start to ASV research and development, which led to more designs from MIT, other academic institutions, and private groups interested in such technology (Manley, 2008). Although most ASVs today exist as prototypes and educational experiments, at least one organization, operating under the name “Liquid Robotics”, has created a popular ASV that is commercially available.

Given the pressure to advance capacity for climate and environmental research, the goal of this project is to determine the feasibility of ASV deployment in oceanic monitoring and task performance research sectors in order to better understand the environmental issues that impact society. We will evaluate how ASVs may be utilized for different types of data collection and surveying. We will also assess ASV task performance such as ocean cleaning, transportation, sample collection, and buoy or beacon functionality. Time, cost, safety and ease of use are four factors that we will consider when comparing the feasibility of ASVs to other data collection and task performance methods.

Chapter 2: Literature Review

This chapter provides background information on autonomous surface vehicles and highlights their potential applications and mechanics. We start by describing the basic components that make up an ASV and continue with the brief history of ASVs. We consider how well the vessel's capabilities can apply to a range of environmental issues and the relevance of autonomous crafts in the context of oceanographic monitoring and climate change. We conclude the chapter with an examination of three case studies to show the position of ASVs in research and development and in the commercial marketplace today. Here we will also introduce SCOUT, the prototype ASV that inspired this report.

2.1 ASV Components

ASVs come in many different forms and vary greatly depending on their intended function and the needs of the engineers who produced it. Some ASVs are even able to switch from autonomous control to human control during their deployment. The few common components of all autonomous surface vehicles are a body (hull), a propulsion system, navigation equipment and some kind of computer control system (see figure 1, below). Together these four elements can make up an ASV, but typically many more technologies and features, such as sensors and sampling equipment, are incorporated into the vehicle to improve function and expand on the benefits of deploying the system.

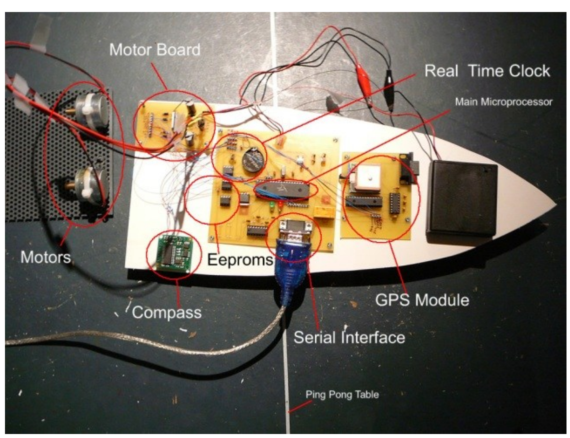

Figure 1: Typical components installed on an ASV (Burnett, 2012).

The hull is a defining aspect of an autonomous surface vehicle. It is the platform on which all other technologies are carried, and is designed in accordance with the vehicle's purpose. The designs can range in complexity from simple hand construction to designs modeled in 3D software and machined with CNC machines. On the other hand, both MIT and Worcester Polytechnic Institute (WPI) have built autonomous surface vehicles by simply using the body of a plastic kayak to serve as their hull. Since the ASVs from both institutions were mainly used for research and education, the hulls did not have many requirements or need specialized design. The plastic kayak was an inexpensive solution that served the vehicles appropriately by simply carrying all the electronics and floating in the water. This example shows the incredible range of ASV design- while these universities used kayaks because they were being deployed only on calm lakes, other ASVs are designed to survive for hundreds of days in heavy seas.

The next component of an ASV is its propulsion system. Again, propulsion systems come in a large variety and depend on design intent. Some major factors in determining a propulsion system is the amount of available power the vehicle can supply, the duration of its movement, and the desired speed of movement. Some different types of propulsion systems seen on today's prototypes are electric motors, gasoline engines, sail power, wave power, and the use of a rotating conveyor belt. Propulsion techniques can be whatever best suits the desired outcome of the vehicle.

The last two components of an ASV are navigation equipment and a computer control system. Due to growth of supporting technologies in both of these fields, ASVs have been able to gain traction in today's world. For example, for navigation equipment, the Global Positioning System Receiver (GPSR) is more accurate, compact and affordable than ever. Navigation equipment also usually includes a type of electronic compass. Computer control systems are the brain of an ASV and can be implemented in a number of different ways. Some control systems include the use of Linux computers or Arduino microcontrollers as the programmable core of the vehicle.

These four components- a hull, propulsion system, navigation equipment and computer control, are only the fundamental building blocks of an autonomous system. The amount of sensors and technological equipment that can be added to an automated vehicle is only limited by the capacity of the boat to support them. The base platform of an autonomous surface vehicle has the potential to be a very versatile tool. New sensors and different technologies can be integrated into the system while old ones are removed, making the vehicle very adaptable to the task at hand.

2.2 History of ASVs

Worldwide, early ASV research can be traced back to the MIT Sea Grant college program in 1993. The MIT Sea Grant program was the first to be established under NOAA's Nation sea grant program in 1970. The focus of these programs was to create educational oceanic projects to solve real world problems. The preliminary prototype created under the MIT program was named ARTEMIS and was designed mainly for testing navigation and control systems for potential future ASVs. ARTEMIS was later used to collect simple bathymetry data in the Charles River in Boston, Massachusetts. In this first prototype, researchers found that small size was limiting the vehicle's endurance and seafaring capabilities. In response, the same MIT group upgraded the previous, unstable, hand built body to a kayak. The new durable hull was tested successfully in the Charles River and was soon equipped with an acoustic tracking system designed to follow tagged fish (Manley, 2008).

Continuing their research in ASVs, MIT developed a new vehicle in 1996, called ACES (Autonomous Coastal Exploration System). This ASV was equipped with new and upgraded hydrographic survey sensors that ultimately were able to complete a more detailed survey of Boston harbor. Finally, students and professors of MIT returned to the lab to continue improvement on the mechanical systems until the year 2000 when they introduced their newest autonomous vehicle called the AutoCat, shown below in figure 2 (Laboratory at MIT Sea Grant, 2012).

Figure 2: MIT's AutoCat moving under its own power
(Laboratory at MIT Sea Grant, 2012).

Since ARTEMIS, a number of small-scale models have been produced. One project called SESAMO (an acronym for Sea Surface Autonomous Modular Unit) was developed by the Italian National Program of Research in Antarctica. After much consideration of past autonomous surface and underwater vehicles, including research of MIT's ACES, their team developed their first prototype ASV in 2003. This vehicle was designed to explore the waters of Antarctica. It had the capacity to collect data and samples of air-sea interface factors such as CO_2 measurements and heat transfer (Caccia, 2003). Another international AVS prototype called the ASC Measuring Dolphin was developed by the German Federal Ministry of Education, Research, and Technology. Designed and constructed from 1998 to 2000, the goal of the model was to enable high accuracy positioning and guidance for carrying measuring devices in shallow waters (Caccia, 2003). These sample ASVs show that even small differences in the mission of the vehicle can significantly change the physical attributes of that vehicle.

Besides the early developments by MIT, most of the growth in ASV has occurred in the last eight years through educational organizations and private parties interested in such technologies. For example, although the US Navy has been more interested in underwater vehicles, they have also found a need for unmanned surface vehicles as well. Such vehicles can be traced back to World War II, when the Navy used these boats for target surveillance. In

2003, for example, the Navy implemented a unit in Iraq manufactured by QinetiQ. The device, named SWIMS (Shallow Water Influence Minesweeping System), can be deployed from a ship and controlled by Navy personnel to search for mines and allow for the safe passage of ships through dangerous waters. The Navy has also explored the use of unmanned surface vehicles for harbor security and patrol. However, most vehicles used by the Navy today are not autonomous; they are simply remote controlled and accomplish their goal of removing the soldier from the scene. Other significant designs and prototypes of autonomous surface vehicles can be recently credited to many different innovators, three of which will be discussed later in this chapter (Caccia, 2003; Corfield, 2012).

Many autonomous surface vehicles today are custom built for a particular task. For example, an unnamed ASV developed as a joint venture between Seqwater, a water supply company, and CSIRO, an Australian research organization, was designed specifically to collect information from a variety of sensors that would relay data about a body of water. However, the boat was only designed to be deployed in one particular lake. It was integrated with an array of anchored buoys that it relied upon for communication. Additionally, the ASV was designed for low winds and calm seas, and it could not right itself in the event of a capsize (Dunbabin, 2009).

By looking at the history of ASV and the variety among the prototypes it is clear that there is no standard in the development and construction of such vehicles. Prototypes have been built by a number of different groups and were mostly experimental. ASVs have been used effectively to collect ocean data; however researchers and scientists still favor other collection methods. Innovators continue to work with ASV technologies, a trend that will ultimately widen their potential and help integrate

2.3 Application and Sensing Capacities for Autonomous Vehicles

The range of applications for autonomous vehicles has been gaining traction in the past couple of years. Like many robotic systems, autonomous boats have the potential to lower costs of operations and extend the capacity of research. These applications can be sorted into two categories: environmental monitoring and task performance. They are discussed in greater detail below.

2.3.1 Environmental Monitoring

Environmental monitoring has particular potential and encompasses a wide range of oceanographic data collection. While the majority of aquatic research and data collection is done in the oceans, ASV can be applied to any large body of water. Some common applications are listed here:

1- Water salinity
2- Water temperature
3- CO_2 content in air and sea
4- Barometric pressure
5- Wave height
6- Wind speeds
7- Bathymetry (water depth)
8- Fish tracking
9- Photographic observation
10- Underwater acoustics
11- Oil spill measurements
12- Pollution measurements

In addition to this list, there are other reasons for monitoring large bodies of water. Some can be as obscure as listening to underwater life. For example, Joe Rizzi, a venture capitalist with a deep interest in listening to whales communicate in real-time, wanted to share this data with the world. His passion inspired the creation of an ASV able to record the sounds of whales with a hydrophone (About, 2012). The ASV he has now been refined by Liquid Robotics, the company he started. Over one hundred of these units have been sold to organizations that use the product for any number of tasks.

Since satellites have a big perspective on our planet's oceans, they are useful for gathering a large amount of marine data, and are particularly useful for tracking storms. One notable source for marine storm data is CIMSS, or the Cooperative Institute for Meteorological Satellite Studies. CIMSS employs a team of researchers who utilize data from satellites to provide real time imagery, derived wind patterns, and other approximations from a variety of satellites and collection methods. CIMSS is one of many organizations seeking to make accurate weather data available to meteorologists and citizens alike. The primary advantage of CIMSS or any other data processing collective is that the organization makes the data available to it more easily available and easier to interpret by those who need it.

Satellites are not perfect, however. Some types of data cannot be observed by these platforms; it turns out that this is often the data scientists need to more accurately predict the behavior of violent weather. For example, Chad Myers, CNN's senior meteorologist, has identified the lack of physical contact with weather as a weakness of the current weather observing system. During a televised broadcast, Myers told the audience, "The computers are not perfect because there's not much data in the ocean. There's no one in the ocean putting up weather balloons for us to know which way weather is blowing" (CNN, 2012). Myers also stated that NOAA's hurricane hunter aircraft flies directly through hurricanes in attempts to use the plane's RADAR and other systems to collect data unavailable through satellite or land based sources. Each time it makes a pass through a hurricane, it does so at the risk of the aircraft, the pilot, and the crew.

While satellites are useful for certain types of data collection, weather agencies still depend on sea based platforms for specific measurements related to wind conditions, barometric pressure, temperature (air and sea surface), and wave data (US Department of Commerce and Atmospheric, 2010). The National Data Buoy Center, for example, uses buoys to build their network of data collection points, all of which fall under two categories: stationary collection points, (either fixed on land or moored to the ocean floor), and drifting collection points (where buoys collect data as they move with the ocean's currents). There are different models of stationary buoys that are strategically placed in the Pacific and Atlantic oceans (mostly located near the coast, but occasionally in the deep sea). The US Coast Guard usually puts these buoys in place by dragging them behind their boat and anchoring them to the sea floor. Buoy hull type and mooring types are chosen based on the requirements of the deployment. NOAA's network of stationary buoys is mapped below in figure 3.

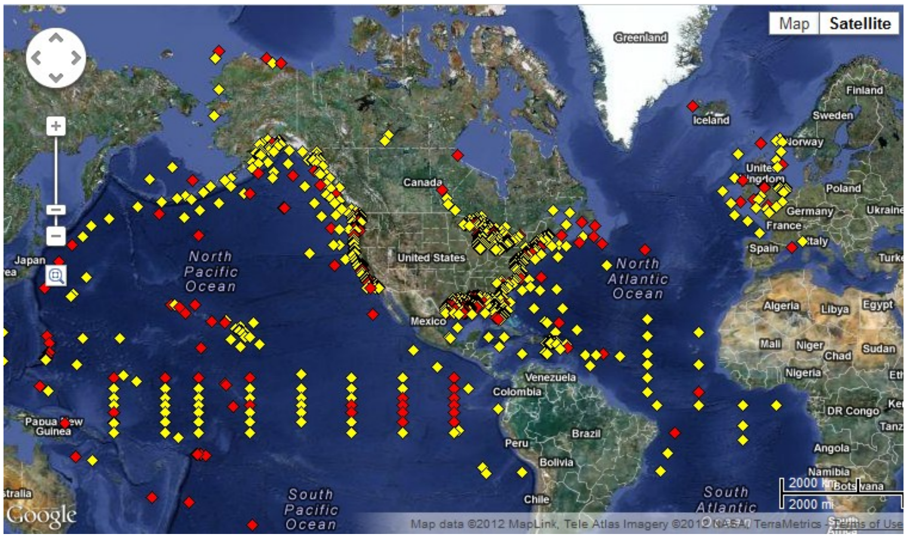

Figure 3: NOAA's Stationary Buoy Chart (US Department of Commerce, 2008).

While some buoys are deployed by government organizations like the National Data Buoy Center, others are deployed by state or local governments. The buoy market is thriving, and a large number of companies offer a variety of buoys designed with different missions in mind. An example of this is the Seawatch buoy, sold by OCEANOR, a company that develops and sells buoys to governments and private companies. The Seawatch buoy, like all of the company's buoys, can be outfitted with customized sensors and payloads (see figure 4, below).

Figure 4: Seawatch buoy anchored to seafloor (Furgo, 2009).

The other surface platform for data collection is the drifting buoy. These are typically expendable platforms that are dropped in specific oceanic areas by ship or aircraft, and collect data as they move with ocean currents or wind. Many times these drifting buoys can transmit data that moored buoys cannot, such as current patterns and deep sea measurements. One example of a drifting buoy array is Argo, a collection of 3,000 buoys that sink to a depth of 2,000 meters and collect temperature and salinity data. They then rise to the surface, transmit the information that they collected, and descend again (see figure 5).

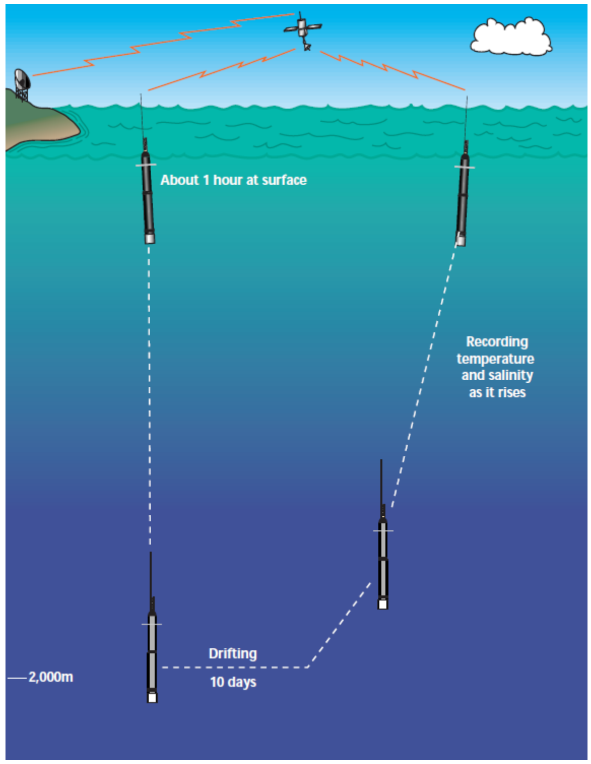

Figure 5: Argo buoy data collection strategy (Wilson, 2000).

Currently, these environmental monitoring systems are gathering the data that scientists need for research and meteorology. These systems are valuable, however they do have limitations and weaknesses. It is important to note that while such systems can gather data independently, much human effort and resources are needed to maintain and put these systems into place.

2.3.2 Labor and Task Performance

Labor and task performance is a second dimension in which ASVs can prove beneficial to scientists. Some of the best applications include:

1. Customizable sample collection
    a. Oil sample collection
2. Defense related tasks
3. Hazard clean up
4. Beacon transmission

5. Transportation
6. Boat traffic markers
7. Fish tracking

The capacity for task performance seems to be expanding. Climate research and other expanding fields of research point to increased demand for vessels that can collect samples or fulfill activities that are not feasible with manned vessels. Here we discuss 2 of the most cited tasks: customizable sample collection and defense related tasks.

Customizable Sample Collection

While some data can be collected directly from sensors on board an ASV, other data must be extracted in a laboratory from samples taken from the area under study. There exist areas of research where samples of seawater must be collected and further analyzed with specific equipment. This is usually the case when sensors are not available to collect that particular type of information, or when available sensors are not accurate enough for a particular task. For example, after the Fukushima disaster in 2011, Greenpeace conducted independent water sampling along the coast of Japan to determine the amount of radiation released into the seawater by that disaster (Collecting, 2011).

Scientists from the US Geological Survey (USGS) have been collecting thousands of water samples from the Arctic Ocean in order to study the levels of acidity in the water and relate those findings to decreased calcification rates in organisms that build shells. An expedition in 2011 took seven weeks; presumably at great financial cost to USGS. As the icebreaker used for this mission costs about $100,000 per day to operate, the Arctic sample collection cost about $4.9 million (National, 2006). Additionally, using this ship for water sample collection meant that it could not be used for other tasks during that time. Although an ASV might not be able to collect as many data samples or samples from deep below the ocean's surface, a fleet of ASVs may be able to reduce the number of missions that manned ships have to undertake (Arctic, 2011).

Oil Sample Collection

One significant example of ocean sample collection concerns the intentional and illegal dumping of oily bilge water from large ships. Standard oil sensors on ASVs cannot collect enough information about the composition of the oil in these discharges, and a sample must be collected and brought back to a laboratory for analysis of both the composition of the oil (that creates a fingerprint specific to a particular ship) and the amount of oil in the water (used to assess damages in a court of law). Equipping an ASV with a water sample collection unit would allow these vessels to travel to the location of an oily discharge as identified by satellite or airplane and take samples that would otherwise have to be taken by an expensive manned boat.

Besides intentional oil discharge, other forms of oil release threaten the environment. While all oil spills and leaks are complicated to manage and detrimental to aquatic ecosystems, spills that take place in particularly vulnerable areas or that release significant amounts of oil can have a greater impact on these ecosystems. For example, the Deepwater Horizon oil spill in April 2010 adversely affected an estimated 40 species of marine life and resulted in an economic cost of tens of billions of dollars (Gulf of Mexico, 2012). This spill alone released 4.9 million barrels of oil into the sea, which spread over time and affected 665 miles of coastline. Consequently, dealing with the aftermath of an oil spill is difficult and expensive. Although there are many different techniques for removing oil from the water surface, the most common method is by mechanical means such as oil booms and skimmers. These clean-up methods are not very effective (Kakalis and Ventikos, 2008).

Due to the difficulties in removing oil from the sea, scientists and researchers are beginning to consider the application of autonomous surface vehicles to skim and clean the contaminated water. Autonomous vehicles have the potential to replace skilled labor or to complement the efforts of disaster clean-up.

Defense Related Tasks

The defense industry is increasingly adopting autonomous surface vessels for a variety of tasks. One example of this is Blackfish, a Navy-operated autonomous watercraft designed to protect a harbor. These units are often outfitted with short range RADAR, communications equipment, and cameras in order to operate as the Navy's eyes and ears. Because the Navy does not have to pay ASVs as it pays its soldiers, products like Blackfish can be easily deployed for relatively long periods of time. However, because Blackfish relies on gasoline to power its systems, its range and mission length are restricted. Accessories like RADAR consume significant amounts of power, and the only feasible way to power them is with gasoline or other nonrenewable fuels (Lessig, 2011).

Although Blackfish is designed to serve as the Navy's eyes and ears, other ASVs have the capacity to be the Navy's gun as well. Developed by Rafael Advanced Defense Systems, a company based in Israel, an ASV called Protector is outfitted with sensors, communications equipment, small caliber weapons, and optional torpedoes. Offered to the US Navy through the defense contractor BAE Systems, Protector has not been a success with the US Navy due to concerns about the offensive nature of the system. Although two human operators would operate the watercraft during a mission and the trigger would be pulled by a person, the US military is not yet comfortable with using unmanned watercraft to fire weapons (Wagner, 2008).

The Navy has instead decided to invest in applications that would enhance the military's informational reach- namely by encouraging the development of drones designed to hunt diesel submarines. Funded by DARPA (the Defense Advanced Research Projects Agency), a 58 million dollar grant was awarded to SAIC, a US military contractor that will design and build these units. While many submarines use nuclear power to generate the power that they use for propulsion, more than 39 nations including North Korea, China, and Iran have diesel submarines. While nuclear submarines can operate without surfacing for hundreds of days, diesel submarines must surface to run their generators and charge their batteries. When they are submerged and switch to operating from these batteries, however, they become nearly invisible. This is the reason for the Navy's interest in new submarine detection technologies; as the undersea arms race continues, detecting and tracking the movements of submarines will become more important (Fellman, 2012).

2.4 Impact of Autonomous Surface Vehicle Applications

The range of detailed information that ASVs collect can reduce human and animal vulnerability to certain environmental conditions. This data can also contribute to better risk management procedures in communities worldwide. The focus on oceanic data collection is to allow for better preparation and information on how the environment can impact us and how we impact our environment. In all cases, corrective action can be taken to improve our world and our way of life.

2.4.1 Risk and Community Vulnerability Applications

The direct and indirect implications of deploying an autonomous surface vehicle vary based on the problem that the ASV is designed to solve. One example of this is regarding the accuracy of weather forecasting models. While problems certainly exist with the models themselves, the information that is fed into the models is just as important to the forecast that these models produce (Danforth, 2007). A lack of accurate data can compromise the output of a weather model.

A huge network of Weather Forecast Offices (WFOs) that are administered by NOAA collects information from field offices, observatories, ships, and satellites and makes it available to other organizations, both in the United States and abroad. The purpose of this network is to supply accurate information to the models that help predict future weather patterns. The accuracy of weather predictions relies on fast computers and plentiful, accurate data (Danforth, 2007).

As we know, accurate weather forecasting can save lives and save property. While autonomous surface vehicles are confined to the sea, information collected by these units can have an impact on coastal and inland forecasting. Hurricanes, for example, can cause huge loss of life and property damage; wind direction, strength, and shear are key components of predicting the movement of a hurricane or tropical storm (NOAA Atlantic, 2012). Hurricane Katrina, for example, caused an estimated $108 billion dollars in damage (Knabb, 2012). These three measurements could be accurately collected with an autonomous surface vehicle. NOAA is pursuing enhanced hurricane tracking systems, and they list unmanned observing systems such as fixed buoys, gliders, and floats as potential platforms to use for data collection to further improve hurricane forecasting (Proposed, 2008).

The cost of hurricanes alone is a staggering burden on local and national economies. Other storms and weather conditions cause billions of dollars in damage every year as well. Flash flooding, for example, is estimated to cause more than 2 billion dollars of damage and is responsible for 100 deaths annually. The death toll of these events can be significant; an estimated 1,833 people died in Hurricane Katrina alone. Recently, President Obama has asked for $60.4 billion in aid for the damages due to hurricane Sandy, a storm that took over 125 lives (CBS/AP, 2012). Internationally, weather related natural disasters have been responsible for the deaths of many more. In Bangladesh, for example, approximately 138,800 lives were lost in the catastrophic cyclone of 1991, while more recent extreme weather events continue to break records around the world (NOAA's Top, 2012).

Weather related disasters have a significant effect on the environment as well. When a storm surge floods a city, toxic materials such as fuel, sewage, and chemicals are spread with the water. Additionally, everything picked up by the flood is redistributed when it recedes, scattering waste everywhere that floodwater reaches. While some floods are caused by earthquakes or other disasters that are difficult to predict, many are caused by storm surge. Storm surge occurs when a low pressure weather system pushes water towards a coast, creating an abnormal rise in sea level that can breach levees, destroy infrastructure, and cause deaths, such as was seen recently with Hurricane Sandy.

While an entire fleet of autonomous vehicles will not stop a hurricane, they would be able to help provide improved forecasts to be used by disaster management teams to plan their approach to the incident at hand. They could also be used to more accurately and more quickly predict the movement of the storm system, ensuring that areas at higher risk of impact receive more attention, and allowing for staging directors to more effectively plan the movement and distribution of supplies and resources during and after the disaster.

2.4.2 Climate and Environmental Hazards Applications

As we have previously discussed, a number of applications exist for autonomous surface vehicles in the area of environmental protection. These include weather observation, weather data collection, and hazardous spill management. Deploying ASVs for these applications would have far reaching impacts for both the environment and society as researchers are increasingly challenged to monitor changes and threats.

Climate change threatens the stability of the environmental systems that regulate everything from drought patters to oceanic acidity. This shift has had a wide range of impacts, including raising sea levels, increasing storm severity, shifting wind and storm patterns, more intense droughts, and many other consequences that are just beginning to be seen (Manning, 2007). Perhaps the most noticeable change is the rising global temperature. In all the years of global recorded weather data, the ten hottest years have been recorded in the past fourteen years. Scientists are now in agreement that "concentrations of CO2, methane and nitrous oxide have increased markedly as a result of human activities and now far exceed pre-industrial values" (Manning, 2007, p. 29). Overwhelming data, as shown below in figure 6, brings a sense of urgency to this topic, raising questions and inspiring decisions that span science, local leadership, and community action (Manning, 2007; Gore, 2006).

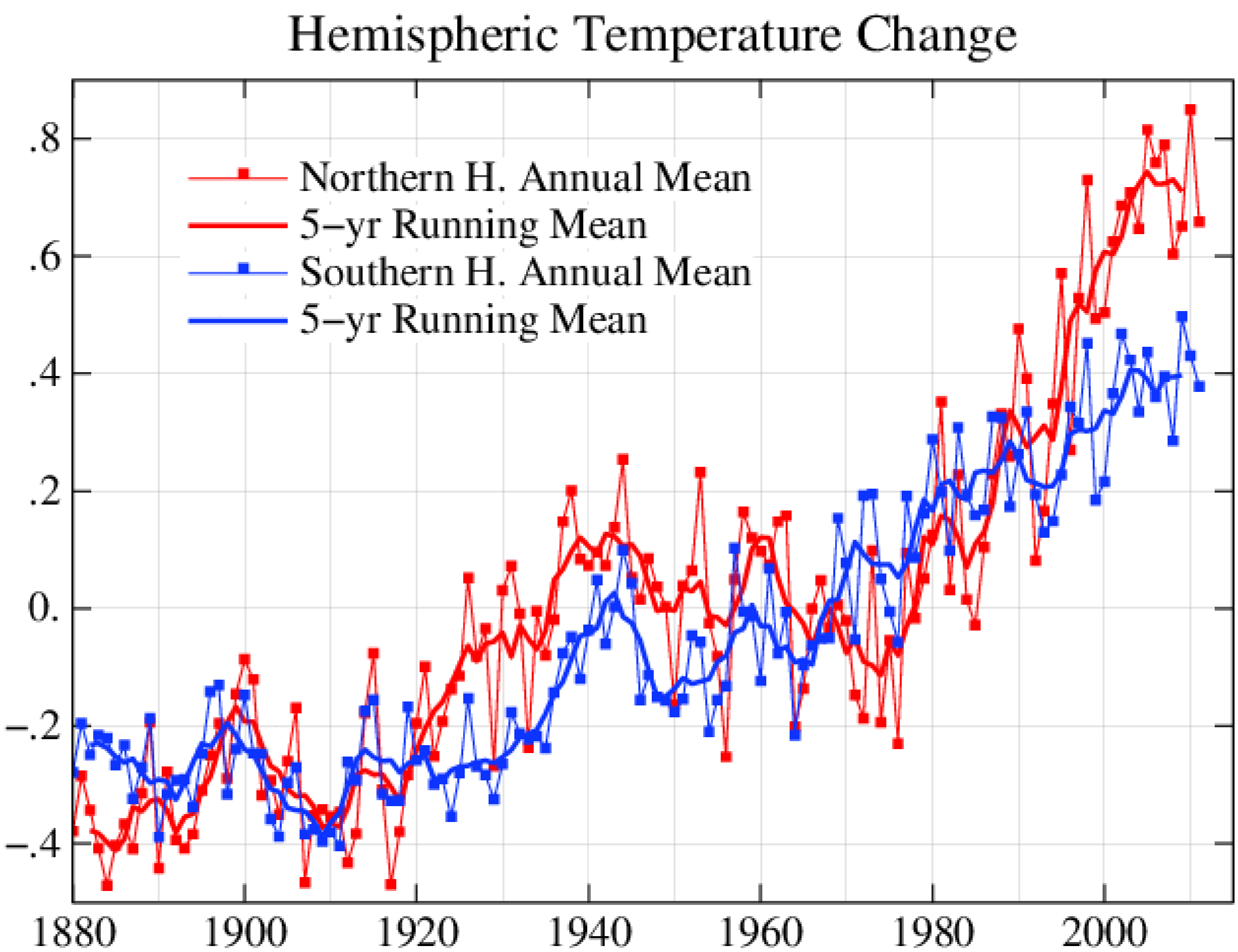

Figure 6: Global temperature plot, showing the increase in temperature (NASA, 2012).

Climate change has forced scientists to look to the ocean for new and relevant data, because ocean temperature, level, and currents have an impact on the world's climate and consequently on vulnerable communities. The ocean is responsible for most of the solar heat absorption, transportation, and distribution around the globe; it also absorbs carbon dioxide, a well-known greenhouse gas (Collar and McPhail, 1995). These changes put a new focus on collecting accurate data about the environment, because, as stated best by Mark Moline in a journal of atmospheric and oceanic technology, "the highly dynamic nature of the coastal ocean and the recent acknowledgment of growing anthropogenic impacts, increasing importance is being placed on the development of coastal ocean observatories and autonomous observational platforms that are capable of highly resolved continuous measurements" (Moline, et al., 2010, p.1). With an array of sensors and the capacity to store or transmit information, an autonomous surface vehicle can improve our understanding of the physical, chemical and biological aspects of specific ocean areas. As these technologies start to meet the demands of scientists, ASVs can transmit data that was either inaccessible or not feasible to retrieve through earlier methods. The vehicle can provide real-time data from varying regions around the world. In turn, this will transmit appropriate information in order to take corrective action on the environmental problem, ranging from the amount of a particular pollutant in the water to sudden and dramatic temperature changes, reversals of currents, or dissolved particulate matter in the water.

Autonomous surface vehicles may also be utilized for observing storms. For major cities such as Boston, or countries such as Bangladesh where the elevation is very near or below sea level, the accurate prediction of a storm becomes crucial to the safety of residents. In extreme cases, a category 5 hurricane can produce winds higher than 157 miles per hour (National Hurricane Center, 2012). In such conditions, no manned surface vehicle could risk heading straight into the storm for data collection. In these cases, satellites, land based RADAR, and specially equipped aircraft are often used for storm observation. These methods for collecting data are useful but do not cover some observations that can only be taken near the surface of the water (US Department of Commerce and Atmospheric 2012). An autonomous surface vehicle capable of traveling into a hurricane and being able to collect and transmit data from it would be useful to scientists observing these storms (Ken Prior, personal communication, September 11, 2012).

The second primary environmental application for ASVs concerns hazardous spill management. Incidents such as oil spills and the effort to respond to such disasters prove to be incredibly costly, both financially and environmentally. Current systems require specialized response ships and methods that are often loaned internationally. These and other factors, such as bad weather, can delay clean up procedures for hours or for days. Other challenges include transporting, storing, and treating the hazardous material that is collected. Many times this material cannot be recycled (Allen, 2004).

Clean-up operations, hazardous waste detection, and oil spill monitoring are other potential applications for ASVs. Instead of simply detecting pollution, an autonomous vehicle could be outfitted with a system to actually remove pollutants from the water. In the case of an oil spill, a boat or fleet of boats could be equipped with an oil removal device and deployed wherever and whenever an oil spill occurs. During the Deepwater Horizon oil spill, no autonomous cleaning vehicles were used, but BP did eventually launch an ASV in order to detect dolphins and whales in the vicinity of the spill, as well as the location of petroleum in the water (Forbes, 2012). These data were used to monitor affected marine life and help guide further cleanup efforts. In sum, ASVs have the potential to collect data and perform tasks more safely, at a lower cost, and more easily than other methods. The use of these vehicles can bring vital information to scientists and communities around the world.

2.5 Case Studies in ASV Research and Development

ASV research and design is an emerging field, and as is clear from the literature, there are numerous applications where such a vehicle can deployed. The design specifications are not set to any standard, so every model has its own attributes associated with the interests of the builder. Here, we evaluate two models that are well documented and already available on the market. We also include a new prototype that is under development by the authors.

2.5.1 MIT's Seaswarm

Seaswarm is an ASV developed by a team of students and faculty through MIT's Senseable City Lab. This vehicle is designed to travel on the surface of the water and work with a fleet of other identical autonomous vehicles to remove oil from spill sites. Although only one prototype has been made, the boats are intended to work in swarm-like formations when removing oil in order to maximize efficiency. They have the capacity to communicate with each other using short range WiFi communications links in order to plan an optimized cleaning pattern.

Seaswarm's hull is five meters long by 2 meters wide. The forward part of the vehicle is where most of the electronics are stationed. Behind this, a conveyor belt-like propulsion system skims the water's surface. On the front of the unit is a solar panel able to supply 100 watts, potentially powering the autonomous vehicle continuously for several weeks. The belt rotates and pushes the boat forward; it serves as both the vehicle's propulsion system and also the method in which oil is removed (see figure 7).

Figure7: Seaswarm prototype showing the belt propulsion (Senseable Sea Labs, 2012).

The belt is constructed with a new nanotechnology also developed by MIT. This nano-fiber is able to absorb oil while repelling water. It is capable of absorbing 20 times its original weight in oil. To remove the oil from the fabric, heat is applied to burn off the oil; the fabric is then able to collect more oil. The Seaswarm can self-apply this heat to the belt as it rotates on the water. This allows the boat to move forward while continuously absorbing oil with every belt rotation. The vehicle can sense the edge of an oil spill and move inward to clean all the oil. As soon as one section of the oil spill is cleaned by a Seaswarm boat, it moves on to another section and continues cleaning. While the Seaswarm project is just a prototype and has not been mass-produced or deployed, further research, development, and production could bring this craft to a very strong position in the market.

The first Seaswarm prototype was tested in the Charles River in mid-August 2010. Besides forward motion, it is unclear if this test did determine the capability of this craft to clean surface oil. However, according to the team's calculations, a fleet of 5,000 Seaswarm vehicles working continuously for a month would be able to clean up an area the size of the Deepwater Horizon oil spill (Senseable Sea Labs, 2012).

Since each vehicle is small and designed to work in a fleet, the Seaswarm project is scalable. Each Seaswarm vehicle has an estimated cost of $20,000, which can be a big factor when considering scalability (PhysOrg, 2012). While the vessel proposes an innovative solution using autonomous surface vehicle in order to solve problems, there are limitations to the units. With such a weak propulsion system and unstable hull, even slightly inclement weather could stop a Seaswarm unit in its tracks. The fact that it would take thousands of the units at a total estimated cost of $60,000,000 to clean a spill the size of the Deepwater Horizon spill over the time span of a month may be an obstacle to widespread applicability of this technology. Additionally, Seaswarm still needs to prove its functionality in the real world (Senseable Sea Labs, 2012).

2.5.2 Liquid Robotics' Wave Glider

Liquid Robotics is a private company based in Sunnyvale California that researches, develops, and builds the Wave Glider, a wave-powered vehicle that can be outfitted with sensors and be deployed on long distance missions that can last many months. A photograph of the ASV from the Liquid Robotics website can be seen below in figure 8.

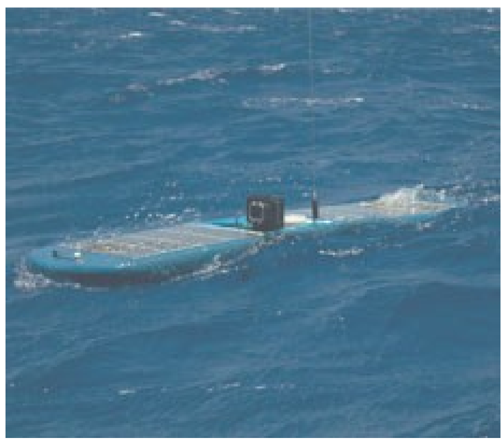

Figure 8: SHARC Wave Glider- the company's defense oriented ASV unit (Liquid Robotics, 2012).

This ASV harnesses the power of the waves to move forward. A system of underwater foils is attached to the float on the surface of the water. As the float forces the underwater unit to rise and fall, the foils oscillate to drag the hull forward, as illustrated below in figure 9.

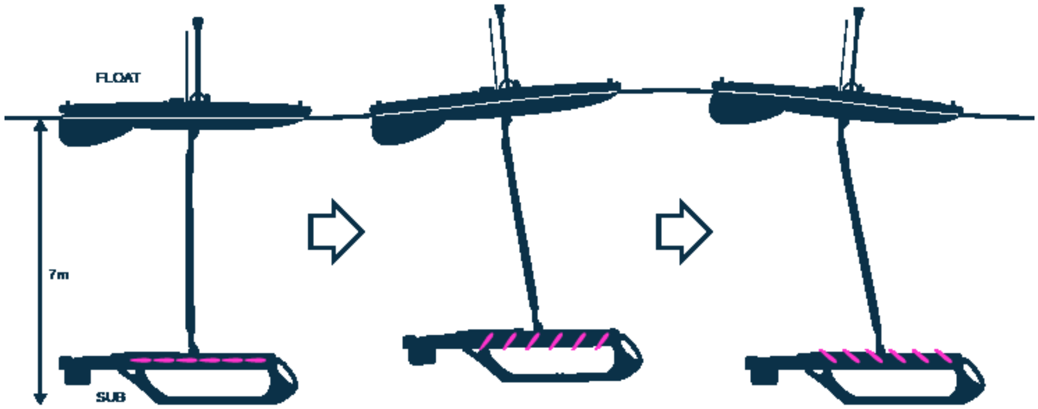

Figure 9: Forward motion of Wave Glider propelled by waves (Liquid Robotics, 2012).

The company, founded in 2007, has over eighty employees and maintains a strategic advisory board of 25 members from government and industry interests. The company was venture funded with $40 million, and sells each wave glider between $200,000 and $500,000 (Liquid Robotics 2012). Approximately 120 Wave Gliders have already been sold to oil companies, to weather services, and to the government. The selling points of the unit are its low cost (relative to a boat or moored buoy), its modularity (sensors can be fitted to the craft easily, enabling users to customize each unit) and the capacity for the platform to move along a pre-programmed course or be remotely controlled by a user.

The Wave Glider also faces a number of challenges. Although the data is unpublished, there is likely to be peak efficiency in terms of wave height from which the unit can harvest energy. Waves above and below this ideal height yield less forward motion. It is also likely that the wave glider performs better in certain types of waves, such as swell, which has long, consistent wave lengths, compared to chop waves, which are short inconsistent waves generated by surface wind. Additionally, the speed of a Wave Glider is not controllable; motion is fully reliant on the energy transferred to the craft by the waves, which restrict its top speed to two nautical miles per hour. While a Wave Glider has a relatively low cost compared to other data collection platforms, a $200-500k price tag can be prohibitive to certain organizations, and especially prohibitive to applications that would require large numbers of the craft. Entanglement in lobster traps and other debris has also been discussed as an issue for the

Wave Glider, a serious drawback as there are millions of lobster traps off the coast of Maine alone (Rindlaub and Taft, 2012).

2.5.3 SCOUT

In 2011, a group of friends in Newport, Rhode Island began building an autonomous boat designed to cross the Atlantic Ocean with no guidance or information sent from shore based systems. The project idea sprung from the hopes that a message in a bottle would reach a friend studying at a university in Spain. To give that message a better chance, the friends decided to develop an ASV to deliver it. While this idea started with simple models and testing, the project took on additional programmers, marine composite engineering students, and electrical engineering students as it evolved into a thirteen foot long carbon fiber boat capable of completely autonomous navigation. While the project started next to a Subaru in a dimly lit garage, it quickly attracted attention of both the media and individuals curious about its background, its construction, and its mission (see figure 10). The project's website is gotransat.com.

Figure 10: SCOUT water test (D. Rodriguez, 2012).

The current version of SCOUT takes the form of a 12.5-foot long boat designed for the sole purpose of ocean navigation. Built from a Divinycell foam core with carbon fiber laminated on the inner and outer surfaces of the hull, it is incredibly strong and designed to take extreme forces while remaining light and buoyant. Figure 11, below, shows the SCOUT construction team fitting a vacuum lamination bag to the bottom of the hull right after the last layer of carbon fiber had been applied.

Figure 11: SCOUT construction using a vacuum lamination technique to apply carbon fiber to the bottom of the hull (Rodriguez, 2012).

But more than a hull, SCOUT holds a set of systems and subsystems designed to take on the barren and unforgiving Atlantic. Every system onboard was designed, built, and tested with its final purpose in mind- guiding the boat to its target, more than three thousand miles away.

SCOUT's electronic systems are redundant and self-calibrating. Similar to a Mars rover, once SCOUT leaves on its journey, the electronics and software will have to work together without any assistance from shore to guide the boat from waypoint to waypoint. Onboard electronics look for any system behavior that falls outside defined parameters and take action to correct these malfunctioning systems. The software, just like the boat, is designed to run continuously for hundreds of hours.

SCOUT relies on an electric motor to perform its duties. Unlike a sailboat or wave powered vehicle, SCOUT's speed can be easily controlled and optimized for the conditions of the sea at any point in time. An electric motor means that the boat isn't threatened by heavy winds, high seas, or windless days, because the extremely low profile of this vehicle means that isn't easily influenced by the wind or capsized by the seas. In the case of a capsizing or full inversion, the boat will simply right itself and continue on its journey.

Unlike expensive ships, buoys, or autonomous wave propelled systems, a SCOUT unit can be built for $5,000- about 96% less than the price of a comparable wave propelled system. The unit's reliance on solar power and an electric motor introduces a reliance on the sun to propel the boat, but the units are built with a capacity to store power in internal battery banks and use onboard computers to plan for nights and cloudy days. Another advantage of the SCOUT system is that the user has full control over the vehicle's speed, compared to wave powered systems that are reliant on wave conditions, or sail powered vessels that are reliant on the wind.

2.6 Summary

The literature revealed that while the current array of prototypes is not fully developed, the future holds considerable promise for ASV application. Some attributes of available models include long duration of time at sea, different types of data collection, and timely feedback of information. At the same time, some weaknesses also persist in published accounts, with many ASVs unable to be implemented due to cost, underdeveloped technology, or lack of interest in adapting conventional designs. After reviewing the development and growth of ASVs along with weaknesses in current environmental monitoring systems, we have identified potential applications for future use of ASVs to help environmental monitoring and task performance. Some of these potential uses for these vehicles can protect property, lives, and the environment.

While autonomous surface vehicles seem to hold considerable promise for the future of oceanic research and task performance, they are still being developed and only a few simple units are commercially available. Our rapidly changing climate needs to be a huge concern to society as it has the potential to affect our day to day lives and more so to be catastrophic for future generations. Now more than ever, environmental monitoring is needed so that we are able to understand the threats that face our environment and can take corrective actions to improve our future. As the supporting technologies advance, so will autonomous vehicles that allow us to explore further, safer and easier than ever before. Our preliminary research clearly indicated that ASVs can be a great tool in helping scientists to mitigate the impacts of environmental disasters earlier and more safely.

Chapter 3: Methodology

The goal of our project was to evaluate the feasibility of autonomous surface vehicle application in environmental monitoring and task performance. In order to achieve this goal we identified the following objectives:

1. Determine the weaknesses of existing systems for environmental monitoring and task performance
2. Identify application demand for environmental monitoring and task performance systems
3. Identify potential clients for ASVs and assess interest
4. Develop a set of feasible recommendations for ASV deployment

In this chapter we describe the methodological strategies we used in order to meet each of these four objectives. The objectives are addressed in a chronological order to facilitate our use of a snowball sampling strategy and allowing the completion of one objective to assist us in understanding the following objective. The details are outlined below.

3.1: Determining Weakness of Existing Systems

Our first objective was to understand the weaknesses of existing environmental monitoring and task performance systems. We wanted to gain a perspective on the current condition of environmental monitoring, common monitoring equipment, and techniques used to collect, interpret, and publish collected data. To engage this process, we compiled a short list of experts in the field, drawn from our background research and from local contacts. These experts include scientists and researchers who interact with these systems frequently. For example, one individual that we contacted was Ken Pryor, a research scientist in the Operational Products Development branch of the Satellite Meteorology and Climatology Division at the National Oceanic and Atmospheric Administration (NOAA). We also interviewed Marco Kaltofen, who collects data for the Boston Chemical Data Corporation, among other environmental organizations. Mr. Kaltofen has used a variety of autonomous platforms to collect data and could speak directly about their strengths and weaknesses. Our initial list of contacts also included Dr. Thomas Webler and Dr. Seth Tuler, both founders and researchers at the Social and Environmental Research Institute (SERI). For our initial contacts we also used Dr. Greg Jones, a professor at URI (University of Rhode Island) and an employee at NUWC (Naval Underwater Warfare Center), maritime compliance manager and attorney Jill Taft, and Liz Rosa, a robotics scientist for the United States Navy.

Due to the wide range of environmental systems and experts with dramatically different backgrounds and scientific focuses, we conducted a semi-standardized interview with each of these contacts. This interview format proceeded with a base set of general predetermined questions, which helped us to focus the conversation on our area of inquiry and ensured that all essential areas were covered. This format also allowed us to develop specific follow-up questions over the course of the interview. The literature review, background research, and pre-interview contact gave the team a strong foundation in conducting an engaging interview (Berg, 2009). Interview guides and sample questions can be found in Appendix A.

Some of these participants had the added perspective of working directly with existing environmental data collection systems and had experience dealing with the quality of the data that is retrieved. These scientists were targeted to tell us exactly what the system was designed to do, and convey technical weaknesses of the system or its implementation that they had uncovered during its operation. Other participants, who held positions that did not involve interaction with existing systems, were sampled to speak more broadly about how different systems affected their line of work and some potential improvements of these systems that would help with their research. After interviewing with the first participants, we used the information that we collected to modify existing questions and add additional questions for future conversations.

We expanded and diversified our subject base by using a snowball-sampling technique with our initial short list of participants (Berg, 2009). At the end of these interviews we asked the participant to refer us to two or three people who might also have an interest in ASV technology. Some of these referrals proved to be very valuable in our research, and we continued to ask these new referrals for additional recommendations of parties who also might be interested in ASV technology. This technique helped us rapidly gain contacts in a relatively close-knit scientific community. In a few cases, the snowball-sampling technique also identified potential clients that we had not previously considered through our research. The Woods Hole Oceanographic Institute (WHOI), for example, was one organization that was referenced frequently in our snowball-sample strategy.

In many of our interviews, we addressed topics that covered each of our first three objectives in one sitting, so that we would not have to set up multiple interview times for different topics. When applicable, we asked permission and recorded the interview, allowing us to later review different statements and specifics of these conversations, and to share this information with any team member that was not present at the interview.

3.2: Identify Demand for Environmental Monitoring and Task Performance Systems

Our second objective was to identify areas and practices in which practitioners require new or better methods for environmental monitoring and task performance systems. To do this, we conducted additional research to expand upon the findings of the literature review. We investigated areas such as weather forecasting, storm predictions, and oil spill management. This provided us with details that we used to identify systems of interest and better construct a base set of interview questions.

For this objective we continued to use the semi-standardized interview format. We found that the information gained from completing the conversation on our first objective (weaknesses in existing environmental systems) transitioned smoothly to a conversation on our second objective (demand for environmental monitoring systems). The semi-standardized interview format was further justified here as we used many talking points from the first section of the discussion in order to form questions specific to this second objective (Berg, 2009). These focused questions were a great help in highlighting system demands for specific organizations.

In these interviews, we focused on identifying the resources scientists need to better satisfy their objectives. We used open-ended questions to get an idea of what potential clients needed and how limitations of current systems affected their work. This helped us clearly define the problems with existing systems and allowed us to design a solution that would solve some of those problems. We first asked if the subject already had a solution to their need in mind and what was preventing them from implementing that solution. We then followed up by asking them about the requirements and specifications of their proposed solutions. Again, this information was valuable for the completion of our third objective.

Mid-way through our interviewing process our team found some difficulties in setting up interview and meeting times. We had a tight timeline and needed more data and contacts to complete our objectives. To combat these difficulties we offered a survey option to some of our contacts when we were attempting to set up interview meetings. We found the response rate to survey questions was much higher than a response in setting up an interview. Although the survey option did not allow for probing questions, it did allow us to make contact with important organizations and led to valuable data in our findings. In some cases follow up survey questions were used to clarify responses.

3.3: Identify Potential Clients and Assess Interest

In order to identify potential clients for ASV platforms, we researched organizations that traditionally use oceanographic vessels. This gave us a starting point of a potential client base in which we later assessed their interests in ASVs. Throughout our research it was also important to consider organizations that do not use oceanographic vessels but could benefit from ASV technologies as potential clients. By being open to many organizations as potential clients we attempted to not limit the range of ASV applicability in our study. As specific organizations were highlighted through research and snow-ball sampling, we assessed their mission statements, goals, and objectives. With this information we could make a baseline assessment as to how the deployment of an ASV could further the organization's goals. If so, this was a potential client. Our preliminary research and previous interview information gave us a base of knowledge to construct accurate and productive investigations of potential clients through select semi-standardized interviews and surveys. In some cases, due to the availability of certain subjects and the global nature of ASV opportunities, we had to revert to phone and email conversations.

In our interviews, we first addressed the organization's objectives and methods they use to achieve those objectives. This helped us gain information about the position of the company in the industry and for what tasks an organization could potentially utilize an ASV. Next it was important to realize that many organizations will not consider ASVs to be a solution to their demands because they are relatively new technologies and are generally in the prototype stages of development. To mitigate this problem we started by asking hypothetical questions in which the organization could ignore costs of an ASV and only consider a perfectly functioning ASV. We then continued with more specific and detailed questions about the specifications and requirements that the organization would need an ASV to have. After considering hypothetical situations, it was important for us to determine how the subject's interests in the ASV platform varied with the cost of implementation.

In order to better understand potential clients, we also conducted a comparative analysis of our potential clients and other organizations that had previously utilized ASVs. We performed a snapshot case study on the company Liquid Robotics, as they are one of the few organizations to have clients for their ASV product (Berg, 2009). We analyzed the similarities and differences between their clients and our list of potential clients (Berg, 2009).

3.4: Develop a Set of Feasible Recommendations for ASV Deployment

In order to develop a set of feasible recommendations for ASV deployment, we compiled our findings from our research and interviews. We started to determine feasible recommendations by analyzing our data and establishing grounded categories (Berg, 2009). We developed criteria in order to categorize our findings into 2 groups:

1- **Known applicable areas** (These fields are known to us because of direct affirmative responses in interview process)

2- **Potential areas of application** (These fields are those that received an uncertain/unclear interview response. These fields could also be areas of application suggested by our research but without back up information from a field expert)

In each of these categories, we described the areas of application and specified how an ASV would offer a solution. We analyzed each area by deriving an index to compare the strength in an ASV's application (i.e. how well will an ASV solve the problem/ fill the need). This index is based on factors such as cost of ASV implementation, time saved by the ASV, ease of implementation, and social/environmental impact. By analyzing these two categories of ASV applicability; current organizations that use ASV technology and the obstacles that face ASV deployment, we were able to develop a list of recommendations that would advance ASV's capacity to meet a broad set of tasks and challenges.

Chapter 4: Findings and Analysis

In this chapter we present our findings on the applicability of autonomous surface vehicles to solve or improve environmental monitoring and task performance challenges. We present our findings in terms of our objectives: to evaluate the weaknesses of existing systems; assess the applicability for ASV development; and to identify potential clients. We also address some obstacles for the advancement of ASVs to be used in future oceanographic research.

4.1 Weaknesses of Existing Systems for Environmental Monitoring and Task Performance

Identifying weaknesses in oceanographic data collection brought us to a wide range of practitioners, scientists, and researchers, representing divergent interests in the community. Among the strongest survey responses was from Marine Habitat Resource Specialist Mr. Mike Johnson. From the perspective of the NOAA National Marine Fisheries Service's Habitat Conservation Division (located in Gloucester, MA), we learned some of the general and overlying limitations on basic ocean data collection. As the mission of his department is to protect, conserve and restore fishery habitats, we contacted Mr. Johnson to gain more information on the value of collecting ocean salinity data and about the methods used to collect this data. While he does not work with the collection of these data, he does use the data for his work. Mr. Johnson carries out his mission by consulting with federal and state agencies regarding actions that might adversely affect essential fish habitat (EFH) as well as other marine environments. Stakeholders including oil companies, fishing groups, and shipping companies, whose activities potentially create these kinds of adverse actions, provide him and his department with data collected regarding their impact on the environment. Mr. Johnson then synthesizes this data and provides the companies with information on how their actions could impact the local habitat. Johnson's team then works with these organizations to provide recommendations designed to mitigate negative environmental impact. These stakeholders, as well as Woods Hole Oceanographic Institute (the largest oceanographic research institute in the United States), are responsible for collecting and presenting data to Mr. Johnson. In his engagement with these kinds of data, Johnson noted that, "standard limitations apply, such as accuracy of the collecting devices, sub-optimal data points collected, inappropriate collecting methods, and spatial and temporal limitations (e.g., seasonal constraints)" (personal communication, Johnson, November 14, 2012).

In an interview with Thomas Webler, our team discovered another general and overlying weakness in ocean data collection. Dr. Webler is a research fellow of the Social and Environmental Research Institute (SERI), and a social scientist whose work concerns the integrity of coastal communities and environmental decision-making. While Dr. Webler is not directly involved in collecting data, he uses the data to form valuable and presentable information that informs educational forums, and presents this information to communities and organizations to initiate actions that positively impact society and the environment. Dr. Webler specifically pointed to ocean salinity data and its value, stating that there is great value in continuous and long-term measurements of ocean salinity data in order to be able to show convincing trends that can support policy change. Continuous and long term data collection can be difficult with current methods due to a number of limitations such as cost, danger, and human endurance. We later found that this issue of long term, continuous data collection is a limitation for many systems currently conducting environmental monitoring.

Our research identified oil spills as a significant event that could utilize ASV technology. We spoke with Mr. Marco Kaltofen who raised two issues with current methods of mapping oil spills. Mr. Kaltofen is both a graduate student at Worcester Polytechnic Institute (WPI) in the department of Civil and Environmental Engineering, and is a researcher at the Boston Chemical Data Corporation, who previously worked in mapping oil spills including the Deepwater Horizon spill in 2011. His primary goal was to map and project the movement of oil for his clients, which were both public organizations and private companies. One of the first issues he raised concerning mapping an oil spill is the cost. At this time, researchers and individuals tasked with cleanup use boats and aircraft to observe and collect data on oil location (as previously described in Chapter 2). These methods are expensive. Mr. Kaltofen gave one personal example of collecting near shore oil data: often only a small boat is needed to navigate around the coast and estuaries. A boat that he used for a survey cost him around $1,400 per day to. For oil spills in less protected waters, larger oceangoing vessels or aircraft are needed, and costs increase dramatically. Secondly, an issue in mapping oil spills that we have encountered in other environmental monitoring applications is the endurance of the platform collecting the data. Oil is constantly moving due to winds and currents, but both aircraft and manned boats have limited range and endurance.

Mr. Kaltofen expanded his concerns in the area of environmental monitoring, citing a case derived from his work with a company called Safecast. Safecast is a nonprofit and volunteer based company whose goal is to provide people with radiation data from a global sensor network, and was well recognized after the Fukushima disaster in Japan on March 11, 2011. This organization dealt with many issues in data collection, one of which was the accuracy of datasets. Many sensors and systems previously available in Japan to measure radiation were not providing data that could be compared to data collected by other means. Part of the problem was that there was no standardized equipment to produce comparable data points. Furthermore, there was not a wide range of data points to observe. The difficulty was in distributing standardized data collection devices around the affected areas as well as receiving continuous updates from those devices. Innovations in electronic design allowed Safecast to build and deploy many standardized radiation monitoring devices that wirelessly updated a database with their measurements. This system has been deployed only in select areas and relies on cellular wireless connections to transmit data, so units are limited in their range if they are fitted to boats.

One very strong system developed for environmental monitoring is the Geostationary Operational Environmental Satellites (GOES). GOES is a system of geostationary satellites used for intensive data collection all over the planet. The data collected by GOES is valuable to meteorologists for storm predictions, general weather forecasting, building climate and storm models, and developing atmospheric research. GOES is able to deliver a significant amount of real-time data over regions of the world that are generally hard to reach, such as the mid-Atlantic. Our team interviewed Ken Pryor, a GOES expert, about the functional aspects of the system. Mr. Pryor, a research scientist in the Satellite Meteorology and Climatology Division of NOAA, directly works with the GOES system and its ongoing development. During our phone interview, he expressed his enthusiasm for the launch of the new GOES-R system expected to take place in late 2015. We asked how he would add to or improve such a system if there was an unlimited budget; he responded that he would like to see a higher resolution sounding or profiling instrument implemented in the new system. Currently the GOES system has a sounding instrument that is able to produce reliable and valuable data, but the resolution is not high enough to compete with that of weather balloons. Higher resolution data would help in the observation and prediction of weather systems such as storms and tropical cyclones.

Our findings were further confirmed after communicating with a number of different Woods Hole Oceanographic Institute researchers in the Applied Ocean Physics and Engineering department. They reported similar weaknesses in their data collection methods, some of which included endurance and cost. WHOI studies many different aspects of the ocean and uses a wide variety of technology to complete their objectives. While buoys, manned craft and satellites are used for research, a significant amount of WHOI's data collection comes from the use of various autonomous *underwater* vehicles. Some of their deep-sea AUVs include *Sentry*, *SeaBED,* and *Slocum Glider*. As we have seen with other organizations, long-term continuous data collection is very valuable. The WHOI researchers raised the concern that these AUVs need to be deployed and often accompanied by a manned research vessel. These vessels are used for deployment, refueling, re-missioning, tracking, and receiving the collected data but can cost $20,000 to $50,000 per day. The expense of these vessels reduces the feasible length of many AUV missions.

Overall, our investigation of the weaknesses of current environmental monitoring systems has led to many similar limiting factors such as data accuracy, danger to human users, sub-optimal array of data points, a lack of standardized equipment between organizations, and cost of operation. We communicated both with the users of such environmental data and the collectors of environmental data. Their responses have all correlated with similar environmental monitoring and task performance limitations. In many cases, these limitations appeared multiple times and in different organizations that have different goals and objectives.

4.2 Application Demand for Environmental Monitoring and Task Performance Systems

Our field interviews yielded many different applications for ASVs. Some of these applications seem to be more feasible or in demand than others, but in all cases an ASV has the potential to expand data accessibility. Some of the more common systems used for environmental monitoring are compared in their capacity to collect data below, in figure 12. Factors such as time, cost, required resources, and ease of use were considered in the comparison.

	Satellite	RADAR	Weather Balloon	Airplane	Buoy	Manned Boat	AUV	ASV
Wind speed, direction	Shaded Green	Shaded Green	Green	Yellow	Green	Shaded Green	Red	Green
Water salinity	Shaded Green	Red	Red	Yellow	Green	Shaded Green	Green	Green
Water temp.	Shaded Green	Red	Red	Yellow	Green	Shaded Green	Green	Green
Barometric Pressure	Shaded Green	Red	Green	Yellow	Green	Shaded Green	Red	Green
Oil mapping	Yellow	Red	Red	Shaded Green	Yellow	Shaded Green	Red	Green

Green	Capable
Shaded Green	Capable but ASV could improve/ is more efficient
Yellow	Unknown, insufficient or not commonly used
Red	Incapable

Figure 12: A comparison of common capacities in available monitoring systems

One in-demand area of application we found was in collecting ocean salinity data. This area of study did not present itself to our team until we talked with Dr. Webler, yet the issue of ocean salinity connects to the bigger issue of climate change. As global temperatures rise, ice masses are beginning to melt and dilute the salinity of the oceans. Reduced salinity threatens sea life and possibly the complex currents that circulate water around the globe. Dr. Webler is planning to survey part of the coast of Maine, specifically areas around Boothbay Harbor, for a research project designed to study the impact of oceanic salinity on shellfish and the resultant impact on the local economy. When asked how he planned to collect this data, Dr. Webler was unsure. He often collaborates with area scientists and researchers to obtain the data, but his main focus is on identifying the social and environmental impact that the data presents. Dr. Webler listed some of the potential impacts of recently changing ocean salinity. These include the creation of a gap in the food chain by reducing the population of certain types of fish in the area. Especially in Northern areas, a reduction in ocean salinity may result in a significant impact on local economies that heavily rely on fishing. While Dr. Webler works mostly with local governments while collecting data and investigating ways to improve conditions, he often works with fishermen. Because the fishermen understand the impact of the research that he does, they are usually accommodating. The information that Dr. Webler collects, processes, and acts on is done to help these fishermen, the economy, and the environment. While ocean salinity data are available, the use of an ASV to have continuous, frequently collected salinity data in specific regions would greatly improve knowledge of the systems that keep the food chain going. In a subsequent interview, Mr. Kaltofen supported what we learned from Dr. Webler, saying that he also thought there would be great value in continuous and long term ocean salinity data collection. An ASV has the capacity to cheaply collect these data for a period of time that is only limited by engineering capabilities – so far proven to be significant.

From our interview with Mr. Kaltofen, we learned of two different applications for an ASV. The first possibility, as mentioned previously, was in collecting radioactivity and chemical release data. An ASV can be applied to radioactivity data collection in any body of water, but during this interview we specifically talked about the nuclear disaster in Fukushima, Japan. Kaltofen's work with Safecast is expanding the perspective of individuals and organizations, and is working to create a more detailed map of the effect areas both near and far from Fukushima. Safecast uses standardized sensing equipment that produces reliable and comparable data points. Currently the company uses many different methods to collect a wide range of data points- they have attached these systems to cars, bikes, boats, aircraft, and have even simply given them away to people walking on the street. An ASV can easily be equipped with one of these systems, which are roughly 6 by 8 inches and draw little power, although they are limited to use in coastal areas because of the limitations of their wireless technology. In this case, a properly equipped ASV could have surveyed local areas near Fukushima as well as distant areas such as the Western United States coast for any radiation carried over by wind or currents. The use of ASVs in the future could help Safecast and the impacted communities to get more data points from a more diverse set of locations.

A second area of application for an ASV that we discussed with Mr. Kaltofen is in mapping oil spills. Building on our findings from our earlier interview, we concluded that his observations are also relevant to our second objective. Drawing on his past work in mapping oil from the Gulf of Mexico spill and his knowledge of current methods used to map oil, he believes that a fleet of autonomous surface vessels could be used with low cost fluorometry sensors to detect oil and send that data back to a central station. ASVs have the potential to be much less costly than current mapping methods, and as we have noted, they offer the ability to continuously collect data without interruption. Mr. Kaltofen did mention that the resolution and quality of the information produced by ASVs would improve as more units are deployed. Specifically, he estimated that a fleet of 30 ASVs would be effective in mapping a spill the size of the Deepwater Horizon spill, but of course this number would vary based on a number of factors such as spill size, weather conditions, the speed required for the spill assessment, and desired resolution of the data.

Our findings also revealed applications for ASVs in the meteorology sector. As good as the GOES system is, and as much as scientists and meteorologists rely on it, Mr. Pryor suggested that the data it produces still needs to be verified by data collected on the surface. An ASV could to this end feasibly serve as a platform to reach mid-Atlantic locations to aid with the verification of GOES data. An ASV that can collect surface data can also serve as a calibration tool for the GOES system. Mr. Pryor said that surface data is important to the GOES system not only for verification and quality assessment but also "to basically train the output from the satellites" (Ken Pryor, personal communication, November 16, 2012). Important data from a surface platform might include water temperature, air temperature, and surface wind speeds and direction. Data collection and transmission intervals could vary depending on the task at hand. Other systems, such as fixed buoys, are now used to gather some of these actual surface measurements. Mr. Pryor said, however, that "it's good to have the flexibility with data;

particularly from platforms that can travel; [….] a blend of both types of platforms [a network of static buoys and dynamic ASVs] would be optimal" (Ken Pryor, personal communication, November 16, 2012).

WHOI has found potential use in ASV technology to assist in the operation of their fleet of AUVs. Mr. Dana Yoerger, who is a senior scientist at WHOI in the Applied Ocean Physics and Engineering department, presented us with a proposal he had worked on with other WHOI scientists. This proposal describes how the use of one or more ASVs can eliminate the need for an escort vessel for their AUV fleet. An ASV can be specialized to track the AUV, transmit the AUV's collected data, and even possibly refuel and re-mission the AUV. This use of ASVs can allow a fleet of AUV to collect data over a longer period of time, over a wider range of locations, and at a much lower cost. ASVs can also assist AUVs in underwater navigation by relaying surface GPS data, as AUVs cannot take advantage of GPS because of the layer of water between the unit and the GPS satellites. Specifically in this proposal, the Wave Glider ASV (mentioned in chapter 2) was used as an example platform for the deployment, however Mr. Yoerger said that there is room for many different ASVs for this application. By eliminating costly escort vessels, ASVs have the potential to expand the amount of data that can be collected by unmanned submersible platforms. While this is one great application for ASVs at WHOI, we were also told that ASVs can be specialized for many different applications and have the potential to be applied to many different areas of oceanic studies.

Many organizations depend on WHOI for their role as a premier oceanographic research institute. Their work in turn benefits a range of local stakeholders, from governmental officials and policymakers, to climate and marine scientists throughout the world. Sharing these data, whether in the form of meteorological observations or SERI's environmental data analysis documentation, unites the social benefit of coordinated data collection. Because of the global research data sharing networks that exist today, we believe that developing technology that can be used by organizations such as WHOI to collect and share data can have far reaching and often unexpected results.

4.3 Potential Client Base for ASV Technology

Our findings revealed a range of applications that could feasibly change and increase the client base that ASVs have traditionally served. With the advancement of technology, ASVs will become more available and easier to use so that more organizations can deploy them for environmental monitoring and task performance. Organizations that could utilize such technology include:

1. WHOI
2. EPA
3. Coast Guard
4. Harbor patrols
5. NOAA
    a. National Marine Fisheries Service
    b. National Data Buoy Center
6. Oil Companies
7. United States Navy
8. American Fisheries Society
9. Government sectors
10. Beachside resorts and businesses
11. Greenpeace, Sea Shepherd, and other environmental activist groups

Regarding the issue of decreased ocean salinity, potential clients for ASVs could include local governments and fishing organizations. With reliable information presented to coastal communities, the impact of decreased oceanic salinity could be monitored and used to develop strategic political policies and regulations. Climate change has the potential to diminish sea life on which many of these coastal communities depend. The data gathered by ASVs could form an informative tool that may inspire action to mitigate environmental damage and insulate local economies from the consequences of this damage.

Other obvious clients for ASV technology result from ongoing oil spill disasters. An interesting dimension of oil spill mapping is that much of it is done for private businesses. For example, beachside resorts need to know the location of oil slicks and the projected path that the oil will take. Because so much of their business centers on beachfront property, resorts and other seaside tourist attractions are significantly impacted by oil on their beaches. In our interviews with Mr. Kaltofen, he mentioned that private resorts often pay from two to four million dollars per mile of beachfront property for a variety of services including oil data collection and cleanup services. Such businesses are also interested in this data so that they are able to receive appropriate compensation from the oil company held responsible for the disaster. For this reason, beachfront resorts and businesses would have great interest in a company that uses a fleet of ASVs to provide information that could aid in the prediction of potential oil damage for their business. Mr. Kaltofen estimated that depending on the spill, each data point collected in a coastal oil slick could be worth approximately $25.

4.4 Obstacles for the Advancement of ASV Development

In an interview with Jill Taft, a maritime attorney and compliance manager, our main areas of inquiry were the legality of autonomous surface vessels and the consequences of their deployment. Because ASVs are a new field of development and have not surfaced on the mass market, the legal dimensions of ASVs are unclear. As Ms. Taft likes to say, "the law clearly lags behind the growth of technology" (Jill Taft, personal communication, November 15, 2012). Ms. Taft stated that there were a number of topics that need to be investigated to proactively establish the legality of ASV deployment. As she pointed out, while the technology is certainly legal, deploying that technology may not be. As maritime law was never intended to address autonomous vehicles, a number of laws and regulations that are in place could potentially block the implementation of ASVs. For example, ASV sized watercraft are technically required to carry a set of flares and a fire extinguisher. Jill did mention that following as many regulations as possible may or may not make a difference in the legality of the deployment if it is challenged.

One of the biggest challenges for the deployment of ASVs is reducing the threat of collision with other vessels. ASVs have the potential to be very small and maintain a low profile. Because of this, ASVs may have no radar signature, especially in heavy seas or adverse weather conditions. Without a radar signature, and because they are so difficult to see, small ASVs run the risk of colliding with other passenger vessels. Some ASV prototypes have been built with collision avoidance systems, and these systems can vary greatly. One possible system, suggested to us by Mr. Kaltofen, is incorporating the data from a website such as *Marinetraffic.com*, which shows updated location and data of registered commercial vessels. These websites use Automatic Identification System (AIS) data, which is transmitted by each boat via Very High Frequency (VHF) radio. A number of issues limit the effectiveness of AIS as a collision avoidance system, including a delay in updated location data and the fact that most vessels do not use AIS. Although there are some areas in which ASVs do not pose a hazard to navigation, future technology will have to be incorporated in order to eliminate ASVs as a danger to other vessels.

Obstacle avoidance is another obstacle facing ASV deployment. Collision challenges for ASVs involve more than just passenger vessels. An ASV has the potential to get caught in buoys, lobster traps, fishing nets, ice, and natural sea debris. There are over 3 million lobster traps off the coast of Maine alone (Rindlaub and Taft, 2012). Keeping an operating ASV away from all possible entanglements while conducting costal environmental monitoring or task performance could prove to be challenging.

Developing system standards for ASVs is another obstacle for their advancement. Currently no standards are in place to regulate construction, software, wiring, and sensors on ASVs. If standards established, ASVs' sensors, software, and navigation equipment could interact with other ASVs and improve the quality of data collection and overall function of the vehicle and networked vehicles alike. Standards would also help the development of user friendly software to interpret and display collected data, making it much easier for organizations to implement such a platform to achieve their objectives and to share that data with others.

Issues may also arise in ASV deployment due to rights of use and travel. For certain bodies of water, ASV travel may not be permitted. For example the United States Navy and Coast Guard often restrict travel zones in certain areas of interest. Another legal hurdle is vehicle registration and international travel; governments may not allow ASVs registered in other countries to operate in their water without permission. A final consideration of this aspect of ASV use is the fact that ASVs also have the potential to be misused. Clear regulations on use, mandatory registration of systems, and other measures may need to be investigated and put into place to ensure that ASVs are used properly.

4.5 Summary and Analysis

The implications of our findings clearly show that ASV technology has strong potential to contribute to future environmental monitoring and task performance systems. Many limitations of current systems include cost of operation, endurance of the system, and the need for human resources. In most areas, the use of an ASV can lessen or eliminate these limitations. With further development of technology, ASVs have the potential to operate at a low cost, continuously monitor an environment without interruption, and reach areas of interest that would be too dangerous or inaccessible to humans.

There are some obstacles that ASVs need to overcome before their use is widely accepted among environmental organizations. One of these obstacles includes eliminating an operating ASV as a navigation hazard to passenger vessels. Another obstacle is developing standards for these vessels to more rapidly bring them to the commercial market. Standardizing components, wiring practices, and data packaging and transmission strategies would reduce the number of proprietary systems on the market and allow for expanded flexibility and ease of use of these systems. These obstacles can be overcome with the further advancement in technology and future experimentation and testing of ASV prototypes. When considering our need to further observe our oceans due to our rapidly changing climate, the benefit of using ASVs will overcome the obstacles facing their advancement.

Chapter 5: Recommendations and Conclusion

Based on our findings and analysis, we are optimistic about the use of ASV technologies in a wide range of applications. Ultimately, we see several options for the way forward in the research and development of these kinds of craft, including existing platforms and newly developed craft designed for specific purposes. Some hurdles must be overcome to allow for the commercial implementation of these systems, but the potential opportunity that ASV deployment offers far outweighs the challenges of implementing these systems.

5.1 Recommendations:

Based on the findings of our study, we recommend the following:

- That further research begins to develop and implement the legal standards for ASV configuration and the regulations for their deployment.
- That the developing ASV industry implements a set of system standards.
- That further research explores the sharing of data collected by ASVs between organizations.

Developing legal standards and regulations for ASVs is critical to the development and deployment of future systems. Without the guarantee that ASVs can operate in territorial and international waters, companies will not want to enter the ASV market. The current legal gray-area that ASVs have been operating under has made investment in these technologies risky. Legal guidelines for ASVs would reduce the risk of investing in these systems and would bring stability to a developing market.

The development of system standards for ASVs could reduce the number of proprietary ASV models that are offered by competing companies. By standardizing components like sensors and other subsystems, the data from ASVs built by different companies could be compared and formed into collective models. If two ASVs use different sensors to collect data, there may be a difference in the specifications of those sensors, and the data from the two units cannot be considered the same. Because in many situations a large number of ASVs must be deployed, standardizing sensory systems would allow ASVs controlled by different organizations to work in concert, a feature that would be very useful for large events such as unplanned oil spills where many organizations would benefit from an accurate set of data. If these organizations could pool their autonomous resources to build this map faster, the subsequent impact of having this information days or weeks faster could be significant.

Exploring a system to share data between organizations would enable data collected by any participating organization to be used by the others to further their research. For example, it makes no sense for two organizations to take separate oceanic salinity surveys in the bays of Rhode Island. Allowing collected data to be shared between organizations would mean that in some cases multiple surveys of the same area could be avoided. As was previously mentioned, essential to the sharing of data between organizations is the standardization of sensory systems onboard the ASVs in use. We see no reason why all surveys taken by ASVs for research purposes could not be uploaded by default to a shared database that encourages use of this information for research that could benefit the environment, society, or any of the organizations that contribute data to the database. Just as how NOAA data is made available to the public, certain features of this inter-organizational database could be made available to the public. As we learned from a number of our participants, creating accurate and comprehensible visualizations of data is of critical importance because having the data is not enough. Using that data to promote change can be difficult if people do not understand the data or the implications of what the data is indicating.

5.2 Conclusion

While autonomous surface vehicles are in their infancy, we believe that tremendous opportunity exists for modular and customized ASVs if some hurdles can be overcome. In addition to saving money over existing systems, ASVs also offer benefits that are currently unmatched by existing systems, which include endurance missions, collection of data in hazardous environments, and swarm behavior that can use multiple units to gather data more quickly. Establishing the legality of ASVs and standardizing sensors would be a huge accomplishment for the future of ASVs, as these two hurdles are what keep ASVs from being mass manufactured and available commercially. Additionally, sharing data and ASVs between organizations with similar missions could become an incredible tool capable of empowering small environmental organizations with the data collection capacity of organizations many times their size.

Because of the challenges to data collection and task performance that ASVs solve, we see this as a tremendous opportunity for environmental organizations to collect data that was previously inaccessible to them at a time when acquiring this data could not be more important. As we have illustrated, ASVs can dramatically improve the capacity for information collection ranging from weather data to oceanic salinity indexing, and this would bring a new level of data and resolution to the hands of the organizations that use this data to make or influence changes to policies and regulations on a national and often global scale. If ASVs can collect more data with better resolution and at a lower cost than traditional systems, the time advantage that these systems give can be leveraged to slow and reverse harmful environmental practices earlier, which may lead to better outcomes. Because it will always be easier to continue using existing systems that simply meet our needs, even though ASVs have been increasing in their feasibility, decreasing in cost, and expanding their feature sets for years, few organizations have moved to accept and implement this technology. Taking steps to implement these systems will enable a more plentiful, accurate data collection method that will only serve to improve our understanding of the oceans which feed millions, allow for the transportation of trillions of dollars worth of goods, and regulate the temperature of our planet.

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Appendix A: Interview Question Guide

1. Baseline questions about the individuals
   - Name
   - Position
   - Mission of their department, objectives, and goals
2. Questions about mission
   - What impact does this mission have/who does it impact
   - What methods do you use to achieve the goals of the mission?
   - Major changes to mission/ goals recently?
   - Major changes in the way you achieve mission
   - How does technology impact your position?
     - What technologies do you use?
     - How do these technologies impact the mission?
   - What are some obstructions that you've encountered in the completion of these objectives?
   - Limitations to the technologies or means in which you achieve your objectives
   - Are there any currently available practical alternatives to the technologies and methods that you use?
   - Are there any up-and-coming technologies that might apply to your field of study?
   - What would be an ideal technology (technologies) that you would like to see developed for use in achieving these goals?
     - What kind of data would this collect?
     - What are some traits of the product that would make it desirable?
3. Questions related to Autonomous Surface Vehicles
   - Are you familiar with the Liquid Robotics Wave Glider? Any other ASVs?
     - [If the subject is not familiar with ASVs, briefly explain to them- their capabilities, infrastructure requirements, and costs.]
   - If cost was not a consideration, would you implement an ASV that could function as demanded?
     - If not, why? (Determine barriers that would prohibit an ASV from being used for their purposes)
   - What requirements would you have for an ASV?

- Are there any specifications, specialized equipment, or tolerances that concern you in ASV deployment?
- What would satisfaction of those requirements mean for your work? How would this improve the results of your work?
- Would this replace the technology that you use now, or just supplement it?

- How much would you be willing to pay for an ASV to suit those requirements?

4. Do you have anyone else in mind that you could refer us to that would have an interest in autonomous surface vessels?