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Analyzing the Current Market of Hull Cleaning Robots

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Abstract

This project is intended to provide a market assessment of the emerging industry of hull cleaning robots to help the United States Coast Guard with their goal of reducing the spread of non-indigenous marine species. We researched the capabilities of these technologies that stakeholders need to be aware of, including the regulations and state of the market. The project resulted in a comprehensive list of every hull cleaner that we were able to identify and their functionality along with design parameters.

Disclaimer

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Executive Summary

Project Background

Biofouling is the buildup of organisms on the side of boat hulls, propellers, and other infrastructure in aquatic and marine environments. It causes a variety of issues for vessels of all types, including large tanker ships, military vessels, and personal watercrafts. Organisms on a ship's hull increase fuel consumption by increasing the ship's drag. Additionally, vessels can transfer marine species from one region of the world to another. When an invasive species is introduced to an ecosystem, there is often a disruption and damage to the environment. For example, new species may not have natural predators and could out-compete native species. The International Maritime Organization (IMO) Secretary-General recognizes invasive species as one of the greatest threats to the ecological well-being of the planet (International Maritime Organization, 2016a).

The United States Coast Guard (USCG), pursuant to the National Invasive Species Act, is interested in investigating new ways of controlling the introduction of invasive species in U.S. marine environments. Unfortunately, current methods for combating biofouling are expensive. Ships must be drydocked, cleaned of current coatings and fouling, and then painted with antifouling paint routinely depending on the class of vessel (Brogan, 2015). Any amount of time that a ship spends drydocked is time that is not spent in the water engaged in normal operations. Many ship owners periodically deploy divers to inspect ship hulls and remove biofouling, however, like drydocks, deploying divers is costly.

Hull cleaners are autonomous or semi-autonomous underwater robots used to scrub ship hulls clean while still in the water. As this is a fairly new industry, information on hull cleaners is scarce but what we have been able to find shows promise. Routine use of hull cleaners could result in fuel savings. Hull cleaning robots may also be able to reduce the risk of spreading invasive species.

Figure 1: Biofouling on side of ship (Fathom Shipping, 2013)

Methodology

This project is intended to help the USCG understand what technologies are available today. In order to obtain effective and usable information for the Coast Guard we defined the following objectives:

1. Identify potential hull cleaning systems and other hull cleaning technologies
2. Determine a criteria for evaluating hull cleaning systems
3. Gather information on both current hull cleaning technologies and ones currently in development

We began by identifying current hull cleaning technologies. It is important to stress that our list is nonexclusive and non-exhaustive.

We then defined the key functions and design limitations of the hull cleaners. This required two crucial steps. First, we determined the regulatory and economic constraints that influence robot design. Second, we investigated the functions that the robot would need to perform to meet the ship owners' needs. We spoke with maintenance experts and naval architects from the USCG, but all of the shipping companies we contacted either did not receive our communication or chose not to reply.

After establishing criteria for hull cleaning robots, we contacted the companies we identified through our research. The criteria shaped our questions to the companies and allowed us to establish a baseline of information to collect. This baseline allowed us to be consistent in our research.

Results

The data we gathered shows the diverse set of hull cleaning robots that are out in the market today. As for any new industry, the technologies will need further development and testing in order to be successful. We compiled the results of all our findings into three different sections. The first section lists all the companies and organizations that are included. The second section describes potential design considerations for hull cleaners. The final section is a list of all hull cleaners and their specifications.

Identified Hull Cleaner Companies

Throughout the project we gained a substantial amount of information on the individual technologies both available and being researched. Since each hull cleaner is in different stages of development it is important to take a step back and properly evaluate the state of the market. Of the 16 hull cleaning robots identified three hull cleaners are from the United States. The remaining 13 are spread amongst eight countries. If we were unable to have a direct correspondence with the company, we still included any information we were able to gather on the robot.

In terms of the commercial availability of these robots, two of the 16 robots are from universities, and are primarily research projects. One project was cancelled, and one company is suspected of no longer being in business. The remaining 12 hull cleaning robots can be grouped into three categories. Six are in use today, or are commercially available. Five are still undergoing development and testing. The remaining robot's status is unknown, because the company chose not to give us information on its status in any capacity.

Developed Criteria

To develop criteria on the functions and design limitations of hull cleaning robots, we needed to first understand what every stakeholder would require in these devices. Shipping companies are concerned with their continually shrinking bottom line. Robot manufacturers are attempting to develop technologies that function in a variety of circumstances and environments, primarily to save their customers fuel costs. Regulators face a difficult task in defining how to use this technology in order to combat invasive species.

Based on this information, we determined the following criteria to be most important in researching hull cleaners.

Table 1: List of Developed Criteria

Criteria
Country of origin
Weight of robot
Size of robot
Adhesion technique
Adhesion force
Cleaning Speed
Type of cleaning apparatus
Sensors included on system
Is the robot able to function while the ship is underway?
Does the robot use a filter?
Mean time to failure
Operational style (autonomous, semiautonomous, manual control)
Is tether needed?
Cost

Hull cleaning robot profiles

We gathered data of the hull cleaning robots, like the ones seen in figure 2, from their manufacturing companies and developers.

Figure 2: Hull Cleaning Robot Example Images (Lowe, 2016)

Table 2 is a list of each technology identified along with quick details about each device. Criteria include but are not limited to the method of operation, the onboard filtration system, the system of adhesion to the side of a ship, and the cleaning system the robot uses.

Table 2: Hull Cleaning Robot Summary Table

Robots	Operating Type	Filter	Holding System	Cleaning System
CleanHull	Semiautonomous	Yes	Turbines	High pressure water
Fleet Cleaner	Manual	Yes	Magnets	High pressure water jets
GreenSea Robotic Hull Cleaner	Autonomous	Yes	Neodymium magnet track System	Brushes using ultrasonic action
Hull Surface Treatment	Manual	Not needed	Magnets	Thermal Shock
Hullbot	Manual	No	3 thrusters	Rotating cleaning disks
HullBUG	Autonomous and Semiautonomous	Yes	Magnetic, or negative pressure	Brushes, and jet based operatic modeler
Hulltimo	Manual	Yes	Suction system	Brushes, roller of polyamide
HullWiper	Manual	Yes	Negative Pressure system	Cleaning discs that pump saltwater
KeelCrab Sail One	Manual	Yes	Turbine	Turbine vacuum, rubber, and nylon brushes
M6 sub sea Cleaning Tool	Manual	Unknown	Magnets	High pressure water nozzles
Magnetic Hull Cleaner	Manual	No	Magnets	Pressure washer
Remora	Autonomous	Unknown	Magnets	Unknown
RovingBAT	Semiautonomous	Unknown	Thrusters, motorized tracks	Uses either hydro-jetting or a brushing system
Underwater Hull Cleaning Robot	Proprietary	Yes	Proprietary	Proprietary
Underwater Robot	Autonomous	Unknown	Propeller	Unknown
(No Name)	Unknown	Unknown	Unknown	Unknown

Observations on the Market of Hull Cleaning Robots

Our observations generally fit into three categories: economic, technical, and regulatory. Economic pressures and the development of robot technologies have allowed hull cleaning robots to quickly emerge as a new industry. The robots possess a diverse and powerful set of technical capabilities that need to be taken into account when looking at solutions to biofouling. Finally, the influence that state, federal and international regulations might have on hull cleaning robot design could shape the industry. Our observations are as follows.

Economic

The economic picture of hull cleaning robots is diverse and driven by a number of factors. This industry is relatively new and still needs a lot of time to mature, but we believe the industry is growing because many of the hull cleaners began development after 2010. Many of these companies advertise that their product can save the ship operators money through lower fuel consumption. This indicates that many of these systems will need additional testing in real world scenarios to confirm the veracity of claims made by industry. We believe that if margins narrow in the shipping industry (Morley, 2016), hull cleaning robots and other alternative fuel saving technologies will grow considerably.

Technical

From a technical perspective, the industry is also extremely diverse. Every company had different goals in mind when designing their robot and, consequently, different approaches to the problem. In terms of the effectiveness of the technologies, we continue to see a lack of conclusive testing. Many of these technologies have only been tested in a controlled environment, and many of the designs present potential concerns in an actual operating environment, e.g. a port or open waters.

An ideal robot would be able to work without disrupting the normal functions of the ship. One robot can perform their tasks while the ship is underway, but the rest are intended to clean the ship while it's in port. Some ports have strict restrictions on hull cleaning which resulted in many companies installing filtration systems onboard their robots.

A great deal of evaluation and testing needs to be performed. There is very little independent testing being done on these technologies. Regulators or ship owners have no independent data determining the veracity of the robot manufacturers' claims. As the industry continues to grow, the effectiveness of the technologies will need to be studied and determined.

Regulatory

Regulations have influenced the development of hull cleaning robots through hull fouling limitations, hull coating restrictions, and prohibiting hull cleaning in port. State, federal and international regulators could positively or negatively affect the hull cleaning industry. If more biofouling regulations are implemented and enforced, hull cleaning robots will become increasingly relevant.

We believe that if regulations on robot hull cleaners were implemented, it is likely to negatively impact the industry. Robotic hull cleaner designs vary wildly, as each utilizes different approaches. This wide variance will make it extremely difficult to establish a definitive standard, even if performance based. If such a standard were to be implemented, creative and innovative solutions may suffer as companies compete to meet the standard.

Our data suggests that regulators have a lot to examine when discussing choices to make regarding hull cleaning robots. A full evaluation of the impacts on each stakeholder needs to be performed before any action is taken. Hull robots are a new and emerging industry, which will be affected by regulations created for addressing biofouling, fuel consumption and cleaning in ports.

Conclusion

This project will be the first report assessing the market of hull cleaning robots. We believe the report will be useful not only to the USCG, but to the shipping industry. We also created a reference binder detailing the different technologies we identified and presented our findings to the USCG. Hull cleaners are an emerging technology and much of their future is unknown, but we now know the state of the market.

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1.0 Introduction

Biofouling is the buildup of organisms on the side of boat hulls, propellers, pier pilings, and other infrastructure in aquatic and marine environments. It causes a variety of issues for all vessels, including large tanker ships, military vessels, and personal watercrafts. Organisms from one section of the ocean can attach themselves to a boat and travel to other areas where they would not be ordinarily present. While sometimes harmless, this can potentially introduce invasive species. The International Maritime Organization (IMO) Secretary-General recognizes invasive species as one of the greatest threats to the ecological well-being of the planet (International Maritime Organization, 2016b). In addition to transferring invasive species, biofouling can cause fuel consumption to rise in ships by 40% and therefore, also can impact a boat's emissions (Mittelman, 1999).

The United States Coast Guard (USCG), pursuant to the National Invasive Species Act, is tasked with controlling the introduction of invasive species. Unfortunately, current methods for combating biofouling are expensive. Ships must be drydocked, cleaned of current coatings and fouling, and then painted with antifouling paint routinely depending on the class of vessel (Brogan, 2015). Drydocking a ship takes not only an incredible amount of money, but time. Any amount of time that a ship spends drydocked is time that is not spent in the water engaged in normal operations. As an interim measure, many ship owners deploy divers to inspect the hulls and remove the biofouling. These divers use scrapers and scrubbers to manually clean the hulls. This method is expensive and dangerous. Additionally, divers run the risk of damaging the antifouling paint. Damaging the antifouling not only releases large amounts of the poisonous paint, but also makes the ship more susceptible to biofouling.

The USCG is interested in learning about the availability of hull cleaners, an alternative method of fighting biofouling. Hull cleaners are autonomous or semi-autonomous underwater robots used to scrub ship hulls clean while still in the water. Hull cleaners show promise because their routine use could result in reducing the spread of invasive species and fuel savings by removing biofouling.

For an example of how biofouling affects fuel consumption, the *EMMA MAERSK,* a 397 meter (m) container vessel, consumes 300 tons of fuel per day. Around 30 tons of that fuel is wasted as a result of biofouling. At 2008 fuel prices, 30 tons of fuel cost around $20,000 (Vidal, 2010). Hull cleaners also eliminate the need for divers, and in theory can outperform them.

This project aims to be an analysis of the current market for hull cleaning robots. In order to properly report on this technology three objectives were determined. The first objective was to identify potential hull cleaning systems as well as other hull cleaning technologies. The second objective involved determining the important criteria for hull cleaning systems. This determination considered the current needs and requirements of the industry, current practices and regulations in regard to biofouling, and finally a discussion with members of the USCG on design challenges that could be present in a hull cleaning system. The third objective was to gather information on both current hull cleaning technologies, and ones still in the development and testing stage.

2.0 Background

This section details our background research. It describes biofouling and how it is affecting the marine ecosystem today as well as the anti-fouling practices being used currently. We then detail Coast Guard regulations and policies on biofouling, as well as their motives for keeping biofouling to a minimum on ships. Finally, we introduce some current technology that may combat biofouling more effectively than the standard practices today.

2.1 Effects of Biofouling on Marine Ecosystems

Biofouling begins with microscopic bacteria that adhere to the ship and multiply rapidly. This forms a film upon which other life can grow. As long as a surface is submerged, a film will form (Cao, 2010). Once the film has formed, other, larger structures can latch on. These might include barnacles, plants, and sometimes even larger marine life such as mollusks or mussels. Fuel consumption can increase by up to 40% once large organisms become attached to the hull Cao, 2010). While the fuel consumption can be drastic with more advanced fouling, even light fouling can increase hull resistance (which in turn increases fuel consumption) by up to 10% (Jim Rooney, Personal Communication, October 31, 2016). Thankfully, hard fouling cannot form on surfaces which have not yet developed a biofilm. Figure 1 below shows how growth can develop, and the increased hull resistance generated.

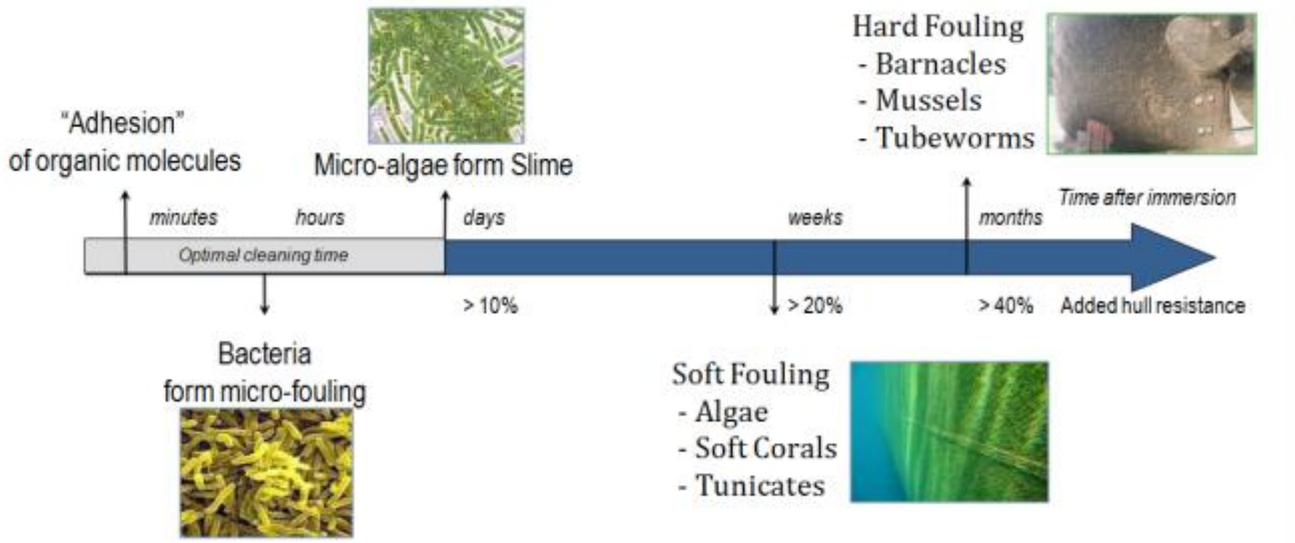

Figure 3: Progression of biofouling growth (Raytheon, 2016)

Fuel consumption is not the only threat created by biofouling. Once a ship becomes fouled, it can serve as a vector for invasive species. Invasive species are the single greatest threat to marine life (International Maritime Organization, 2016a). Biofouling shows the diversity of the marine ecosystem. Fouling organisms have evolved to thrive in specific environments and, consequently, often fulfill a specific biological niche or role in the ecosystem. For instance, some species serve to control the population of other species through filtration or predation. Others might contribute to the oxygenation of the water column or control and limit the accumulation of nitrogen. When a species is lost or moved to another ecosystem, there is often a disruption and damage to the ecosystem. Any change to an ecosystem can have long lasting and catastrophic results if the community as a whole does not adjust. An introduced species will often not have predators sufficient to controlling its proliferation and will drive out other species. We can see this on land with species such as the mountain goat, red deer and even cats (Invasive, 2012). According to Cranfield and colleagues, "Eighty-seven percent of all documented Non indigenous marine species (NIMS) in New Zealand are likely to have been introduced via biofouling" (ResearchGate, 2016). These invasive species can have terrible costs to the environment. Once they take hold, they are very expensive and difficult to remove. For instance, the Fish and Wildlife Service estimates that if zebra and quagga mussels were to invade the Columbia River, the damage could cost the region's hydroelectric facilities alone up to $250-300 million annually (U.S. Fish & Wildlife Service, 2012).

2.2 Current Antifouling Practices

Since biofouling can increase fuel costs so significantly, several techniques are employed to try to mitigate or control it. There are three main control measures used: antifouling paints, drydocks, and dive crews.

Antifouling paints are by far the most common. Most antifouling paints work by releasing a toxin into the ocean that kills marine species attempting to adhere to the surface of the boat. Some others attempt to prevent the organisms from adhering in the first place. Paints generally come in three categories: ablative paints, vinyl paints and epoxy paints. Ablative paints work by rubbing off (Earth Easy, 2014**)**. Vinyl and epoxy paints create a surface in which toxins are always present on the surface layer (Bay Marine BoatWork.inc, 2014).

Drydocking is the most costly. Drydocking is the process of completely removing a ship from water and performing maintenance or repairs, which is performed twice over a five-year period (Apostolids, 2012). A large ship can cost up to $1-2M, every time it must be drydocked (Apostoilds, 2012). Since drydocking is so expensive, companies are not motivated to do it often.

When a boat is drydocked, crews scrape off old paint and fouling and apply a fresh coating (TeeKay, 2016). Antifouling paints are extremely toxic and must be disposed of as hazardous waste. In fact, these operations are so toxic that every worker painting the boat wears a full body suit for their protection.

The final technique used is dive crews. A team of trained workers dive underwater and attempt to manually remove fouling structures. This is typically used as a stopgap measure to prevent larger fouling structures from forming on the surface of hulls, but is insufficient for long term cleaning. Costs can easily exceed tens of thousands of dollars to deploy dive crews (Simon Doran, Personal Communication, November 7th, 2016).

All these techniques have economic and environmental consequences. The current solutions present an unpleasant choice to the many organizations that deal with biofouling: spend large amounts of money cleaning ships, or damage the environment and reduce fuel efficiency.

2.3 USCG Authority and Motives

The USCG has 11 missions. For this analysis, the most relevant is marine environmental protection. It is their duty to enforce environmental regulations and prevent the spread of invasive species (Go Coast Guard, 2016). Per the National Invasive Species Act of 1996, the USCG operates a ballast water program to minimize the risk of introduction of invasive species (Office of Law Revision Counsel, 2016) The USCG also implements programs to prevent oil and chemical spills, and stop all unauthorized ocean dumping (Go Coast Guard, 2016).

The Environmental Protection Agency (EPA) administers the Vessel General Permit (VGP) which is issued to commercial ships in US waters. As part of VGP 2.2.23, vessel owners are required to remove fouling organisms from the vessel's hull, piping, and tanks regularly and properly dispose of any and all removed substance in accordance with local, state and federal regulations (Copeland, 2013). In addition, all ships equipped with a ballast water tank must clean tanks, anchors and anchor chains, removing organisms and sediments at their places of origin.

Furthermore, the EPA requires vessel owners/operators to minimize the release of copper based antifouling paint into the water during any cleaning of their vessel. Vessels that use copper based antifouling paint are required to refrain from cleaning the hull in copper impaired water within the first 365 days after the initial paint application short of a significant visible indication of hull fouling (American Bureau of Shipping, 2013).

However, our research has shown that VGP 2.2.23 is inconsistently enforced. We were not able to find any data suggesting that any shipowner had ever been cited for failure to comply (Lieutenant Lucas Elder, Personal Communication, November 9th, 2016). This is understandable, given how difficult it would be to catch ships violating the regulation. As 2.2.23

currently reads, there is no performance based standard included. It simply states that "vessel owners/operators must minimize the transport of attached living organisms when they travel into US waters from outside the US economic zone or when traveling between COTP zones" (Environmental Protection Agency, 2013). It's not clear what minimizing would mean, or how that would be evaluated and enforced.

Despite difficulties enforcing some parts of VGP, EPA regulation is very important. However, the most far reaching regulations come from the International Maritime Organization (IMO). The IMO, comprised of different administrations from around the world, creates policy and guidelines globally. Global issues must be solved by global solutions. A single country enacting regulations for their ports may solve part of the problem, but in order to make a tangible change, the regulations must come from the IMO.

2.4 Hull Cleaners Overview

Hull cleaners are autonomous or semi-autonomous underwater robots used to scrub the hulls of ships clean while still in the water. These systems have the potential to reduce fuel use and invasive species introduction. Hull robots may also preserve the life of antifouling paint. Over time these robots could reduce or replace divers for hull cleaning between drydocks.

Hull robots attach to the hull and remove biofouling. Common adhesion techniques include large permanent magnets, negative pressure and water jets. Removal techniques vary. Some robots use brushes, some use water jets, and some use heated water to kill the biofouling without scrubbing. Each robot typically has a diverse platform of sensors that allow it to operate in a marine environment. Some technologies have advanced sensors that give the robot additional capabilities. These features may include hull inspection, fouling detection, obstacle avoidance and autonomy. Robots are used in one of three operation modes- manual, semiautonomous and autonomous. In manual mode, the robot is completely under the control of a human operator – in autonomous, the robot operates with no interaction from humans. Semiautonomous robots automate some of their functions but not all.

3.0 Methodology

This project intended to report on the emerging industry of hull cleaning robots. This data will allow the USCG to be better informed which will help with their mission of reducing the spread of non-indigenous marine species in their exclusive economic zone. In order to obtain effective and usable information for the USCG we defined the following objectives:

1. Identify potential hull cleaning systems and other hull cleaning technologies
2. Determine the criteria for evaluating hull cleaning systems
3. Gather information on both current hull cleaning technologies and ones currently in development

Objective 1: Identify Potential Hull Cleaning Systems

First, we identified current hull cleaner technologies available commercially, and in development around the world. We did thorough online searches for robots, finding as many as we could that were publicly available. After we exhausted searches of traditional Internet searches we scoured the United States Patent and Trademark Office's online database using their advanced search feature. USPTO's advanced search allows the use of logic statements, which we used to find more useful patents. Below is an approximate list of search terms used:

1. (hull AND robot)
2. ((hull AND ((clean OR scrub) OR brush))
3. (((hull AND ((clean OR scrub) OR brush)) AND autonomous))
4. (((hull AND ((clean OR scrub) OR brush)) AND autonomous) AND ((ship OR boat) OR vessel))
5. (((hull AND (((clean OR scrub) OR brush) OR pressure washer)) AND autonomous) AND ((ship OR boat) OR vessel))

Objective 2: Determine Criteria for Evaluating Hull Cleaning Systems

Analyze Current Needs and Requirements of the Shipping Industry

In order to gather effective and relevant data on hull cleaning robots, we had to gather information on the needs of the industry. First we determined how regulations and policies might influence hull cleaner design. Second we investigated the practical considerations of using a hull cleaner. We spoke with maintenance experts and naval architects at the USCG which helped us understand how a large fleet operates and the requirements an organization might have. We attempted to contact the industry, but the shipping companies we contacted either did not see our message or chose not to reply.

To determine how regulations might affect hull robots, we established a list of reliable experts in the Coast Guard who could inform us about the regulations and policies with which ships must comply with in order to lawfully operate in U.S. ports and waters. We conducted in person open ended question interviews in order to attain adequate and reliable information. Specialists often expanded on their answers and often informed us about something that we had not considered.

Determine Current Practices and Regulations in Regard to Biofouling

In order to properly understand the problem with current antifouling methods, we needed to understand the current practices of both the USCG and the ship industry. We began by contacting to naval architects and those who influence policies in the USCG about current practices. Additionally, we spoke with organizations at the USCG who specialize in maintenance and fleet upkeep.

Identify Design Challenges Present in a Hull Cleaning System

We met with USCG experts on frequently to discuss the potential challenges that a hull cleaning system might face. Concerns raised varied from economic considerations, to technical or regulatory ones. Our Coast Guard liaison assisted us in scheduling meetings once or twice per week with appropriate experts. Each person interviewed was asked questions related to their expertise.

Objective 3: Gather Information on Both Current Hull Cleaning Technologies and ones Currently in Development

Since the industry for hull cleaners is so new, information is scarce in regards to their function, cost and operation plan/schedule. We had to attempt to get into direct contact with companies and organizations that were working on hull cleaning technology. We initially uncovered organizations through press releases, pages on their company sites, or patents filed.

Once we made contact with these companies, we either scheduled phone interviews or we began an email correspondence to obtain information about their design. Our questions were based on what we gathered from members of the.

If a company of organization did not get back to us in order to answer our questions directly, we found as much information as possible that was publicly available on the system in order to attempt to report on the technology.

4.0 Results

After conducting interviews with USCG experts, and hull robot developers, we compiled our findings into five sections. The first section lists the companies and organizations that we identified Section 4.2 briefly details hull design. Next, the third section describes regulations that hull cleaners must comply with, either now or in the future. Section 4.4 raises potential design concerns for hull cleaning robots. Finally, the last section enumerates known hull cleaners and their specifications.

4.1 Identified Companies

We identified 16 different hull cleaning robots. Below is a list of every identified company and technology, the organization's origin, and. If we were unable to have a direct correspondence with the company, we still included any information we were able to gather on the robot.

Table 3: Identified Companies

Product Name	Company/Developer	Country of origin	Status of Contact
CleanHull	CleanHull Ltd	Republic of Cyprus	Contacted, no info given
Fleet Cleaner	Fleet Cleaner	The Netherlands	Attempted
GreenSea Robotic Hull Cleaner	Raytheon Company	United States	Successfully contacted
Hull Surface Treament (HST)	Commercial Diving Services Pty Ltd	Australia	Attempted
Hullbot	Hullbot Ltd	Australia	Attempted
HullBug	SeaRobotics Corporation	United States	Successfully contacted
Hulltimo	Hulltimo	France	Attempted
HullWiper	Gulf Agency Company Environhull	United Arab Emirates	Successfully Contacted

KeelCrab Sail One	Aeffe s.r.l.	Italy	Attempted
M6 sub sea Cleaning Tool	VertiDrive	The Netherlands	Attempted
Magnetic Hull Cleaner	Technip Cybernetix	France	Successfully Contacted
Remora	University of Southampton	England	Attempted
ROVINGBAT	ECA Group	France	Attempted
Underwater Hull Cleaning Robot	Samsung Heavy Industries	South Korea	Contacted, no info given
Underwater Robot	Daewon Systems Co Ltd	South Korea	Successfully Contacted
(No Name)	Carnegie Mellon University	United States	Attempted

4.2 Issues Pertaining to a Ship's Design

This section is intended to show the diversity of hull design, size, and niche areas. In order for a hull cleaning robot to be successful it should be designed with these discrepancies in mind.

Hull Design

The design of the target hull is important when considering the performance of a hull cleaning system. Depending on weather and design requirements, vessels can have a single hull (monohulls) or multiple hulls (multihulls). The type of hull can determine the turning radius of the vessel. There are multiple hull types; these include displacement, semi-displacement hulls and planing hull (Khasnabis,2016).

Displacement hulls are shaped roughly like a bathtub. They are lower in the water and much of the volume of the ship is submerged. As the ship speed increases, the same amount of the hull remains in the water. Since the entirety of the vessel stays in the water, as the speed increases, the drag increases linearly with speed. This makes it much more difficult to reach high speeds. However, the design greatly increases the amount of cargo space available, and simplifies the design. Cruise, tanker and cargo ships all share this design (Khasnabis,2016).

Semi-displacement hulls form sharper curves, which causes the buoyant force to lift the front end of the vessel higher as it picks up speed. This improves the speed and reduces the drag on the vessel, but it can be less stable. Semi-displacement hull forms cost valuable cargo space as a result of their shape (Khasnabis,2016).

Planing hulls use beveled curves to push the front end of the vessel entirely out of the water. At lower speed the hulls characteristics resemble displacement hulls which allows them to plow through water. These ships are able to skim along the surface of the water at high speed (Khasnabis,2016).

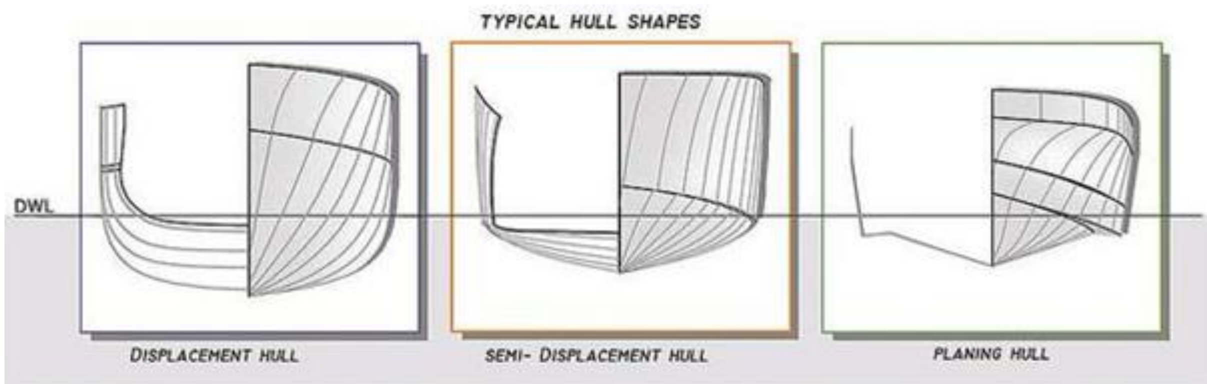

Figure 4: Types of hulls (Boat International, 2015)

Hull Size/Area

Along with the shape, the ship's size is an important factor in determining the performance criteria for a hull cleaner. In order to calculate the average surface area of commercial hulls, we used data in a report from ABS Consulting (ABS Consulting, 2010). The report was intended to estimate the cost of biofouling on a vessel based on its square footage. They determined that the cost to remove one square foot of biofouling was $0.33. In order to extract the surface area of the ship, we divided the data by that factor. What follows is a brief description of each class of commercial vessel. Classification of the vessel is determined by either dead weight tonnage (DWT) or twenty-foot equivalent unit (TEU). DWT is a measure of maximum weight, while a ship's TEU represents the number of 20 foot containers that can be loaded onto it (Dokkum, 2003).

Bulk Carriers are ships specially designed to transport unpackaged bulk cargo such as grain, clay, cement, or sand.

Table 4: Bulk Carrier Hull Size

Type	DWT	Square feet of a hull
Handy	<50,000 DWT	161,593
Panamax	50,000-80,000 DWT	212,936
Capesize	>80,000 DWT	266,884

Tankers are vessels designed to transport liquids or gases in bulk. There are 5 different classifications of tankers.

Table 5: Tanker Hull Size

Classification	DWT	Square feet of a hull
Handy	<35,000 DWT	150,606
Handymax-Aframax	35,000-120,000 DWT	276,976
Suezmax	120,000-160,000 DWT	294,176
VLCC	160,000-320,000 DWT	259,558
ULCC	>320,000 DWT	241,333

Container ships are designed to transport cargo inside of standardized containers. There are five different classifications of container ships

Table 6: Container Ship Hull Size

Type	TEU	Square feet of a hull
Feeder	<500 TEU	223,860
Feedermax	500-1000 TEU	225,267
Handy	1000-2000 TEU	128,909
Subpanamax	2000-3000 TEU	275,127
Panamax	>3000 TEU	300,048

Niche Areas

With size and shape established, we now turn to specific installations on a hull that a robot would have to be able to navigate. Installations include but are not limited to bulbous bows, thrusters, stern tubes, seawater inlet chests, stabilizers and keels (Dokkum, 2003). These are collectively referred to as "niche areas".

Bulbous bow: a sphere-like bulb at the bow of the ship that lies just under the water line. The bulbous bow disrupts the wave at the front of the vessel by creating a second flow of water that will cancel out the first and allow the boat the move with less resistance (Chakraborty, 2016).

Thruster: an additional propulsion device that can be built into the hull during construction, or installed later. A thruster can increase the vessel's speed or allow the vessel to change direction faster. The different types include bow thruster, azimuth thruster, and transverse thruster (Dokkum, 2003).

Stern tube: a long shaft that connects the vessel's engine and the propeller. This is also known as the propeller shaft (Dokkum, 2003).

Seawater inlet chests: a rectangular or cylindrical recess in the hull of a ship. This creates a reservoir that a ship can draw raw water for cooling shipboard operations (Bullions, 2016).

Ship stabilizer: (retractable, un-retractable) a fixed fin stabilizer (foreground centre) and bilge keels (left background). Stabilizers have similar functions of wing flaps on airplane. They are positioned on the sides of vessels underwater and prevent the ship from rolling. Stabilizers add resistance at the cost of a smoother ride (Grant, 2014).

Vessel keel: a blade extruding into the water from the bottom of the vessel. It has two main functions: holding the ballast, allowing the boat to stay right side up, and to prevent it from being blown over by the wind (Dokkum, 2003).

All of these factors must be taken into account when a hull cleaning robot is being developed, as well as when a hull cleaning robot is being chosen. It is possible that not all hull robots will work with all ships, so ship owners must choose the proper system for their own vessel.

4.3 Regulations Affecting Hull Cleaners

While regulations do not exist that are written with automated hull cleaning systems in mind, there are IMO and US hull cleaning regulations in regards to in water hull cleaning. Other countries have passed laws that regulate the maximum amount of biofouling on vessels entering their ports.

New Zealand will be adopting regulations in May of 2018 that seek to regulate biofouling entering their ports and waters (Ministry for Primary Industries, 2016). This regulation puts all ships entering its waters into two categories, long-stay vessels, and short-stay vessels.

Long-stay vessels are any vessels that plan on spending 21 days or more in New Zealand. Vessels are automatically long stay if they plan on visiting any place other than those that have been designated as 'Places of First Arrival'. These areas were determined by the New Zealand Biosecurity Act as areas that are able to accept vessels into New Zealand. Short-stay vessels are vessels that plan on spending 20 days or less in New Zealand, and plan on only visiting areas designated as Places of First Arrival (Ministry for Primary Industries, 2016).

Long-stay vessels have to meet very simple but rigorous standards for the amount of biofouling they can have. All long-stay vessels are allowed to have no more than a layer of slime and goose barnacles present on their entire hull surface (Ministry for Primary Industries, 2016). Unlike short-stay vessels which have different rules for different parts of their hulls, long-stay vessels must follow this standard for all parts of their hull.

Short-stay vessels have three different sets of standards and regulations they must meet for three different sections of their hull. There are regulations specifically for the wind and water line of the hull, the main hull area, and niche areas of the hull as well. These zones each are unique in what is and is not allowed to occur in them.

For the wind and water line, the short-stay vessels are allowed to have green algae growth, as long as it is no more than 50mm in frond, filament, or beard length (Ministry for Primary Industries, 2016). Brown and red algae are also allowed as long as it is not more than 4mm in length (Ministry for Primary Industries, 2016). The wind and water line can also have incidental coverage of one organism type, which may include tapeworms, bryozoans, or barnacles. This incidental coverage cannot cover more than 1% of the total area, can only be isolated individuals or small clusters, and can only be made up of a single species or what appears to be a single species.

The main hull area of short-stay vessels cannot have algae growth of more than 4mm in length. Additionally, they cannot have continuous strips and or patches of more than 50mm in width (Ministry for Primary Industries, 2016). Like the wind and water line, they are permitted incidental coverage.

Niche areas such as sea chests and propeller cavities on short-stay vessels have algae growth of more than 4mm in length. Continuous strips or patches of algae can exceed no more than 50mm in width. Unlike the other parts of the ship, they are permitted to have scattered coverage of one organism type. These can be either tubeworms, bryozoans or barnacles. This incidental coverage can account for a maximum of 5% of surface area. Organisms may be widely spaced infrequent patchy clusters. Organisms are not permitted algae overgrowth and must appear to be a single species. Niche areas are also allowed to have incidental coverage, in the same way that the main hull area and wind and water line can have. (Ministry for Primary Industries, 2016)

The process of using a hull cleaner will have to follow similar best management practices (BMPs) as dive crews when cleaning a ship while in the water. The IMO's BMP calls for the use of cleaning techniques to minimize the release of biocides for hulls coated in anti fouling paint. They also require in their BMP to minimize the release of viable macrofouling organisms into the water, meaning that any macrofouling scraped off the side of the ship must not have a chance of surviving in the water where it is removed. For regulations set forward by the EPA in their Vessel General Permit (VGP), it's the content is similar. However, they additionally stipulate that when cleaning the process cannot produce a visible plume of paint or biological material. The State of California has their own regulation, which prohibits all underwater hull cleaning unless conducted using the best available technologies that are economically feasible. Using biocide free anti fouling paints is allowed. However, copper based anti fouling paints are banned in impaired waters. The State of Massachusetts does not allow discharges from underwater cleanings within three nautical miles of the shore (EPA, 2011).

4.4 Potential Concerns Regarding Hull Cleaners

Robotic hull cleaners face a variety of challenges in both their design and implementation. These issues include the use of magnets to attach to the side of hulls, as well as the disposal of biofouling that is removed from the hull. The robot must also be economically feasible and more effective than existing antifouling techniques.

The Use of Magnets

One potential risk for hull cleaners is the use of magnets as a means for adhesion. Concerns were raised that powerful magnets on the hull of a ship could disrupt and damage instruments aboard the ship. Furthermore, the electromagnetic signature ships use to identify themselves in ports could be disrupted by a very powerful magnet. However, there appears to be a great deal of controversy on the exact effect magnets would have, if any. Until there is more testing, these concerns cannot be verified. While military vessels are of particular concern, a company sold magnetic robots to the French navy. It is unclear what the outcomes of those robots were. Some hull cleaners have eliminated this risk by instead using negative pressure to attach to the ship.

Contamination of Waters

Another concern is the contamination of biofouling that is being scrubbed into the water. If a hull cleaner operates when the ship is docked in port and has no system for filtering the biofouling, the hull cleaner might inadvertently facilitate the spread of invasive species and chemical pollutants found in hull coatings. Federal and state regulations prohibit the discharge of debris resulting from hull cleaning in state waters. However, outside the exclusive economic zone (EEZ) of the United States the discharge of hull cleaning debris is not prohibited. Unfortunately for shipping companies, the EEZ reaches 200 nautical miles from shore. This makes deploying cleaners, robotic or otherwise, expensive and difficult.

Economic Feasibility

One major concern for the hull cleaning system is that the cost of developing and deploying the technology will be greater than the savings generated. Divers may remain the only effective way to completely clean the hull. Ship companies are most concerned with cutting costs. The robots need to be able to clean with coverage and completion that parallels that of divers. Cost benefit is likely to remain a concern for the foreseeable future as the efficacy of these robots has yet to be determined.

4.5 Developed Criteria

Based on the information gathered in the previous section we determined that the following criteria are the most important in researching hull cleaners.

Table 7: Identified Criteria

Criteria	Reason for criteria being important
Company	Understanding what the company is and what they do is crucial. Their motivations will vary depending on the industries they typically engage in.
Country of origin	It is important to know where the technology is being developed. Understanding where these companies are headquartered is vital because each company may be targeting different regulatory requirements. Furthermore, we want to determine if the majority of companies are from specific regions. It's also helpful to understand the diversity of the available technologies.
Weight of the robot	The weight of the robot may indicate the payload it is able to accommodate. It also can reflect on the size of the ship it intends to target, although it is not a direct connection.
Size of the robot	The size of a hull cleaner largely dictates the spaces it will be able to access. It also gives an idea of the amount of fouling it will be able to process, much like weight.
Adhesion Technique	Different hulls will require different adhesion techniques (Roger Butturini, Personal Communication, December 9th, 2016). Some adhesion techniques may also be susceptible to falling off of the side of a ship if there are extrusions or inlets in the hull.
Adhesion force	The robot must be able to remain attached until it's desired otherwise. Currents and waves must not be able to dislodge the robot during operation.
Cleaning speed	The cleaning speed of the robot is vital, as some of them clean very slowly. Gargantuan ships will need large robots to be able to clean in a short period of time.

Type of cleaning apparatus	The type of cleaning apparatus will determine the functionality of the robot. Using water pressure will pose different challenges than using brushes.
Sensors included on platform	In order to properly understand the full capabilities of the robot, it is important to know the full suite of sensors that the platform has installed.
Is the robot able to function while ship is underway?	This is an important question to ask of every hull cleaner. Ships are in the business of quick turnaround times, having to pause at frequent intervals would cut into profits for the ship companies.
Does the robot use a filter?	Due to current regulations on in water cleaning of ships it is important that hull cleaners do not cause unnecessary discharge of either antifouling paint, or marine life.
Mean time to failure	It is important to know how long a specific hull cleaner is expected to last before it is necessary to replace the system, or perform large scale maintenance/repairs.
Operational style (Autonomous, semi autonomous, manual control)	The operation style of a hull cleaning robot dictates the management of the robot in terms of its daily life on a ship. If a robot is autonomous, daily operation remains unaffected. If the robot requires manual operation, it is important to understand who will operate it and how.
Is a tether needed?	A tether could helps with ensuring the robot will not become lost while in use.
Cost	As with any technology, cost affects its ability to perform. A high cost device must be able to produce excellent results.

4.6 Robotic Hull Cleaner Data

The following section contains the information that was gathered on the robotic hull cleaners that were identified. There is a matrix which displays identified technologies. Additionally, the matrix reports their current state of development and our level of contact with them. Next, there is a matrix containing quick details about each hull cleaner identified. Finally, there's an individual page created for each hull cleaner which shows specific details about each technology.

Overview of technology

The following table is a list of each technology identified along with an overview of details about each technology. The robot's operating type is split into three categories. Semiautonomous means that the robot handles some of its operations without user intervention, but not all. Autonomous operation means that the technology requires no interaction from the user to operate. Manual operation means that every command the robot executes is directly inputted by a user. A profile of the robot's features is also provided. The robot's capacity to filter biofouling, its method of remaining attached to the hull, and cleaning system are reported.

Table 8: Overview of Hull Cleaners

Product Name	Company/Developer	Operating Type	Filter	Holding System	Cleaning System
CleanHull	CleanHull Ltd	Semiautonomous	Yes	Turbines	High pressure water
Fleet Cleaner	Fleet Cleaner	Manual	Yes	Magnets	High powered water jets
GreenSea Robotic Hull Cleaner	Raytheon Company	Autonomous	Yes	Neodymium magnet track system	Brushes using ultrasonic action
Hull Surface Treatment	Commercial Diving Services Pty Ltd	Manual	Not needed	Magnets	Thermal Shock

Hullbot	Hullbot Ltd	Manual	No	3 thrusters	Cleaning rotating disks
HullBUG	SeaRobotics Corporation	Autonomous and Semiautonomous	Yes	Magnetic, or negative pressure	Brushes, and jet based operatic modeler
Hulltimo	Hulltimo	Manual	Yes	Suction system	Brushes, roller of polyamide
HullWiper	Gulf Agency Company EnvironHull	Manual	Yes	Negative pressure system	cleaning discs that pump saltwater
KeelCrab Sail One	Aeffe s.r.l	Manual	Yes	Turbine	Turbine vacuum, rubber and nylon brushes
M6 sub sea Cleaning Tool	VertiDrive	Manual	Unknown	Magnets	High pressure water nozzles
Magnetic Hull Cleaner	Technip Cybernetix	Manual	No	Magnets	Pressure washer
Remora	University of Southampton	Autonomous	Unknown	Magnets	Unknown
RovingBAT	ECA Group	Semiautonomous	Unknown	Thrusters, motorized tracks	Uses either hydro-jetting or a brushing system
Underwater Hull Cleaning Robot	Samsung Heavy Industries	Proprietary	Yes	Proprietary	Proprietary
Underwater Robot	Daewon Systems Co Ltd	Autonomous	Unknown	Propeller	Unknown
(No Name)	Carnegie Mellon University	Unknown	Unknown	Unknown	Unknown

4.7 Hull Cleaner Profiles

Each of the following pages provides a more detailed profile of each individual hull cleaner. It contains data on each criterion, as well as a short description of each robot. Even with data on every criterion, each hull cleaner is unique in its own way. Some data was unavailable, either because the company refused to contact us. References are available in Appendix D.

GreenSea Robotic Hull Cleaner

Raytheon Company - Waltham, Massachusetts, United States

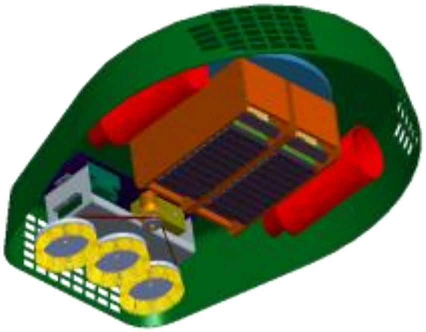

Figure 5: GreenSea Robotic Hull Cleaner

The development for Raytheon's hull cleaning robot is no longer active. GreenSea was designed to be able to be used while a ship is underway. By using extremely powerful neodymium magnets, it is able to remain attached to the hull of a ship at speeds up to 26 knots. In an effort to simplify use, the robot charges its battery using turbines attached to the robot. Apart from periodic maintenance, the robot is completely autonomous and can react to dangerous conditions.

Status	Terminated
Contact	Successful
Cost	$400,000
Grooming Speed	1,500 m^2/ h
Grooming System	Brushes using ultrasonic action
Usable While Underway	Yes
Dimensions	6 x 36 x 24 in
Weight	225lbs
Max Depth	1500
Mean Time to Failure	5 year
Holding System	Neodymium magnet track system
Holding Force	Holding pressure/force totaling up to 2,250 lbs
Sensors Included	Multi-axis inertial sensor, angular sensor locator
Filter	Yes
Tethered	No
Operation Type	Autonomous

HullBUG

SeaRobotics Corporation - Stuart, Florida, United States

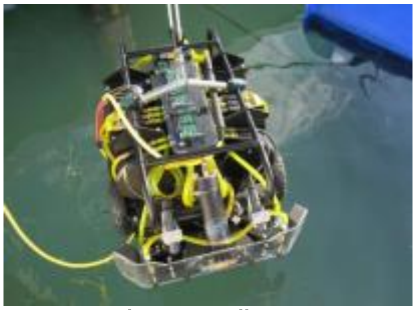

Figure 6: HullBUG

The Hull Bio-Inspired Underwater Grooming System (HullBUG) is a hull cleaner being developed by SeaRobotics and the Office of Naval Research. HullBUG is a platform that supports a diverse set of modules. It's highly adaptable and is not limited to hull cleaning. Hull integrity inspection and marine research are obvious alternate missions, though more exist.

Status	Development and testing
Contact	Successful
Cost	Base price $160,000 – options available
Grooming Speed	400-600 m^2/h
Grooming System	Soft/hard brushes and dual dome jet based operatic modeler
Usable While Underway	No
Dimensions	75 x 150 cm
Weight	55kg
Max Depth	Unknown
Mean Time to Failure	5 years
Holding System	Magnetic system or negative pressure for naval ships
Holding Force	130 lb
Sensors Included	Biofilm detector, Compass, Attitude, Video With LED, Illumination, High Frequency Sonar, Fiber Optic Gyro, Imaging/Profiling, Hull Plate, Thickness Sensing, Encoders, Health Sensors, and Additional Sensors Possible
Filter	Yes
Tethered	No
Operation Type	Autonomous and semiautonomous

HullWiper

Gulf Agency Company EnvironHull -
Dubai, United Arab Emirates

Figure 7: HullWiper

HullWiper is a hull cleaner designed by Gulf Agency Company EnvironHull. Currently 15 units have been produced, and are in use in 12 ports across the world. A support platform is required for the HullWiper. The support platform provides power and water pressure, which is used to clean the surface of the hull. The filter is able to handle 50 cubic meters of fouling per hour.

Status	In use
Contact	Successful
Cost	$1,000,000
Grooming Speed	2000 m^2/h
Grooming System	3 cleaning discs that pump saltwater
Usable While Underway	No
Dimensions	330 x 170 x 85 cm
Weight	1200 kg
Max Depth	100 m
Mean Time to Failure	Unknown
Holding System	Negative Pressure system
Holding Force	Unknown
Sensors Included	Camera, Depth sensor, oil pressure sensor, level oil sensor, and water pressure sensor
Filter	Yes
Tethered	Yes
Operation Type	Manual

Magnetic Hull Crawler

Technip Cybernetix - Marseille, France

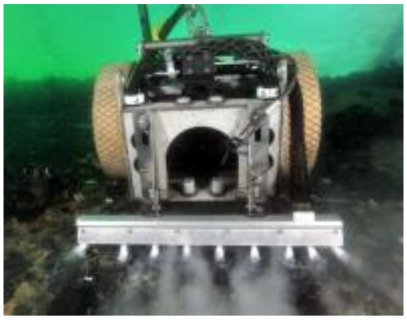

Figure 8: Magnetic Hull Crawler

Magnetic Hull Crawler or MHC was designed with the commercial shipping industry in mind, as well as the offshore oil and gas industries. The system has been in use since 2005, and was originally designed for the purpose of hull inspection. In addition to hull cleaning, MHC can provide detailed models of hulls, pipelines and rigs. This allows users to detect issues The cleaning system is able to reach up to 1000 bar.

Status	In use
Contact	Complete
Cost	Highly variable
Grooming Speed	100-200 m^2/h
Grooming System	Pressure washer
Usable While Underway	Up to 2-3 knots
Dimensions	600 x 500 x 500 mm
Weight	65 kg without payload. 100 kg with payload
Max Depth	50m depth rating
Mean Time to Failure	Replace nozzles every 24-48 hours’ worth of use
Holding System	Magnets on undercarriage
Holding Force	300-400 kg
Sensors Included	Cameras, Analog UT probes, CP reading tool, IMU & Depth sensor.
Filter	No
Tethered	Yes
Operation Type	Manual

Underwater Robot

Daewon Systems Co Ltd - Shiheung South Korea

Figure 9: Underwater Robot

The goal of the project was to develop a cleaning platform capable of real time underwater location tracking. It is government funded, and still in development.

Status	Development
Contact	Successful
Cost	$400,000
Grooming Speed	200 m^2 /h when cleaning barnacles, 630m^2/h when cleaning moss
Grooming System	Brushes
Usable While Underway	No
Dimensions	170 x 100 x 68 cm
Weight	315 kg
Max Depth	Unknown
Mean Time to Failure	1000 hours
Holding System	Thrusters
Holding Force	Unknown
Sensors Included	PRS-8080 camera, depth sensor, USBL, DVL, IMU, and DGPS
Filter	Unknown
Tethered	Unknown
Operation Type	Autonomous

CleanHull

Cleanhull Ltd – Limassol, Cyprus

Figure 10: CleanHull

CleanHull is designed for use on larger ships. CleanHull currently is in ports such as Mongstad, Karsroe, Goteborg as well as others.

Status	In use
Contact	Successful, no information given
Cost	Proprietary
Grooming Speed	800-1000 m^2/h
Grooming System	High pressure water
Usable While Underway	Able to operate in difficult conditions
Dimensions	Proprietary
Weight	Proprietary
Max Depth	Proprietary
Mean Time to Failure	Proprietary
Holding System	Turbines
Holding Force	Proprietary
Sensors Included	Cameras
Filter	Yes
Tethered	Yes
Operation Type	Semiautonomous

Fleet Cleaner

Fleet Cleaner - Leeuwarden, The Netherlands

Figure 11: Fleet Cleaner

The Fleet Cleaner hull cleaning robot was developed for vessels in the shipping industry. It uses high powered water jets to remove and capture fouling.

Status	Testing
Contact	Attempted
Cost	Unknown
Grooming Speed	1,200 m^2/h
Grooming System	High powered water jets
Usable While Underway	No
Dimensions	1.8 x 1.8 x 0.6 m
Weight	Unknown
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	Magnetic
Holding Force	Unknown
Sensors Included	Unknown
Filter	Yes
Tethered	Yes
Operation Type	Manual

Hull Surface Treatment

Commercial Diving Services Pty LTD - Australia

Figure 12: Hull Surface Treatment

Hull Surface Treatment (HST) uses thermal shock instead of brushes or water jets. This cleaning system heats seawater to roughly 70^{o}C and kills fouling using heated water. There is no need for a filter. When the ship reaches open waters, the dead fouling is washed away by the waves. The compact design of the HST allows it to be used on any surface, including sea chests and propellers. HST is unique because it claims to be able to cover 100% of the target hull. However, it is unable to clean any kind of hard fouling.

Status	In use
Contact	Attempted
Cost	Roughly 15% of fuel savings
Grooming Speed	Unknown
Grooming System	Thermal Shock
Usable While Underway	No
Dimensions	Unknown
Weight	Unknown
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	Magnets
Holding Force	Unknown
Sensors Included	Unknown
Filter	Not needed
Tethered	Yes
Operation Type	Manual

Hullbot

Hullbot Pty LTD - Rotterdam, Netherlands / Sydney, Australia

Figure 13: Hullbot

Hullbot is a hull cleaning robot primarily designed for use on yachts. It uses disk shaped rotating cleaning pads to clean vessels while at anchor. The Hullbot is designed to do a cleaning once every four hours. It uses a pre-loaded model of the yacht in order to determine its orientation as well as the percentage of surface area cleaned.

Status	Development and testing
Contact	Attempted
Cost	Unknown
Grooming Speed	Unknown
Grooming System	Cleaning rotating disks
Usable While Underway	No
Dimensions	Unknown
Weight	Unknown
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	3 thrusters
Holding Force	Unknown
Sensors Included	Unknown
Filter	No
Tethered	Yes
Operation Type	Currently manual with controller, developing autonomous control system

Hulltimo

Hulltimo - France

Figure 14: Hulltimo

Hulltimo is designed primarily for sailboats and motorboats. It comes equipped with a camera and remote control with a display. The robot must be controlled by a trained operator, and is able to clean a 34-foot boat in approximately an hour. The suction system installed on the robot allows it to move along sharp angles on the hull surface.

Status	Suspected to be no longer in business- website is down
Contact	Attempted
Cost	$3,105
Grooming Speed	Unknown
Grooming System	2 brushes, one roller made of polyamide
Usable While Underway	No
Dimensions	51 x 67 x 37 cm
Weight	Unknown
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	Suction system
Holding Force	Unknown
Sensors Included	Camera
Filter	Debris collecting filter
Tethered	Yes
Operation Type	Manual

KeelCrab Sail One

Aeffe s.r.l. - Bulgarograsso, Italy

Figure 15: KeelCrab Sail One

The KeelCrab Sail One was designed to clean sail boats, yachts, and maxi yachts. The robot is designed to not only clean hulls, but to also perform hull inspections.

Status	In use
Contact	Attempted
Cost	€ 3,299
Grooming Speed	1.5 m^2/min
Grooming System	Turbine vacuum, rubber, and nylon brushes
Usable While Underway	No
Dimensions	42.5 x 42.5 x 32 cm
Weight	9.5 kg
Max Depth	Unknown
Mean Time to Failure	Guarantee 24 months or 500 hours of use
Holding System	Vacuum force driven by turbine
Holding Force	Unknown
Sensors Included	High-resolution underwater camera IP68
Filter	Yes
Tethered	Yes
Operation Type	Manual

M6 Sub sea Cleaning Tool

Vertidrive - Ridderkerk, The Netherlands

Figure 16: M6 Sub sea Cleaning Tool

The M6 Subsea Cleaning Tool is a manually operated device primarily made for use on floating productions, storage and offloading units (FPSO), or off shore working platforms. The M6 is built with a swing boom with a 2-meter reach. Water is pumped through the boom to remove fouling in a wide radius around the robot.

Status	In use
Contact	Attempted
Cost	Unknown
Grooming Speed	Unknown
Grooming System	High pressure water nozzles
Usable While Underway	Unknown
Dimensions	750 x 750 x 350 mm
Weight	85 kg
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	Magnets
Holding Force	Unknown
Sensors Included	Unknown
Filter	Unknown
Tethered	Yes
Operation Type	Manual

Remora

University of Southampton - Southampton, England

Figure 17: Remora

Remora is a robot in development by students at the University of Southampton. The goal of this project is to design an autonomous robot, with the ability to function and clean a ship's hull while a ship is in motion. Remora uses a hydrodynamic shell that allows the robot to function at up to 8 knots. With upgrades and further testing the students believe the system will be able to handle 15 knots.

Status	Development
Contact	Attempted
Cost	Unknown
Grooming Speed	Unknown
Grooming System	Unknown
Usable While Underway	Up to 8 knots
Dimensions	Unknown
Weight	Unknown
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	Magnets
Holding Force	639 kg
Sensors Included	Ultrasonic Sensors
Filter	Unknown
Tethered	Unknown
Operation Type	Autonomous

ROVING BAT

ECA Group - La Garde, France

Figure 18: ROVING BAT

The ROVING BAT by ECA group is a hull cleaning robot built for FPSO and oil rigs. ROVING BAT can autonomously connect to the hull of the ship using four propellers. ROVING BAT is also able to perform a hull inspection while it is removing biofouling.

Status	In use
Contact	Attempted
Cost	Unknown
Grooming Speed	Unknown
Grooming System	Uses either hydro-jetting or a brushing system
Usable While Underway	Unknown
Dimensions	41” x 41” x 17”
Weight	265lb
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	6 thrusters, 2 sets of motorized tracks
Holding Force	Unknown
Sensors Included	Sensors for accelerometer, temperature, water ingress, amperage, positioning
Filter	Unknown
Tethered	Yes
Operation Type	Semiautonomous

Underwater Hull Cleaning Robot

Samsung Heavy Industries – Seoul, South Korea

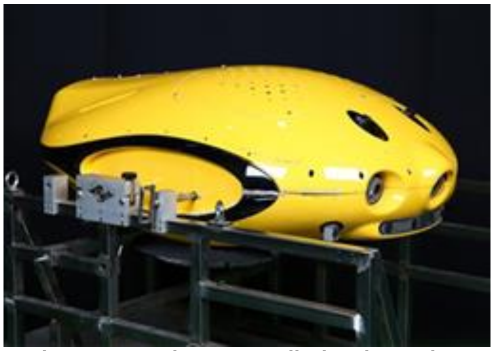

Figure 19: Underwater Hull Cleaning Robot

Samsung Heavy Industries' (SHI) hull cleaning robot is designed to clean SHI's LNG carriers during and immediately after production. While we were able to make contact with Samsung, they chose not to release any information on their hull cleaner.

Status	Unknown
Contact	Successful, no information given
Cost	Proprietary
Grooming Speed	Proprietary
Grooming System	Proprietary
Usable While Underway	Proprietary
Dimensions	Proprietary
Weight	Proprietary
Max Depth	Proprietary
Mean Time to Failure	Proprietary
Holding System	Proprietary
Holding Force	Proprietary
Sensors Included	Proprietary
Filter	Yes
Tethered	Proprietary
Operation Type	Proprietary

(No Name)

Carnegie Mellon University – Pittsburgh, Pennsylvania, United States

Figure 20: Carnegie Mellon Seal

The robot was developed by students at Carnegie Mellon University during an internship at Tsuneishi Shipbuilding Company’s headquarters in Fukuyama Japan. Little is known about this robot, and little was found on the project. All that is known is that they were given three tasks: To develop a retrofit sensor network, to develop a welding robot, and to develop a ship hull cleaning robot.

Status	Unknown
Contact	Attempted
Cost	Unknown
Grooming Speed	Unknown
Grooming System	Unknown
Usable While Underway	Unknown
Dimensions	Unknown
Weight	Unknown
Max Depth	Unknown
Mean Time to Failure	Unknown
Holding System	Unknown
Holding Force	Unknown
Sensors Included	Unknown
Filter	Unknown
Tethered	Unknown
Operation Type	Unknown

5.0 Observations

Our observations generally fit into three categories: economic, technical, and regulatory. Economic pressures and the development of robot technologies have allowed hull cleaning robots to quickly emerge as a new industry. The robots possess a diverse and powerful set of technical capabilities that need to be taken into account when looking at solutions to biofouling. Finally, the influence that state, federal and international regulations might have on hull cleaning robot design could shape the industry. Our observations are as follows.

5.1 Economic

The industry is extremely diverse and international. Of the 16 robots we identified, 13 were developed outside of the U.S. It is interesting to note that many technologies are based in the Netherlands. This is true of underwater robots in general because of The Netherlands' diverse and organized robotic sector. Companies ranged in size from less than 10 people to 325,000+ at Samsung. Some of the technology is proprietary, but for many others, information on the hull cleaning robots is readily available.

The industry is still in its infancy. Only 6 of 16 robots are in use today, while 5 are currently in development and testing. For the remaining 5, their programs are proprietary, terminated, defunct, or are research projects through universities. We can see obvious growth in these new technologies, and we expect more to appear in the coming years.

Companies developing this technology all point to fuel savings as the primary benefit. In general, the robots appear to be able to generate cost savings, though without evaluation from an independent organization, the veracity of such claims are impossible to determine. Some manufacturers believe the most appealing price structure for both shipping companies and hull robot providers would be in which shipping companies would be charged a percentage of the fuel savings generated. The sharing of fuel savings encourages ship owners to integrate the product and eliminates large upfront costs. The manufacturer is incentivized to design a system that saves fuel in order to generate a consistent revenue stream.

While environmental benefits are noted in many of the promotional materials, it appears not to be the primary concern. Companies are attempting to reduce their emissions. Their greenhouse gas emissions are already regulated, whereas biofouling is not. Furthermore, shipping companies are not interested in investing in technology that doesn't provide clear value to their bottom line.

We believe the market was in part generated by unrelated regulations. In the last 20-30 years, antifouling paint regulation has tightened significantly because of its toxic properties. Lead was phased out in favor of copper, which is now being phased out in favor of more environmentally friendly, but less effective antifouling paint. Biofouling growth on hulls was much less of an issue when lead and copper paints were being used. Without toxic ingredients, newer paints are less effective at controlling biofouling. Furthermore, the IMO ECA sulfur regulations have resulted in increased fuel prices, which make it harder for shipping companies to continue to generate a profit (Morley, 2016). ECA compliant fuel is sold at a 92% premium over older, more sulfur rich fuels (Bloomberg, 2015). As a result, shipowners are looking into new and innovative ways to save fuel, which has created a market for hull cleaning robots.

Overall, the economic picture of hull cleaning robots is diverse and driven by a number of factors. This industry is relatively new and still needs a lot of time to mature, but we believe the industry is growing because many of the hull cleaners began development after 2010. We believe that if margins narrow in the shipping industry (Morley, 2016), hull cleaning robots and other alternative fuel saving technologies will grow considerably.

5.2 Technical

From a technical perspective, the industry is also extremely diverse. The technologies are difficult to group into categories, because each has several unique features that set them apart from the rest. Every company had different goals in mind when designing their robot and, consequently, different approaches to the problem. In terms of the effectiveness of the technologies, we continue to see a lack of conclusive testing. Many of these technologies have only been tested in a controlled environment, and many of the designs present potential concerns in a practical environment despite being able to perform in laboratory conditions.

Many robots appear to only clean the two dimensional surfaces of the hulls. That is to say, they clean the sides of the hull rather than niche spaces like sea chests or propellers. The hull is where the majority of the drag is generated and therefore, would result in the most fuel savings if cleaned. However, the other areas still need to be cleaned to reduce the risk of invasive species introduction, and it's unclear whether or not a hull robot that doesn't reach niche areas will be able to replace a dive crew.

According to the manufacturers, cleaning in niche spaces is an extremely difficult design problem. When asked, one company suggested that it was impossible to reach niche spaces. However, there is one Australian company that claims to be able to clean in niche spaces, so it may be surmountable. Because of the economic concerns discussed earlier, many designs seem to avoid cleaning niche spaces in favor of faster cleaning. This is particularly true if a large ship is in port and only has a few hours to perform the cleaning.

Only a handful of these technologies can operate while the ship is underway, and only one claims to be able to do so at speeds of over 20 knots. When the ship is travelling at speed, the forces on anything attempting to cling to the hull become enormous. Many companies have understandably determined that use while underway is impractical. This means that the majority of these robots operate in port. In order to operate in port, however, the robots need to have a filtration system to collect the fouling as it's removed from the vessel.

Robots use two main adhesion systems. Most use magnets to adhere to the hull. During our project we have received very mixed opinions on magnets. Some Coast Guard officers note that shipboard systems and degaussing operations might be affected by the use of large magnets, while other officers don't believe there to be a problem at all. In one instance, a company using magnets has sold robots to a contractor working with the French navy, though it's unclear if magnets presented a problem during use. Additional testing is required to conclusively determine if magnets pose a hazard.

The second adhesion system is negative pressure. By creating a pressure differential between the outside water and the robot, it can hold itself onto the hull. This presents its own concerns – if the robot accidentally navigates over a sea chest, will pressure be lost? One company working with the Office of Naval Research provides a choice between the two systems, so there are clearly considerations for both.

Many companies claim that their cleaning system doesn't cause damage to antifouling paint. While we do believe this is true, it's impossible to determine without comprehensive independent testing. The paint is designed to come off, and some of the technologies use an incredible amount of force to remove fouling.

A great deal of evaluation and testing needs to be performed. There is very little independent testing being done on these technologies. Regulators or ship owners have no independent data determining the veracity of the robot manufacturers' claims. As the industry continues to grow, the effectiveness of the technologies will need to be studied and determined.

5.3 Regulatory

Regulations have influenced the development of hull cleaning robots through sulfur limitations, hull coating restrictions, and now, invasive species control. State, federal and international regulators could positively or negatively affect the hull cleaning industry. If more biofouling regulations are implemented and enforced, hull robots will become increasingly relevant.

When fouling regulations tighten in areas such as New Zealand, we believe there is potential for a new market. Robots can already provide detailed inspections of hulls, but tools for regulators and inspectors to evaluate biofouling on a ship will become essential. Without these tools, how will biofouling be judged? The New Zealand requirement is clear, but exactly how individual ships will be inspected is still to be determined. A hull robot may be a cost effective and efficient tool for evaluating ship fouling.

It is currently unclear if hull robots will be able to comply with the New Zealand regulations. For that matter, it is unclear if any existing antifouling technique will be able to comply with the standard. Many robots do not appear to be capable of achieving 100% hull coverage.

We believe that hull cleaning robots can extend the life of antifouling paint by keeping fouling off of the hull. However, existing paint certifications do not account the new technology, and require repainting on a rolling schedule regardless of the paint's condition. If hull cleaning robot users had their antifouling paint certifications extended, they may be more likely to have a role in the life cycle of a ship. Currently, since there are limited biofouling regulations, and no regulations related to hull cleaning robots, biofouling removal is not integrated into the day to day operations of a shipping company.

The EPA prohibits hull cleaning that produces a visible plume when within the EEZ of the United States. However, many robots have a filtration system available that prevents effluent and biofouling from being released. The performance of the filters should be evaluated to understand their limits and how best to utilize them. It is unclear if filters would be able to comply with EPA regulations.

Based on our analysis, we believe that if type approval of hull cleaners were implemented, it is likely to negatively impact the industry. Type approval is the process of officially confirming that a product meets certain performance standards. There are many small robot manufacturers, which are unlikely to be able to afford the testing required to achieve type approval. Furthermore, the design types vary wildly, as each are using different approaches. This wide variance will make it extremely difficult to establish a definitive standard, even if performance based. If such a standard were to be implemented, creative and innovative solutions may suffer as companies compete to meet the standard.

Our data suggests that regulators have a lot to examine when discussing choices to make regarding hull cleaning robots. A full evaluation of the impacts on each stakeholder needs to be performed before any action is taken. Hull robots are a new and emerging industry, so when regulating fouling, fuel consumption, and cleaning in port, the impact on hull robots should be considered.

6.0 Conclusion

Our project examines current motivations and capabilities of hull cleaning robots. Shipping companies are concerned with their continually shrinking bottom line. Robot manufacturers are attempting to develop technologies that function in a variety of circumstances and environments, primarily to save their customers fuel costs. Regulators face a difficult task in defining how to regulate this new and diverse industry. There are only two regulations on the subject and only one seeks to create a quantifiable limit to biofouling.

We have prepared several supplementary deliverables that accompany our report. First, we developed a binder that details all of the hull cleaning robots we were able to identify. This is seen in the report as section “4.5 In Depth Hull Cleaner Pages”. We created a poster that was presented at WPI DC alumni event, hosted by Congressman James McGovern’s office. It has since been delivered to the Coast Guard. Finally, we assembled a presentation detailing our findings which was presented to Rear Admiral Paul Thomas, among others.

The project encountered several obstacles. First, we had difficulty understanding the concerns of the Coast Guard and their interest in these technologies. Initially the project was a mile wide and an inch deep; we were stretching ourselves far too thin. After arriving at the Coast Guard we were able to clearly define the scope much more easily with the help of our liaison. We were surprised by how deep such a narrow topic turned out to be.

Next, we had to learn to understand the perspective of the regulator. Bias to one technology over another can cause severe issues. Not only does the report suffer, but it can open the USCG to liability.

Finally, we had difficulty gathering information from many companies. The industry is new and many of them understandably intend to keep their product details proprietary. Whether we presented ourselves (with permission) as the USCG, or as students, many companies either didn’t see our attempts to contact us or chose not to reply. We suspect this is simply the nature of a new industry. Overall though, we’re very happy with the data we’ve gathered and the opportunity to learn about this emerging technology.

This project will be the first report assessing the market of hull cleaning robots. We believe the report will be useful not only to the USCG, but to the shipping industry. Hull cleaners are an emerging market and much of their future is unknown, but we now know the state of the market.

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Appendix

Appendix A Current Coast Guard Biofouling Rating System

Type	Fouling Rating (FR)	Description
Soft	0	A clean, foul-free surface; red and/or black AF paint or a bare metal surface.
Soft	10	Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.
Soft	20	Slime as dark green patches with yellow or brown colored areas (advanced slime). Bare metal and painted surfaces may by obscured by the fouling.
Soft	30	Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in color; or soft non calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand.
Hard	40	Calcareous fouling in the form of tubeworms less than ¼ inch in diameter or height.
Hard	50	Calcareous fouling in the form of barnacles less than ¼ inch in diameter or height.
Hard	60	Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height.
Hard	70	Combination of tubeworms and barnacles, greater than ¼ inch in diameter or height.
Hard	80	Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another, ¼ inch or less in height. Calcareous shells appear clean or white in color.
Hard	90	Dense growth of tubeworms with barnacles, ¼ inch or greater in height; Calcareous shells brown in color (oysters and mussels); or with slime or grass overlay.
Composite	100	All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering (tunicates) growing over various forms of hard growth.

Appendix B Hull Cleaner Product Interviews

Raytheon Interview Questions

- What problem was Raytheon trying to fix originally when they began research into the hull robot?
- Is there any form of press packet, or information besides the patent available online?
- Where does the Hull Robot program stand currently?
    - Abandoned:

        - Why did Raytheon decide to abandon the project?
    - Still in development:
        - What are difficulties you are facing with the project?
            - Many patents for Raytheon approved in March of 2014
        - What is the developmental timeline looking like?
    - Finished development
- What is the projected cost of a product like this?
- How effective is the system?
    - Square feet an hour
    - How clean are surfaces it cleans?
- What is the durability/lifespan of the system?
    - With the claim of being able to operate during ship operation is it still going to be safely secure?
        - Max speed the “bot” can withstand in water
    - How long can the bot be expected to operate without maintenance?
- How does one operate the robot?
    - Any form of user manual? Autonomous? Semiautonomous?
- Claims to bring up:
    - Can be used while boat is in motion
        - Apparently uses the flow of water over/through the robot to power itself
        - Can still run without the boat moving?
- Characteristics of the robot
    - Cleaning system:
        - Brushes
        - Wipe
        - Lasers
    - Movement system
    - Navigation Technology
    - Tethered?
- Have any in water tests been run yet?

SeaRobotics Interview Questions

- What was the original motivation for SeaRobotics to pursue a hull cleaning robot?
- What is the current status of both the hull cleaning robots?
    - Abandoned
    - Early stages of development
    - Late stages of development
    - Finalized product
- What is the cleaning speed of the system? (square meters per hour)
- What is the projected cost of a Hullbug?
- Is the system able to be used while the boat is in motion?

- Is a tether needed to keep the system constantly connected?
- What cleaning system does the Hullbug use?
- What is the mean time to failure for a HullBUG?
- What sensors are included on the platform?
- Have there been any conditions that the hullbug has had trouble handling?
- It looks like SeaRobotics was aiming for a 2015 demonstration of the Hullbug's capabilities, but nothing seems to be readily available online about this demonstration, what happened with it?

GAC EnvironHull Interview Questions

- What was the original problem you were trying to solve with an automated hull cleaner?
- What is the current status of the HullWiper?
    - Abandoned
    - Early stages of development
    - Late stages of development
    - Finalized product
- How does the system stay attached to the hull of the boat?
- Why did you decide to go with a pressure washer instead of brushes or other options?
- Can the system handle barnacles and other forms of macrofouling or is it more confined to just microfouling?
- Is the system autonomous? Semiautonomous? Completely controlled by an operator?
- Who is the intended market? (UAE company, made in Norway to Norwegian standards)
- How much does a system like this system cost:
    - To build?
    - To have used on a ship?

Appendix C Authority of the USCG and Biofouling

Existing laws that the USCG enforce to prevent environmental problems, caused by the spread of invasive species or Biofouling include:

- 33 CFR 151.2050(b): Minimize or avoid uptake of ballast water in specified locations
- 33 CFR 151.2050(c): All Boats must clean their ballast tanks regularly, making sure to remove all sediments. Sediment must be disposed of in accordance to state law.
- 33 CFR 151.2050(d) ship are required to discharge only the minimal amount of ballast water essential for vessel operations while in the waters of the United States.

- 33 CFR 151.2050(e): Which states any vessel fitted with ballast tanks operating in U.S. Waters are required to “rinse anchors and anchor chains when the anchor is retrieved to remove organisms and sediments at their places of origin”(American Bureau of Shipping,2013).
- 33 CFR 151.2050(f): Which requires all vessels to remove fouling organisms from the vessel’s hull, piping, and tanks regularly and properly dispose of any and all removed substance in accordance with any local, State and Federal regulations
- 33 CFR 151.2050(g): Maintain a ballast water management (BWM) plan that has been developed specifically for the vessel and that will allow those responsible for the plan's implementation to understand and follow the vessel's BWM strategy and comply with the requirements of this subpart. The plan must include
- 33 CFR 151.2050(h): All ships must train their commanders on the application of ballast water and sediment management and treatment procedures.
- 33 CFR 151.2050(i): Ships are only allowed to discharge ballast water to reception facilities that have an NPDES permit to do so. (Cornell University Law School, 2016)

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