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Call for paper next conference

Review of Robotic In-Water Hull Cleaning

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Abstract

This paper describes the development of robotic hull cleaning from academic research in the 1980s to current industry standard, including likely further paths of developments towards mass-produced, standardized robotic designs with more advanced capabilities.

1. Introduction

In the quest for future, more sustainable hull management strategies, some of the most promising contenders involve frequent 'pro-active cleaning' or 'grooming' to remove the biofouling at an early stage, e.g. *Oftedahl and Enström (2020), Hunsucker et al. (2018), Swain et al. (2020)*. "Frequent" may mean every two weeks, to give an idea. Such frequent cleaning would remove biofilms before advanced calcareous fouling can develop, addressing issues of aquatic invasive species and energy efficiency at the same time. In order to be widely available and affordable, such proactive cleaning would have to be largely robotic.

The required technologies have been coming together, recently maturing to commercial applications. Perhaps the appearance of a dedicated Wikipedia site on in-water cleaning can be seen as a sign of the generally larger interest in the theme: https://en.wikipedia.org/wiki/In-water_surface_cleaning. We may be at the dawn of a new era of mechanical cleaning (by robots), *Bertram (2020)*.

2. Diversity and fragmentation in a young industry

In-water cleaning robots come in a large variety of designs/concepts and are usually one-of-a-kind productions. This fragmented approach with its lack of standardization is typical for young industries. (Most of the developments started within the last decade). *Noordstrand (2020)* discusses the typical issues of young industries afflicting currently the in-water robotic cleaning market.

The current state of the industry with its design diversity has various reasons:

- The appropriate cleaning approach depends on the paint coating used on the hull, e.g. soft dissolving self-polishing copolymer paints, mechanically sensitive foul release coatings, or hard varnishes.
- The in-water cleaning industry is highly fragmented and relatively small in total volume. The market leader for robotic in-water cleaning, HullWiper, is at best a small-to-medium enterprise with less than 50 employees.
- Cleaning companies develop their own designs and build or have them built in near-by workshops, in a "do-it-yourself" style typical for young industries. (Think of how the first automobiles or PCs were designed and built in private garages.)
- There are no standards yet for design or production of such robots.

With time, we should see some consolidation of market and robot designs as we did for other industries (automotive, airplanes, PCs, …).

Eventually, we may see dedicated in-water robot cleaning robot manufacturers supplying the service providers with mass produced or at least mini-series produced robots, possibly with modular design approaches to allow the necessary flexibility while maintaining low-cost production. We will also see robot design move from "do-it-yourself" assembly design moving to more professional approaches, using computer-aided design including hydrodynamic optimization, as indicated by *Lee et al. (2012).*

3. Past, present and prospects

3.1. Past – The academic research era

Research into hull cleaning robots started probably in the 1990s. *Bertram (2000)* mentions some research projects. The robots of the time were bulky do-it-yourself assemblies of academic research laboratories, Fig.1. Several EU projects advanced robotic inspection and cleaning technology, e.g. the AURORA project, Fig.2, *Armada et al. (2004)*. However, while these efforts prepared the ground for today's state-of-the-art, they remained research focussed and did not directly translate into industrial applications.

Fig.1: Cleaning robot of Hiroshima University, *Bertram (2000)*

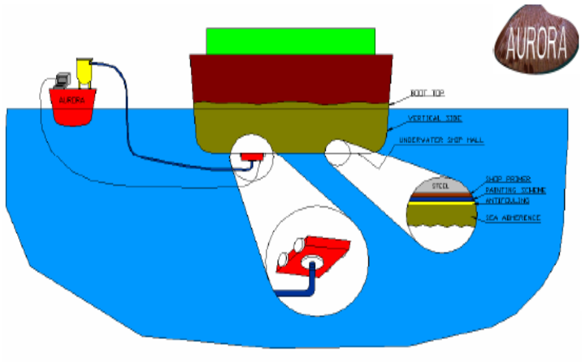

Fig.2: AURORA cleaning robot, *Armada et al. (2004)*

3.2. Present – The start-up and adapt era

My overview benefitted from previous surveys which are highly recommended for more in-depth information, namely *Souto et al. (2015), Albitar et al. (2016), Curran et al. (2016), Song and Cui (2020)*. Table I lists current in-water cleaning robotic solutions.

Table I: Overview of commercial in-water robotic cleaning solutions

Robot	Country	Adhesion system	Cleaning system
COLLECTOR	Norway	Magnetic	Waterjet
Daewon robot	Korea	Thrusters	Brush
Fleet Cleaner	NL	Magnetic	Waterjet
Hullbot	Australia	Thrusters	Brush
Hull BUG	USA	Magnetic/Vacuum	Brush/Waterjet
Hull Cleaner	USA	Magnetic	Brush/Ultrasonic
HullSkater	Norway	Magnetic	Brush
Hull Surface Treatment	Australia	Magnetic	Thermal shock
HullWiper	UAE	Vacuum	Waterjet
KeelCrab	Italy	Vacuum	Brush
Vertidrive M-series	NL	Magnetic	Waterjet
Magnetic Hull Crawler	France	Magnetic	Waterjet
Magnetic crawler	USA	Magnetic	Ultrasonic
Rovingbat	France	Vacuum	Brush/Waterjet
Scrufy	Greece	Magnetic	Brush
SeaBadger	Denmark	Thrusters	Waterjet
ShipShiner	Singapore	Thrusters	Waterjet
ITCH	Norway	Ship flow field	Brush

Within 5 years, for a third of the robotic solutions listed in *Curran et al. (2016)*, there were no longer supported websites or more recent publications, suggesting that these would-be contenders had left the market. There are fewer new entries than drop-outs. This is partly due to Table I listing only commercial solutions, partly due to the still volatile market where start-ups disappear or are absorbed in merger & acquisitions.

There are many ways to categorize in-water cleaning robots, including:

- Cleaning technology (brushes, high-pressure or cavitational waterjets, laser, …)
- Adhesion technology (magnetic, vacuum (negative pressure), thrusters, …)
- Level of autonomy (diver controlled, remotely controlled, more or less autonomous)
- Region/country (USA, Europe, Japan, …)
- Market (pleasure boats, commercial ships, navies, …)
- …

Most systems on the market favour magnetic adhesion by now, making them unsuitable for aluminium, reinforced plastics and wooden hulls commonly found in the pleasure craft industry. Vacuum (= negative pressure) adhesion is also popular, while use of thrust force, e.g. *Ishii et al. (2014)*, *Souto et al. (2015)*, or adhesive elastomer materials in research applications is rather exotic, *Song and Cui (2020)*. Adhesion by flow forces of the moving ship is only applicable for largely flat sides, not the ship ends and the ship bottom, *Freyer and Eide (2020)*.

Rotary brushes and waterjets are commonly used, with waterjets taking a more prominent role in the most recent developments. This shouldn't come as a surprise, as the concept of gentler and more frequent cleaning in itself has been accepted by a wider public only in recent years. Ultrasonic technology and laser cleaning technology have been proposed by various researchers, but do not play a significant role in industry practice, *Song and Cui (2020)*. (Note that ultrasonic antifouling protection in stationary installations for niche areas and internal pipes gains in popularity, e.g. *Kelling (2020)*, but use of the technology in underwater robots is rare.) *Akinfiev et al. (2007)*, *Morrisey and Woods (2015)*, *Song and Cui (2020)* give more in-depth discussions of cleaning technologies.

3.2.1. Key players for commercial applications

Several companies have defined the state of the art through pioneering developments and presentations at professional events like HullPIC and PortPIC:

- HullWiper, www.hullwiper.co, is the market leader in terms of size (employees and probably turnover) and ports served (10 ports in late 2020, with 3 more planned for 2021). The Hull-Wiper robot, Fig.3, *Doran (2019,2020)*, "collects marine fouling removed from hulls, rather than polluting local port water and risking the spread of harmful invasive species.

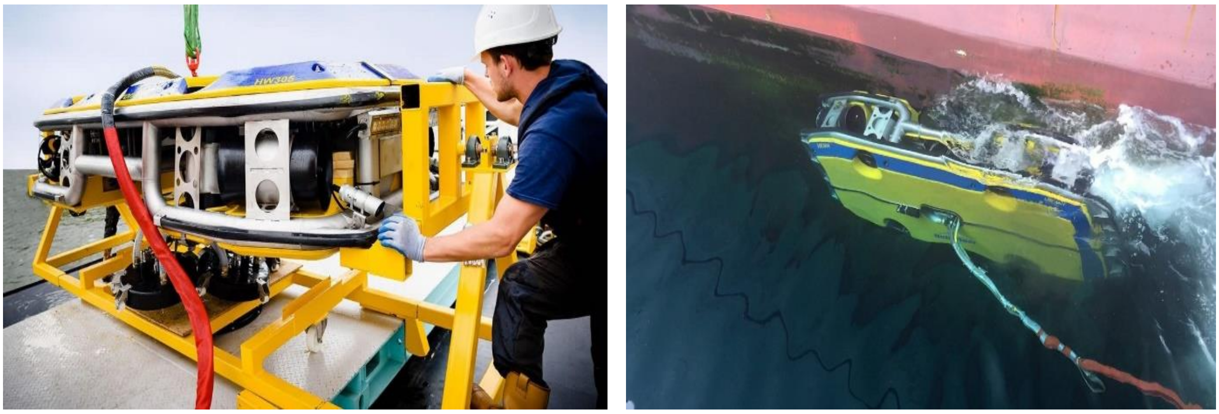

Fig.3: HullWiper robot, www.hullwiper.co

Captured residues are pumped into a filter unit and then deposited into dedicated drums on-shore, which are collected by a [locally approved] environmental waste disposal company. [… The robot] sprays adjustable high-pressure seawater jets directly onto a ship's hull at a very high velocity to dislodge waste materials, without using scrubbing, harsh chemicals or abrasive materials required for traditional methods. […] The use of high-pressure jets for cleaning ensures that HullWiper does not damage the ship's […] antifouling coatings.” The robot is relatively large (3.3 m (L) x 1.7 m (W) x 0.85 m (H)) and heavy (1275 kg).

- Fleet Cleaner, www.fleetcleaner.com, has developed its robotic cleaning solution since 2011, with first field trials in 2016, *Noordstrand (2018)*. In subsequent years, the service was extended to all Dutch ports and eventually also to Belgian ports, *Cornelis et al. (2020)*. The self-developed robot uses magnetic attachment and cleans with high-pressure waterjets. The design is relatively compact (2.0 m (L) x 1.8 m (W) x 0.6 m (H)). Cleaning a ship takes typically 10 h with the latest technology. Like the HullWiper robot, the Fleet Cleaner robot is collecting the removed debris for proper disposal.

Fig.4: Fleet Cleaner robot, www.fleetcleaner.com

- ECOsubsea, www.ecobsubsea.com, started in 2008 in Norway, but has its main operational base in Southampton. Its robot ‘Collector’, Fig.5, uses magnetic adhesion, waterjet cleaning and collects the debris, giving “more than 97.5%” as collection rate. The ‘Collector’ has similar size as the HullWiper (3.0 m (L) x 2.0 m (W) x 0.7 m (H)), but is considerably lighter (715 kg). Cleaning a ship takes typically 5 h. The collected debris is properly disposed and serves to generate biogas. The service is offered in 19 ports according to the company’s website, Fig.6, mainly covering North Sea and Baltic ports.

Fig.5: ‘Collector’ robot

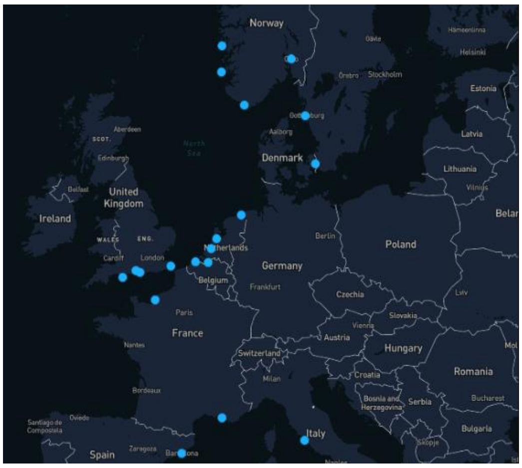

Fig.6: Ports served by ECOsubsea

- SeaRobotics, www.searobotics.com, developed the ‘Hull BUG’ (BUG = bioinspired underwater grooming) funded by the Office of Naval Research in the USA, Fig.7, *Schütz (2012)*. The robot uses vacuum suction for adhesion and brushes to remove biofilm. It is designed for autonomous operation, like a robotic lawnmower or pool cleaner. Onboard sensors allow it to steer around obstacles, and a fluorometer lets it detect biofilm to be removed. The robot is relatively small (1.5 m (L) x 0.75 m (W) x 0.75 cm (H)) and light (55 kg). This makes it easier to cope with curved parts of the ship. SeaRobotics has continued the development with the SR-HullBUG, Fig.8, which is larger (1.5 m (L) x 1.1 m (W) x 0.75 cm (H)) and heavier (370 kg). It has changeable grooming or cleaning tools, listing cavitational waterjet tools explicitly. As the SR-HullBUG addresses cleaning at the biofilm stage, before macrofouling can develop, there is no need to collect the removed fouling.

Fig.7: Hull BUG

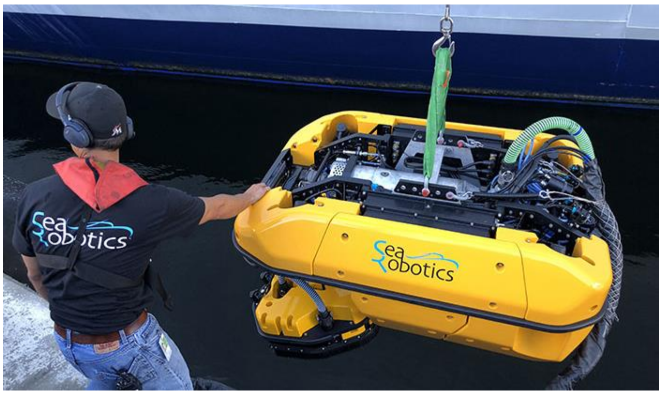

Fig.8: SR-HullBUG

- Jotun, https://jointherevhullution.com, launched its HSS (Hull Skating Solutions) in 2020, Fig.9, which was developed in partnership with Kongsberg, Semcon, Telenor, DNV GL and Wallenius Wilhemsen. The Hull Skater robot uses magnetic adhesion and soft brush cleaning. As it is only intended to remove biofilm, there is no need to collect debris. The Hull Skater robot, https://octagavs.com/JotunHSS_mobile/, travels on-board with the ship, and is launched and retrieved by the crew.

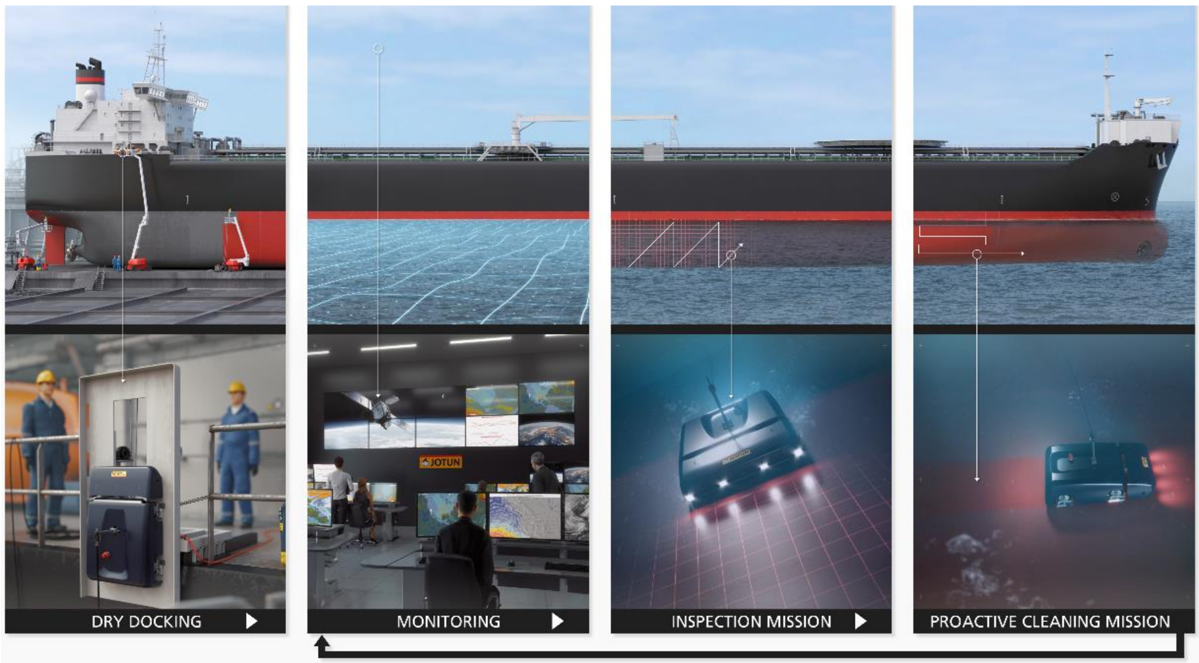

Fig.9: Hull Skating Solutions with (from left to right) robot launched by crew; performance monitoring and remote control of robot by Jotun experts; inspection mode to identify no-go areas with fouling beyond biofilm; and subsequent cleaning of biofilm

The inspection and cleaning missions are remotely controlled by Jotun. During inspection, the robot identifies areas of advanced fouling, which are not cleaned by the robot and are subject to later cleaning by other means allowing collection of removed advanced fouling to prevent spread of aquatic invasive species. The Hull Skater is relatively small (1.6 m (L) x 1.0 m (W) x ~0.5 m (H)) and light-weight (200 kg), https://semcon.com/uk/jotunhullskater/. Cleaning a (150 m) ship takes typically 4-5 h.

3.2.2. Flanking measures

Besides the technical and economic development of in-water cleaning robots, there are additional measures needed to develop the 'eco-system' of in-water, in-port cleaning:

- Guidelines are needed for various aspects, such as accreditation for in-port cleaning, matching of cleaning method and coating, collection and disposal of removed fouling, documentation of cleaning results, etc. E.g. *Oftedahl and Enström (2020)*, *Sørensen (2020*), the NACE TG 581 on NACE's Standard Practice 'Inspecting and Reporting Biofouling and Antifouling System Condition during an Underwater Survey', and several proposals for the due update of IMO's 'Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species' are such useful contributions benefitting the industry at large.
- Ports need to adapt policies to the changing coating and cleaning technologies, requiring adequate proof of environmentally acceptable procedures, but also allowing in-port cleaning if required documentation can be given by service providers. E.g. Belgian ports, *Cornelis et al. (2020)*, set a good example in this respect. Policies should be aligned at least within regions, to avoid the "wild west" unaligned and unregulated practice rightfully lamented by *Noordstrand (2020)*.

3.3. Prospects

"Prediction is very difficult, especially about the future", as Nobel laureate Niels Bohr so wisely said. Still, we can look at recent research and development and make speculate on what may come:

- Team capability in cleaning robots – Cooperative robotics is one of the major research areas within the robotics community. The basic idea is to have two or more robots working as a team on a task. In the maritime field, there have been some applications of such cooperative robotics, e.g. for mapping of seabed, establishing towline connections, or search/patrolling tasks, e.g. *Odetti et al. (2016)*, *Lewis (2017)*. For hull cleaning, cooperative robotics would allow parallelization of work and thus much shorter cleaning times. One could also imagine smaller robots focussing on areas of high curvature, while a larger robot is used for large flat areas. The technology of robot location, ship surface mapping, and communication between robots (and possibly a central surface control centre) is available, we need "just" to get the robotics community and the hull cleaning industry connected. It seems a perfect opportunity for an EU project.

- System solutions – Mismatching coating solution, cleaning technology and procedures has led repeatedly to problems and finger-pointing between the various stakeholders. While we hear repeatedly the mantra that cleaning and coating should be matched properly, a multitude of products/services coming from a multitude of changing suppliers seems like a recipe for failures to happen. We need system solutions, at least in the form of clear instructions for cleaning coming from the coating suppliers and procedures that ensure that these instructions were received and understood by the cleaning providers. Information loss between stakeholders is best avoided by integrated solutions. Jotun's Hull Skating Solutions, *Oftedahl and Enström (2020)*, are a role model that hopefully will inspire larger parts of the industry to follow. Here, coating, robotic cleaning, performance monitoring (to trigger the cleaning and monitor the effect on performance) and contractual warranties come under one umbrella.

- Port services or on-board equipment – Most robotic cleaning solutions assume a dedicated service provider, providing the robot and the cleaning service in certain (and, so far, few) ports. Exceptions from this rule have appeared in 2020 with Jotun's hull skating solutions and Shipshave's ITCH (In Transit Cleaning of Hulls) semi-autonomous robot. Both are launched and retrieved by the ship's crew, travel with the ship and are thus independent of available port infrastructure. On-board cleaning robots overcome issues with scarce port services. In-port services have the advantage that equipment is utilized over many ships, with the associated economies of scale. In the long term, these economies of scale may favour in-port service providers, echoing a similar development away from multi-purpose ships (with their underutilized on-board cargo handling equipment) towards containerships (relying on port-side services), but this requires wider deployment of port-side robotic cleaning solutions which I am confident we will see, but which will take time. In the meantime, we may see more rapid growth of on-board solutions.

4. Conclusion

Robotic in-water cleaning technology has come a long way from early research attempts to the current state of the art. We are currently in a steep part of the learning curve and the development of this still young industry. Technology, regulatory frameworks and procedural guidelines, as well as markets, are developing dynamically. Teething problems and occasional set-backs (or learning moments) are to be expected, but the future looks rather bright for this particular segment of the maritime world.

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Re-Creating 3D Ship Geometries as Maps for Inspection and Reporting

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Abstract

This paper gives an overview of describing hull surfaces, with a special focus on re-creating existing hulls where the original hull design description is not available in digital format. Key technologies are parametric hull descriptions and 3D scans. It is recommended to use dedicated service providers for the task.

1. Introduction

The shipping world is striving towards a sustainable future, not just on decarbonization, but also on many other aspects. One of these other aspects is biofouling management with the focus on preventing the spread of aquatic invasive species. Both decarbonizing shipping and biofouling management tie in with hull cleaning. If we further add the desire to eliminate release of paint particles (including microplastics) and biocides in the hitherto dominantly popular self-polishing copolymer (SPC) coatings for ships, a logical conclusion is predicting a mechanical era of hull management using, e.g., robotic cleaning of large surfaces coated with non-biocidal paints and ultra-sonic protection for niche areas, *Bertram (2020)*.

The rapidly evolving field of robotic hull cleaning comes with many detail issues that need to be addressed on the way to technically and economically mature solutions. 3D hull descriptions are an example, where such descriptions would be useful for:

- Mapping - Underwater inspection and cleaning robots should cover the hull completely, but with minimal overlap. Especially when envisioning team robotics, a common 'map' of the ship is a base for efficient robotic path planning. This applies particularly for crawler robots, Fig.1, but to some extent also to free-floating robots that follow the hull keeping a short distance to it, Fig.2.

Fig.1: Hull Skater crawler robot, source: Jotun

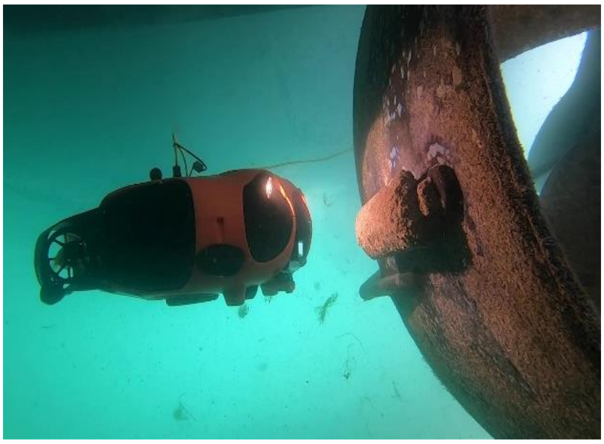

Fig.2: Seasam free floating robot, source: Notilo+

- Reporting – Ships are 3D objects. Reporting benefits from intuitive 3D maps where findings can be attached as text and/or images. Industry practice is using simple generic sketches, where divers mark findings qualitatively, Fig.3 (left). *Guéré and Gambini (2021)* present already and improvement, appropriate for digital inspection and reporting purposes, albeit still based on 2D schematic displays, Fig.3 (right). Using 3D models with very intuitive marking of findings on such a 3D map, similar to Google map pins, has been successfully used e.g., for ship structural hull condition monitoring, Fig.4, *Cabos et al. (2010)*. This approach has been implemented for years in DNV's ShipManager software, https://www.dnv.com/services/hull-integrity-and-ship-maintenance-software-shipmanager-hull-1531. *Cabos et al. (2017)* envision even wallpaper mapping of drone inspection images on the 3D model to allow viewing in Virtual Reality, Fig.5.

Fig.3: Manual 2D sketches (left) have progressed to digital 2D displays (right), source: Notilo+

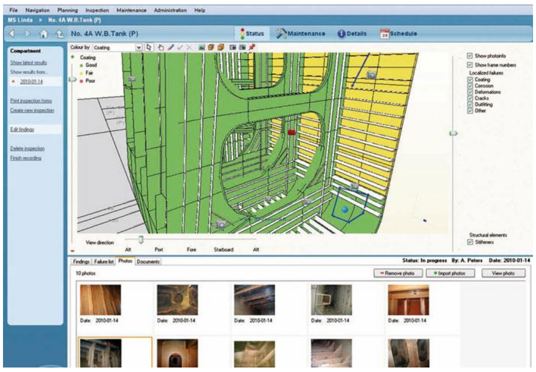

Fig.4: DNV's ShipManager (Hull)

Fig.5: Vision of drone-based images mapped on 3D model and viewed in VR, *Cabos et al. (2017)*

But most of the time, ship owners do not have any hull description for their ships. This problem occurs also for other applications, e.g. for hull condition assessment schemes, *Cabos et al. (2008)*, and trim optimization, *Hansen and Hochkirch (2013)*. "One of the issues of creating the hull models for existing ships is the eventual lack of information. Whenever the only data available are the drawings available onboard the ship, the model must be developed from a reduced set of data and also in a short period of time […] [T]he simplified model should be […] developed from the information on the drawings commonly existing on board the ship, such as the general arrangement, body plan, docking plan, midship section, shell expansion, transverse and longitudinal bulkhead.", *Cabos et al. (2008)*.

There are two key reverse engineering techniques to recreate CAD (computer aided design) descriptions for existing ship geometries, namely parametric hull design techniques, e.g. *Harries (1998)*, *Veelo (2004)*, and 3D scanning. These will be described in more detail in the following.

2. Hull description options for re-creating existing hulls

2.1. CAD surface descriptions

When re-creating an existing hull, the aim is to come up with a mathematical representation that is close to the ship as designed, built or in service. The purpose of the reverse engineered description is not to replicate the ship for reproduction in another shipyard, but rather to make the geometry digitally available for (i) high-fidelity hydrodynamic analyses, e.g. as needed for trim optimization, performance monitoring and advanced weather routing, and (ii) for services such as cleaning, inspection and reporting. The former requires an accurate model while the latter can accept a coarser approximation.

In general, for the re-creation of geometry, the same mathematical methods are used as for the original generation of ship hulls, propulsion systems, propellers, rudders etc. at the design stage. Both a designer and an engineer tasked with re-creating the hull would use so-called boundary representations (BReps) as offered within major Computer Aided Design systems (CAD) such as CAESES, Catia, NAPA, NX, Pias, Rhino, etc. In these systems curves are typically established from point data, for instance, points to be interpolated or points with which a curve is associated as for B-splines, *Piegl and Tiller (1995)*. Surfaces may also be generated by means of point data, for instance, via the vertices of a B-spline's defining polyhedron.

Typically, ship hull surfaces are generated via sets or meshes of curves, Fig.6. A hull mesh may comprise intersecting curves in different dimensions, such as sections, waterlines, diagonals etc. These curves need to be defined before they serve as input to surfaces. Setting up curves and surfaces manually from point data is rather tedious. Moreover, it calls for skillful interactive work by an expert familiar with the CAD system at hand. This is quite costly. Typically, several days of work are required.

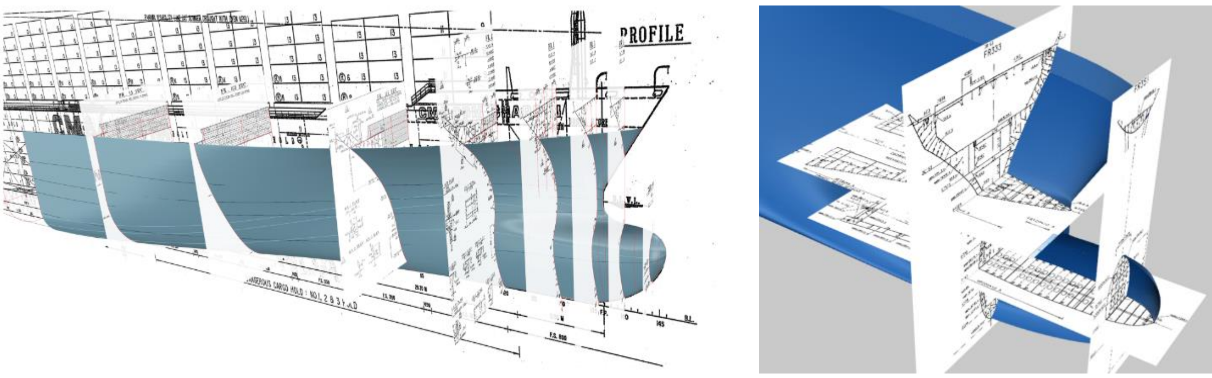

Fig.6: 2D hull information can be combined to 3D hull description

An alternative approach to curve and surface modeling is to utilize sophisticated parametric modeling. Here, the geometry of interest is described using a reasonably small set of parameters that serve as high-level descriptors. Typically, a hull form can be sufficiently defined by 30 to 50 parameters as soon as the topology has been selected, *Harries (1998,2010)*. Parametric ship hull models are tailored to specific ship types, using key differentiators such as:

- number of hulls, i.e. monohull, catamaran (possibly SWATH), trimaran, etc.
- type and number of the propulsors, i.e. classic propeller, ducted propeller, Voith-Schneider propeller, podded drives, etc.
- type of aftbody, i.e. single integrated skeg, twin-skeg, etc.
- type of forebody, i.e. straight stem, integrated bulbous bow, etc.

Re-using such tailored macro-models for a suitable ship hull can bring about a CAD definition within just a few hours of work. Information for the required parameters can be retrieved from

- General Arrangement plans (main dimensions, center plane contour, deck contours, amidship contour),
- Steel plans (some further cross section contours over the length of the ship)
- hydrostatics tables/stability book (longitudinal center of buoyancy and displacement volume at various drafts),
- selected measurements and photographs, e.g. from dock stays,
- scans,
- and even from educated guesses, e.g. from similar ships where actual or re-engineered hull descriptions exist.

Fig.7 gives an illustration of a parametric model of the forebody of a container carrier. Similarly, Fig.8 shows a parametric model for a conventional propeller for which even fewer parameters are needed to establish a mathematically closed definition. For further examples and animations see https://www.caeses.com/industries/marine/.

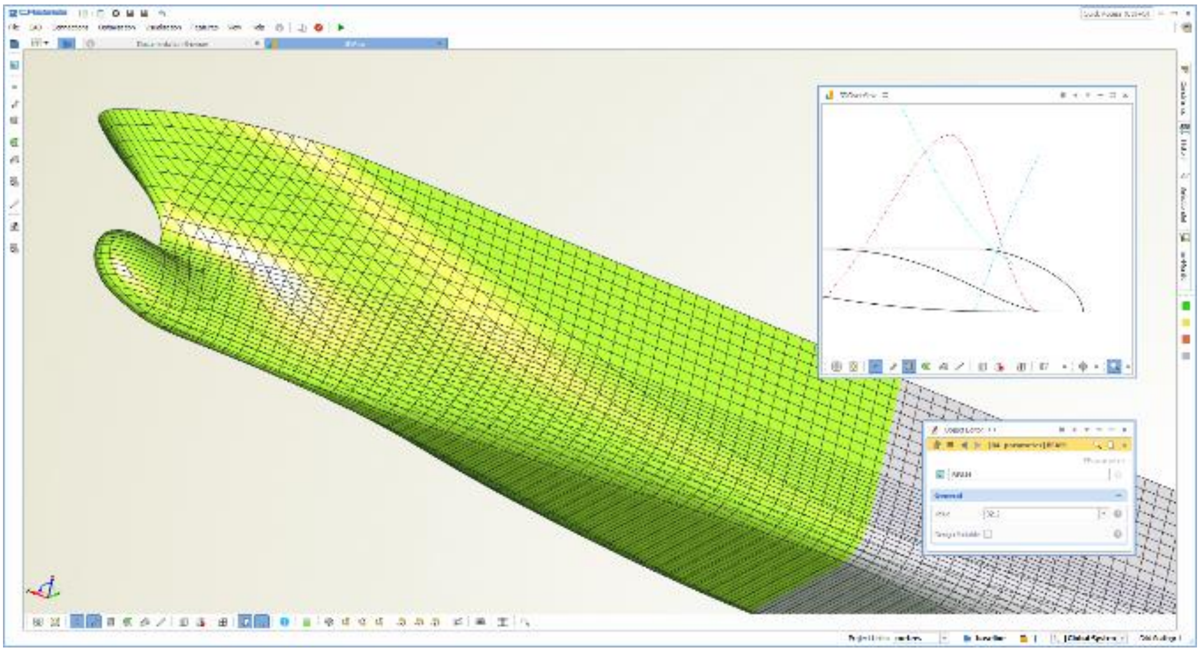

Fig.7: Parametric form description for containership hull (as implemented in CAESES)

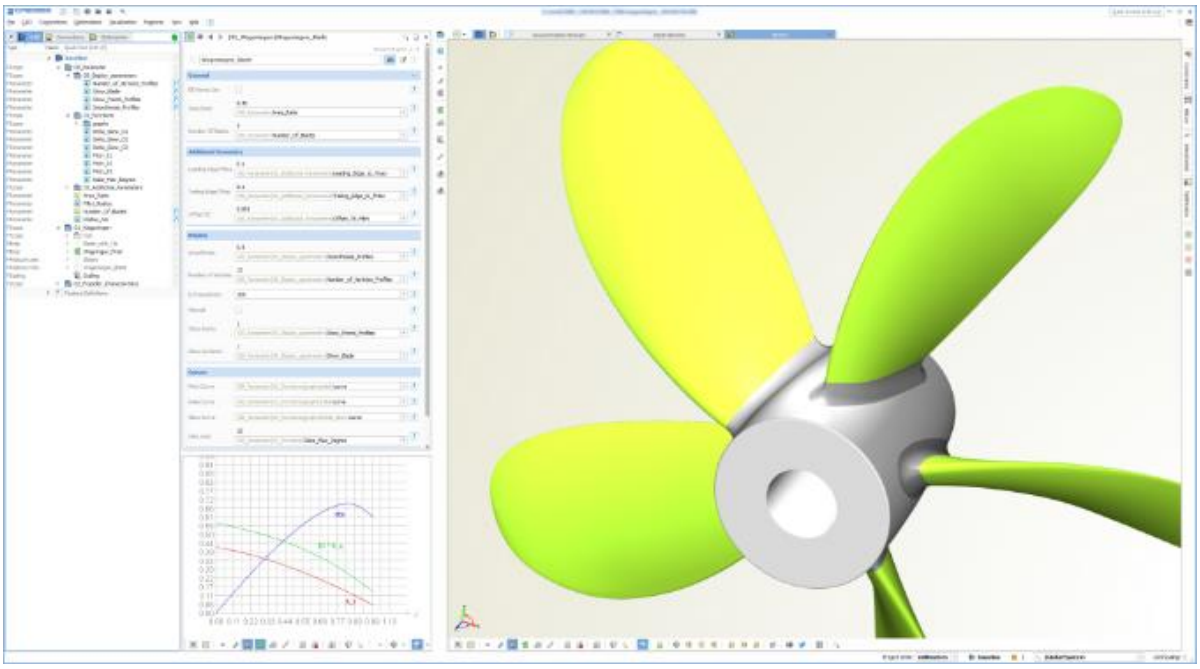

Fig.8: Parametric form description for propeller (as implemented in CAESES)

Details of various parametric modeling techniques are given in *Harries et al. (2018)*. For a general understanding it may suffice to point out the decisive difference between a standard CAD approach – as would be used in an interactive re-creation process of a ship – and its parametric counterpart: In the standard approach the curves and surfaces are produced first from which important characteristics of the shape, e.g. the displacement, the area of the design waterline etc., are derived, while in the parametric approach the process is turned around, i.e., the desired characteristics are compiled and, subsequently, the curves and surfaces are computed accordingly.

2.2. 3D scanning

The prime application for 3D scanning inside ships are retrofit projects. The state of the art is very mature, allowing to import 3D scanned point clouds directly into widely used CAD software, *Blom and Czapla (2021)*. Laser scans on ships can be combined with photographic color information to create realistic 3D models which look like the real ship, but allow also extracting geometrical information such as quantifying space and distance between objects, Fig.9.

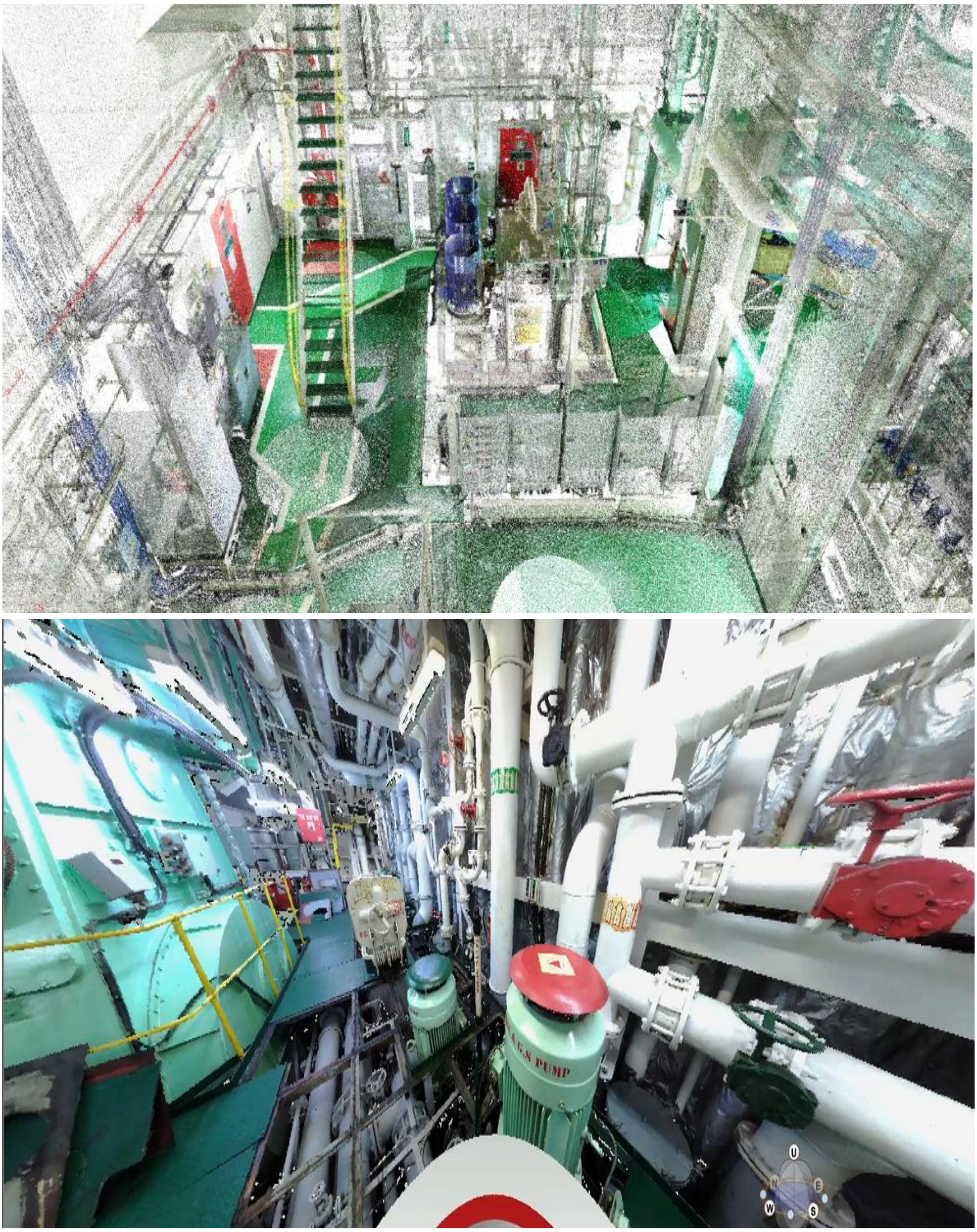

Fig.9: Laser scans (top) can be combined with photos to create realistic 3D representations (bottom), source: Blom Maritime

Scanning ship hulls from the outside in drydocks is similarly straightforward; however, in-water scanning of ship geometries is much more complicated, due to the relative motions between underwater robots carrying scanning devices and ships (which move due to natural waves always present). Using self-referenced underwater color laser scanners, this problem can be solved, Fig.10, and highly accurate underwater scans are also possible, with resolution of 0.01 mm on crawling robots and 0.5 mm on free-floating robots, *Paranhos (2020)*.

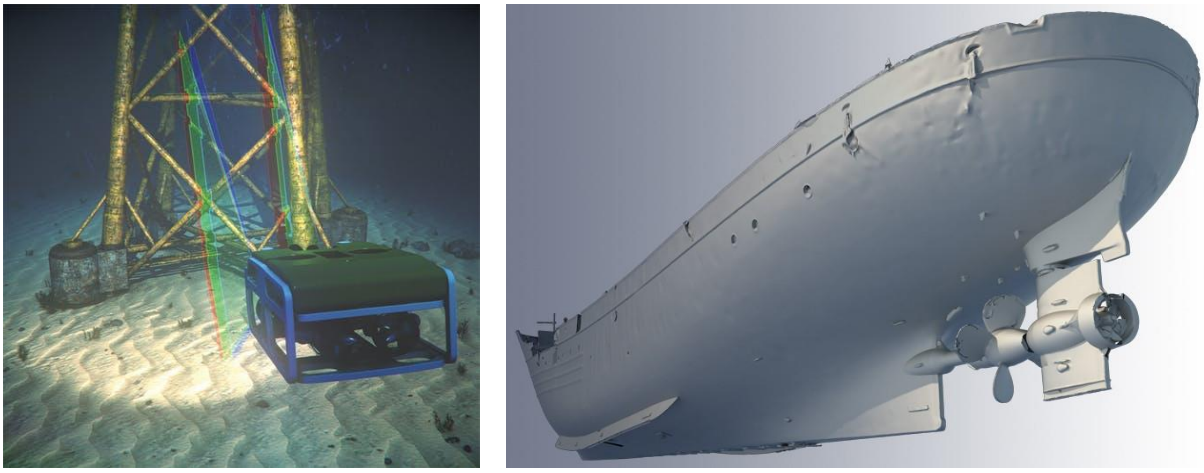

Fig.10: 3D underwater scanning can reproduce accurate as-built/as-is reproductions of hull geometries, source: Kraken Robotics, Kroes Marine Projects

Naturally, both parametric hull design and 3D scanning can be combined in order to increase the level of accuracy of producing a geometric twin and to cover blind spots not accessible (or not accessed) by the laser when scanning, respectively.

3. Conclusions

Various reverse engineering approaches to recreate ship geometries exist and some have reached industry maturity, most notably

- parametric hull descriptions using naval architectural parameters to describe the hull;
- 3D scanning which by now is also possible under water

As the involved processes require special software and know-how, and as they are only performed once for each ship, the reverse engineering tasks should be outsourced to dedicated service providers.

Finally, using such recreated hull and propeller geometries for purposes such as trim optimization, Condition Assessment Schemes, or biofouling management activities does not violate the intellectual property of shipyards, as the recreated approximation is not used to create products made by the shipyard.

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Evolving Inspection and Cleaning Technology

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Abstract

Ports and authorities around the world are implementing stringent measures to combat the harmful effects of biofouling on our delicate marine eco-system and the environment. This paper describes in brief detail some of the technical advancements being made in the development of sustainable biofouling hull management solutions within the shipping industry.

1. Impact of Marine Fouling

Marine fouling on vessel hulls, Fig.1, is associated with the largest percentage of invasive issues in our oceans and is an environmental emergency. The IMO call it "one of the greatest threats to the ecological and economic well-being of the planet."

Fig.1: Examples of marine fouling

Biofouling is the accumulation of microorganisms, plants, small creatures and algae that attach to a ship's hull and is then transported to foreign waters. The introduction of these foreign species to a new environment leads to the rapid decline in the health of local marine fauna and flora.

Aquatic fouling on a hull increases the vessel drag, resulting in decreased operational efficiency and an increase in fuel consumption. With more than 80% of world trade being carried by sea, the shipping industry produces more than 2% of global emissions.

2. Measures for containment

Over the centuries, different anti-fouling methods have been employed:

- The first recorded treatment for ship efficiency comes from an Aramaic scroll dated about 142 BC which stated, "The arsenic and sulphur have been well mixed with Chian oil, with the mixture evenly applied to the vessel sides so that she may speed through the blue waters freely and without impediment."
- By the 3rd century, Romans and Greeks were recorded as using tar and wax to coat their ship's bottoms.
- Between the 8th and 11th century, Vikings were known to use pitch, oil, resin and tallow for hull treatments.
- The period between the 13th and 15th century saw the Chinese using a mixture of lime and poisonous oil to protect the wood from worms.
- Near the end of the 20th century, hull coating using Tributyltin (TBT) was considered the ideal solution for preventing the development of detrimental marine growths on vessel hulls as it

effectively halted the accumulation of biofouling. Studies soon revealed the harm TBT was causing to aquatic life and TBT was eventually banned by the IMO in 2003.

- Divers with brushes or karts then became the traditional method for hull cleaning and this is still in use today. Abrasives and chemicals are used to remove fouling with much of the removed residue falling back into the sea.
- The need for an eco-friendly hull cleaning solution with marine fouling capture technology capabilities resulted in innovative development with the first Remotely Operated Vehicle (ROV) being introduced to commercial shipping in 2003.

But further measures to combat the spread of invasive aquatic species are needed. Marine fouling contributes to a significant number of global CO_2 emissions. Various industry related institutions and associations have adopted an ambitious strategy to reduce Greenhouse Gas Emissions (GHG) by 50% by 2050.

Ports around the world are implementing strict measures aimed at eliminating the cross-pollination of foreign aquatic marine species and some require vessel-specific biofouling managements plans which include the biofouling management strategy to be in place.

Assorted guidelines have been developed to assist ship owners and owners to align their fleets with the sustainability goals:

- International Maritime Organisation (IMO) - Biofouling Guidelines
- GloFouling Partnerships Project - Accelerate the development of technological solutions to help prevent hull fouling
- Global Industry Alliance (GIA) for Marine Biosafety - Collaborate and address environmental issues caused by marine biofouling and GHG emissions from ships
- The Marine Environment Protection Committee (MEPC) - A-E rating incentive aimed at improving the carbon efficiency of vessels
- BIMCO and AMPP - Technical steering committees writing active legislation for global hull cleaning and inspection standards

3. HullWiper's solution

Heeding the call for sustainable solutions within the shipping industry, HullWiper's ROV features have been designed in-line with the findings of our year-long consultation and survey with major shipping lines to seek their views on the best development of existing hull cleaning solutions. The results showed that ship owners wanted solutions which deliver both tangible operational and sustainability results.

HullWiper is a unique, eco-friendly brush-and-diver-free underwater hull cleaning system which uses adjustable pressure seawater to remove fouling from vessel hulls without the scrubbing, harsh chemicals or abrasives employed by traditional methods. Unlike traditional brush cleaning, HullWiper leaves expensive anti-fouling surfaces intact and does not harm the delicate marine environment.

The HullWiper difference:

- Granted permission/pre-approval to clean vessels in port
- No divers are used which eliminates the risk to human life
- Cleaning can be done day or night, during cargo or bunker fuel operations, and in most weather conditions
- Fast, efficient and safe hull cleaning for all types of vessels
- Collects marine fouling removed from hulls via its onboard filter unit rather than releasing it into port waters
- Removed fouling is deposited into dedicated drums onshore for safe disposal by a locally approved environmental waste company

- Cleans up to five times faster than conventional methods
- Resulting cleaning improves vessel long-term operational efficiency, supports significant savings on fuel consumption (up to 40%) per voyage, and reduces carbon emissions
- All operations are in line with IMCA and IMO guidelines, and carried out in accordance with local legislation
- Award winning technology recognised for innovation and contribution towards green shipping

Technological advancements for ROV hull cleaning solutions continues to make significant progress in ensuring that the units are more precise, efficient, and eco-friendly.

Some of the industry developments include:

- Complete 3D mapping of vessels using specialised camera software
- Underwater wireless communication
- Improved battery technology to remove the use of the umbilical cords
- ROV positioning on the ship during cleaning
- Reduce the environmental impact of inspection/cleaning methods

R&D plays a critical role in the ongoing design and production of HullWiper's ROV. We are committed to further developing the unit as the most eco-efficient, progressive, and environmentally sound hull cleaning solution.

We are specifically looking into:

- Increasing the effective size of fouling that can be cleaned and reclaimed
- Improving video image quality to provide higher resolution video and images for our customers
- Enhancing efficiency of the ROV to clean faster while maintaining an effective cleaning operation on the vessel hull
- Making the ROV smaller and easier to handle
- Allowing the ROV to operate in higher sea currents
- Enabling the ROV to follow a cleaning line automatically without the need of the operator to do adjustments
- Smaller filtration system with improved capabilities
- Cost-effective ROV without compromising on quality and reliability

Compliance with port and shipping authority's anti-biofouling regulations and meeting BIMCO reclamation standards requires a proactive management plan from ship owners and operators.

HullWiper joined forces with International Paint, a subsidiary of ship hull paint and performance coatings specialist AkzoNobel, and underwater drone ROV specialist Orobotix to provide a comprehensive and green hull care maintenance support package.

The combination of remote inspection, advanced cleaning technologies and big data monitoring into a system will set new standards for operational efficiency.

Advantages include:

- Mitigates damage to high performance coatings, optimises foul release performance, delivers a clean hull, and minimises the effects of translocation of invasive aquatic species
- Regular inspections, analysis and reporting to track hull condition
- Savings on fuel consumption while enhancing vessel speed and operational efficiency
- Compliance with port and shipping authority anti-biofouling regulations worldwide
- Meet BIMCO reclamation standards

- ROV inspection information in quarterly reports
- Annual condition reports which include biofouling development assessments in line with the ISO 19030 standards
- One of the most sustainable hull performance packages in the marine industry
- Designed to maintain performance over operational cycle of a vessel
- No special modified coating systems or upfront capital investment for vessel modification required

HullWiper delivers on the core principles of corporate sustainability targets. We are one of the four founding members of the IMO's Global Industry Alliance (GIA) for Marine Biosafety. GIA works with the IMO's GloFouling Partnerships Project to help accelerate the development of technological solutions to help prevent hull fouling. We are also actively involved within BIMCO and AMPP technical steering committees, contributing our inputs in the crafting of active legislation for global hull cleaning and inspections standards.

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Remote Ship Hull Inspection using a Robotic Crawler

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Abstract

Ship hull performance is impacted by corrosion, degradation, and marine growth, demanding regular manual inspections and thickness measurements during costly ship dry-docking events. Thus, maritime robotics development has focused on remote and autonomous operations performed under water. Fraunhofer CML has developed and tested a concept for ship hull inspection and thickness measuring above and below water together with HGK Shipping using a magnetic crawler to reduce dry docking times as well as provide fast and simple incident investigations. Results were compared to the measurements taken by a certifying company, acting as a baseline. The comparison showed that the crawler system is able to achieve sufficiently accurate thickness measurements taken remotely in the dry dock and under water. Approximately 81 % of all measurements taken by the crawler were equal to or within the tolerable limit of ± 0.15 mm compared to the baseline measurements. Hence, this study shows the potential of the crawler system and its capability of reducing costs for dry-docking since necessary measurements can be taken while the ship remains in the water.

1. Introduction

Ship hulls suffer from corrosion, degradation, and mechanical failure due to the constant exposure to saltwater, elevated levels of friction and marine growth. Thus, a demand for regular ship hull inspections and auditing exists to keep ships and their crews save and the transportation of goods economically sound, *Ventikos et al. (2018), Bressy and Lejars (2014).* Several entities have been established, responsible for producing regulations and rules that define the inspection conduct and intervals, as well as provide action plans for subpar ship conditions. Hence, surveys of ships must be conducted frequently but can also include additional or unscheduled surveys (in case of incidents) and depend on the age of the ship. One of the most important parameters examined by a ship certification organization is the thickness of the ship hull in specific areas, *LR (2020).* Up-to-date, these measurements are conducted manually in the dry dock, where the ship must be taken out of the water to be examined by technicians. Even though these dry-docking events are also used to conduct regular maintenance on the ship and, from time to time, apply a new coat of anti-fouling paint, the associated expenses are very high, *Apostolidis et al. (2013).*

The development of underwater robotics has seen significant progress in recent years, in particular for such inspections performed without the need for dry-docking. Here, the group of magnetic crawlers is favored, which adhere to a ship directly and allow for a safe and reliable application of an instrument of choice (e.g., optical system or an ultrasonic thickness gauge) to the ship's hull, *Milella et al. (2017).* Therefore, Fraunhofer CML has developed an alternative method for the ship hull inspection and thickness measuring together with HGK Shipping to reduce dry docking times as well as present a faster and simpler method for incident investigations and reports.

2. The VISION Project

Within the scope of the VISION project, which is an acronym for '**V**essel Hull **I**nspections with Crawler and **S**ensor **I**mproving dry dock **O**peratio**N**s', Fraunhofer CML has developed an alternative method for the ship hull inspection and thickness measuring together with HGK Shipping to allow remote measurements without requiring preceding dry-docking. This alternative method uses a crawler with magnetic wheels, able to attach to and drive along the metal ship hull and use a thickness sensor above as well as below water.
The main objective of the conducted experiments was to show that the crawler system presents a valid

alternative to manual thickness measurements and delivers high-quality results, demonstrating its versatility not only for the type of measurements but also application potential. Therefore, the first goal of the experiments was to determine if the crawler system presents a feasible solution to perform high-quality measurements of the thickness of ship hulls in the dry dock, able to compete with those executed manually by an independent contractor performing the measurements in compliance with the classes standards and able to award the necessary certification for ship operation (hereinafter referred to as the certifying company). The second goal was to determine whether the quality of the crawler measurements would also suffice under water to present a more cost-efficient alternative to inspect the hull thickness (after collisions or grounding events) without the costly effort of pulling the ship out of the water first. Therefore, comparative measurements were taken by a representative of the certifying company in the drydock and repeated by the robotic system in the dry dock and under water to enable a qualitative comparison of measurement results.

3. Materials and Method

For the experiments, the robotic system DT640 MAG Utility Crawler by DeepTrekker was used, which can traverse ship hulls even on vertical surfaces and hanging upside down, above and below water. This crawler has three magnetic wheels that enable the attachment to any ferrous metal surfaces. In addition, it has a zero-turn radius, making it highly maneuverable and allowing the inspection of areas otherwise difficult to access. Using a hand-held remote connected via a tether cable, the wheels and the contained equipment, like the front-facing camera and headlights, can be controlled.

This crawler system also allows multiple add-on's, among others the ultrasonic thickness gauge by the Cygnus, *Cygnus (2014),* that was attached to the crawler with a specialized mount. This mount enables the lowering of the sensor onto the hull’s surface to take the desired measurements. The Cygnus sensor uses a pulse-echo principle as depicted in Fig.1. The sensor head acts as transmitter and receiver simultaneously, and first transmits short ultrasound pulses that enter the object in question. Then, it listens for return echoes that are subsequently converted into electrical signals. The time between the transmitted pulse and the echo is then processed to determine the thickness of the material. Using the complementary Cygnus Software Cyglink, the sensor data can be observed, and measurements logged. The measured values have an accuracy of ± 0.1 mm.

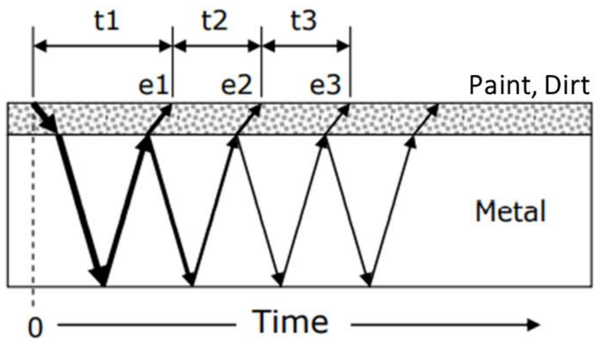

Fig.1: Measurement process of the Cygnus Sensor with multiple-echo beam travel path over time, illustrating the timing method. In reality, the beam path is straight and perpendicular to the surface as the ultrasonic energy reverberates up and down within the metal. A valid thickness measurement is only displayed when t2 = t3. The delay between echoes at the probe face (t2 and t3) is exactly equal to the time taken to pass through the metal twice, therefore coatings such as paint are ignored, and the measurement displayed is the metal thickness only (modified from *Cygnus (2014)*).

Fig.2: Magnetic crawler vertically sitting on a ship hull. The sensor and mount are attached to the crawler, with an overhead camera attached to provide documentation of the measuring process. Further, the crawler is connected to the remote via tether cable and an additional safety rope as a precaution.

For the purpose of the experiments, another downward-facing camera was attached to the crawler using a 3D printed mount to allow detailed documentation of the measuring process. The complete robotic system is depicted in Fig.2.

Since thicknesses along the hull may fluctuate significantly (in part due to different material thickness of the walls and the bottom of the ship), the measurement points were painted onto the hull to ensure the quantification of similar positions for all three measurement activities. For these points, four areas of interest were identified on the ship hull. These areas represent cross-sections at varying distances to the stern and will be referred to as "Ring (A-D)" in the following. In total, 13 points were painted along each ring, while the ship was undergoing routine maintenance in the dry dock. Two points were painted on either side of the ship, one above the waterline at empty cargo (only submerged in water when ship has full payload) and one below (constantly submerged in water). Furthermore, one point was placed directly on the curvature where the wall connects to the bottom of the ship, and the remaining seven points were painted on the bottom as indicated in Fig.3. This figure also indicates the areas at the bow and stern that were traversed by the crawler without the sensor mount to assess the crawler's ability to navigate in particularly difficult positions and locations on the hull.

As initial step to the experiments, a representative of the certifying company took measurements at the indicated points using an ultrasound sensor. A conductive gel was applied between the hull and the sensor at highly corroded points to get a sensor reading. Afterwards, the measurements were repeated using the crawler system, which could not rely on the gel application. The crawler was steered to the indicated points, then the sensor was lowered onto the surface until the software indicated a readable value from the Cygnus sensor. Thickness measurements were then logged using the CygLink software and the measuring approach reiterated three times by lifting and lowering the arm repeatedly to ensure high quality measurements and prevent irregularities from skewing the results. For the data analysis, the average of these three measurements was used. In case the readings were inconclusive, the crawler was moved around to find a measurement spot better suited for a reading. However, all measurements were taken within a 5 cm radius of the original point to ensure comparability.

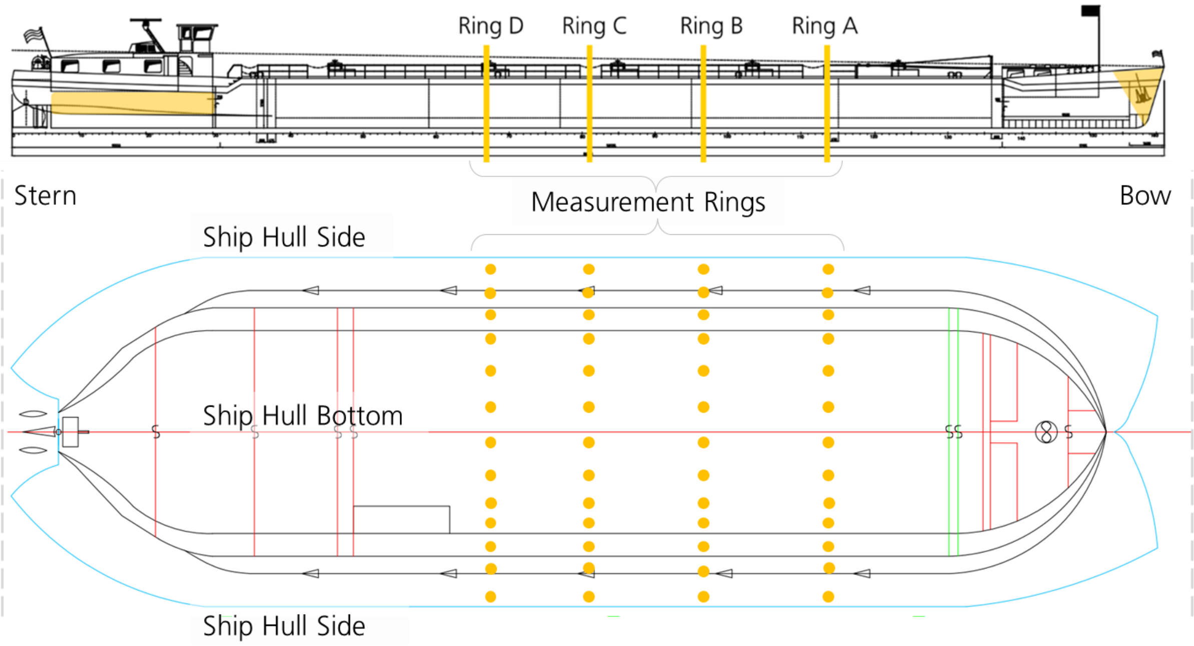

Fig.3: Sketch of the test ship. The yellow lines indicate the locations of the rings with the measurement points that were traversed and measured by the crawler. The yellow highlighted areas at the front and back of the ship indicate the areas that were traversed as a test of difficult terrain without taking measurements.

4. Results

4.1. Comparison of the Three Measurement Methods

All measurements were summarized and compared. Since the crawler measurements were taken three times per measurement point, the values were first averaged and then used for the comparison. The measurements taken by the certifying officials are typically used to determine the need for restoration and maintenance required before a ship can be certified to operate again. Hence, they also served as a reference frame for the real thickness of the hull to assess the quality of the values obtained by the crawler. The crawler measurements in the dry dock and under water were taken on different dates and the components were cleaned and, in case of the sensor membrane, replaced. Thus, deviations between the crawler measurements in the dry dock and under water are less likely to be caused by calibration errors or membrane failure pervading throughout the measurements.

During the measurements, it was determined that the specialized mount holding the sensor was initially designed for flat surfaces only, and hence did not reach far enough down to touch the surface of the hull on the curvature. As an alternative, a side-ways approach was tried, where the crawler was first driven onto the curvature head on and then rotated by 90° to point the sensor towards the measurement point. While this was possible and allowed the measurement of some points, these actions were very complex and even more difficult, due to the constraint camera angle on the crawler, prohibiting a clear view of the point. Based on these difficulties, the points located on the curvature of the ship hull (P3 and P11 for each ring) were excluded from the following comparison. Therefore, the number of measurement points per ring was reduced to 11. After discussions with the ship operator HGK Shipping, a deviation of ± 0.15 mm between the values obtained by the certifying company and crawler measurements was tolerated as it is the common tolerance for the certified measurements.

The measurements for all three methods are presented for each ring in Fig.4. In general, when comparing the results of the three measurement methods, most of the values show very little deviation. The first two rings (A and B) show results very close to the ones of the certifying company with small deviations and most of them below ± 0.15 mm. These deviations do not follow a certain pattern of consistently being lower or higher than the certifying company's measurements but appear to be random. Hence, no clear calibration error of the crawler sensor could be determined, and the measurements adjusted accordingly. The only exceptions are ring A P10, where the measurement on the dry dock deviates from the ones of the certifying company by -0.25 mm, and ring B P13, where both crawler measurements in the dry dock and under water deviate from the certifying company ones by 0.63 and 0.77 mm, respectively.

At Ring C P5, the last of the three measurements was accidentally logged while the value was still fluctuating and resulted in an abnormally large thickness measurement. However, since no fourth value was recorded when the measurement had stabilized, this abnormally high value was excluded from the calculations and only the two other values were used for calculating the mean. The rings C and D show more deviations than the first two, and measurements of ring C show the highest number of deviations, regardless of dry dock or underwater measurements. At P2, P8, P10 and P12, the resulting values obtained in the dry dock deviate from the certifying company's measurement by -0.22, 0.2, 1.35, and -1.2 mm, respectively. Similarly, the points P1, P2, P10, P12, and P13 show deviations of 0.27, 0.35, 1.03, -1,25 and 0.2 mm under water, respectively.

Comparing the measurements of the dry dock and the certifying company for ring D, the points P4, P7 and P10 indicate greater deviations. At P4, it was impossible to measure any thickness while the ship was in the dry dock due to high levels of corrosion at the selected point and the area around it with a 5 cm radius, even after multiple tries. Thus, the value for the dry-dock comparison is missing. Yet, it was possible to measure the thickness under water. Therefore, only the values measured by the crawler under water and the certifying company can be compared. Furthermore, P7 showed high deviations of 0.6 mm in the dry-dock and P10 of 1.27 mm during the underwater measurements.

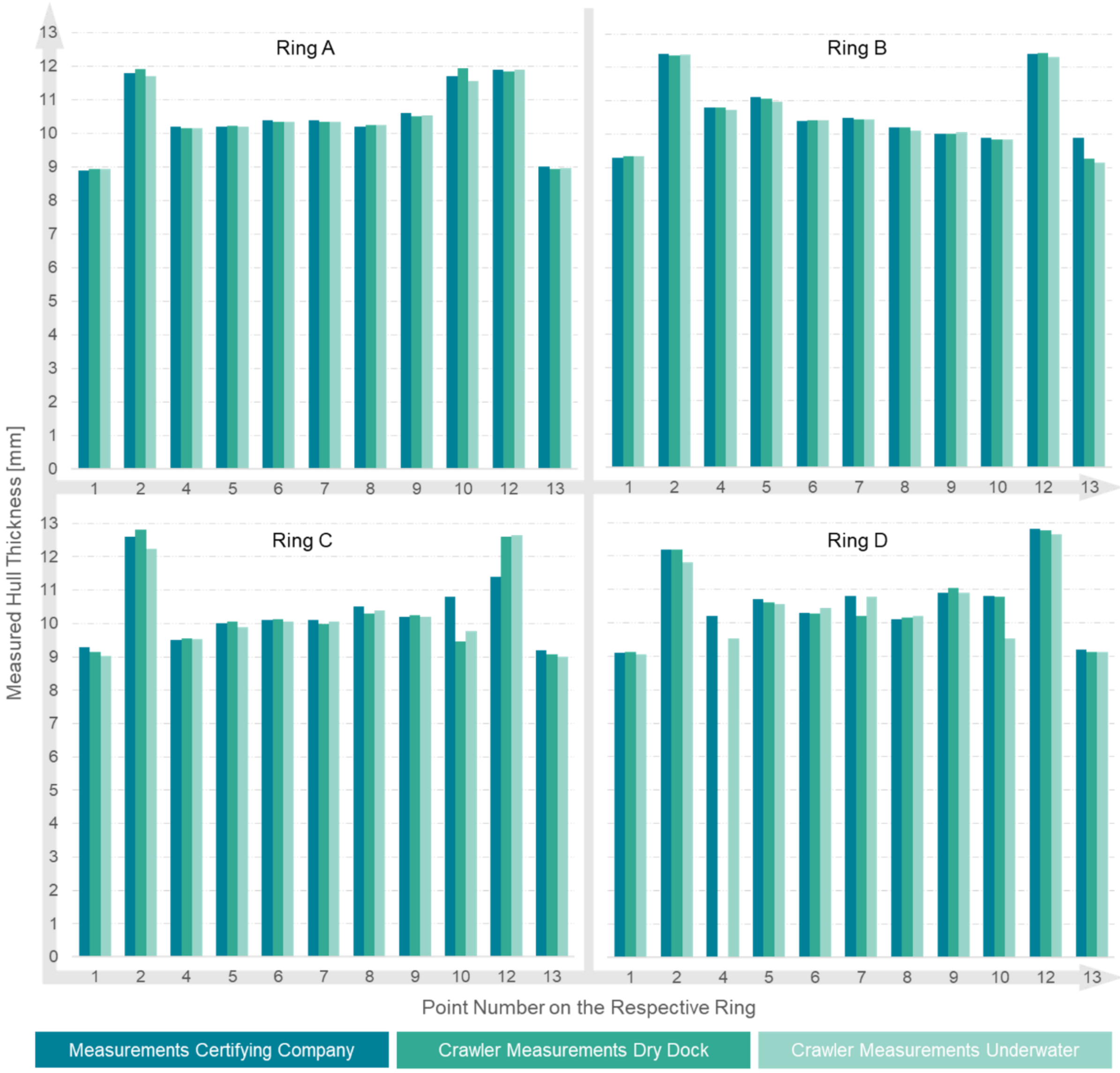

Fig.4: Comparison of the thickness measurements resulting from the three different measurement methods for ring A, B, C and D. The points '3' and 11' were omitted due to the difficulty of using the given robotic systems to reach the hull surface with the sensor on the curvature.

4.2. Navigating the Crawler on the Ship Hull

While traveling on the surface of the ship hull, the crawler system encountered several artifacts and surface structures like heavily corroded and therefore uneven surfaces, abrupt edges from steel plates, as well as vertical and horizontal welding seams as depicted in Fig.5. None of these artifacts or obstacles presented a significant challenge for the crawler to traverse the hull. While the effects were slightly larger during dry-dock measurements due to the prevalent gravity and its effects on the crawler's weight, they did not present a limitation for crawler navigation on the hull.

As indicated in Fig.3, the bow and stern were also traversed. Traveling on the bow in the dry dock and overcoming its narrow curvature was no problem for the crawler, Fig.6. Again, the gravity acting on the crawler impeded a smooth transition from one side to the other especially on the bottom of the bow; however, did not render the task impossible. Contrary, the stern was traversed while the ship was back in the water. Here, the encountered limitations were not displayed by the crawler system itself but the limited visibility in water and subsequent lacking localization of the crawler on the hull, which made it too risky to pursue further investigation of anchor, shafts, or propeller by the crawler, Fig.7.

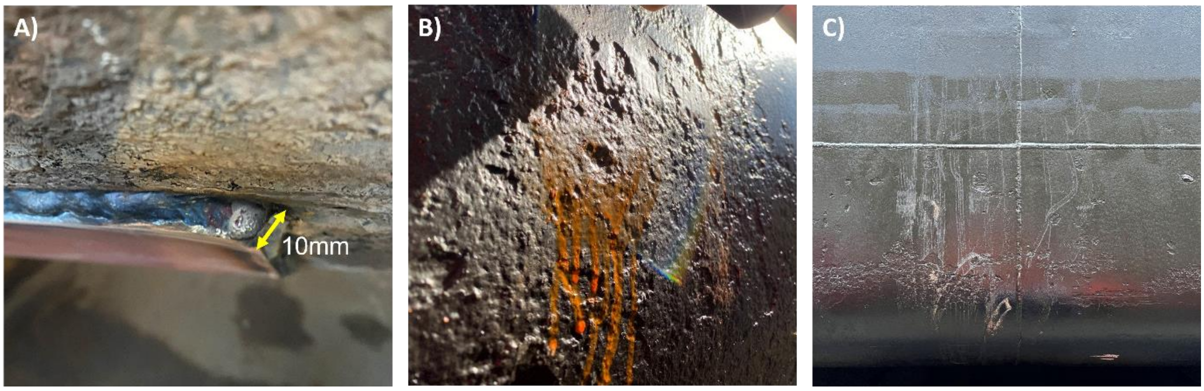

Fig.5: Hull surface structures encountered by the crawler system: A) Steel plates pre-paint coating (thickness ~10 mm), B) high levels of corroded surfaces creating small craters and uneven surfaces, C) vertical and horizontal welding seams (height ~5 mm).

Fig.6: Crawler traversing the bow of the boat. As shown, the crawler is able to drive over the curvature even hanging upside down, and therefore move from one side of the ship to the other with only minor difficulties.

Fig.7: Photo capturing the limited visibility under water, which prohibited the traversing other features of the stern due to an increased risk of entanglement or damage to the crawler system without the means of retrieval.

5. Discussion

5.1. Measurements and Data Quality

The measurement deviations between the three methods do not follow a consistent pattern, which does not indicate a calibration or measurement error. However, 84 % of the dry-dock measurements and 77 % of the underwater ones remain within the tolerable limit of ± 0.15 mm, resulting in a total success rate of ~81 %. Therefore, measurements can be interpreted as fairly accurate. In addition, most of the crawler measurements taken in the dry dock and under water show deviations smaller than ± 0.1 mm among themselves, indicating that the quality of the crawler's measurements is consistent. These small deviations can be tolerated, since the sensor placement at each point may have varied slightly and the additional effect of water between the hull surface and the sensor membrane.

In general, the measurements for the three techniques show very little deviation with a few exceptions. Even though much effort was put into ensuring the measurement of the same points by the certifying company and the crawler in the dry dock and under water, it was not always possible to achieve measurements on the same spot, which may be due to high corrosion levels of chosen surfaces or other interfering factors. Therefore, the sensor did not always measure the exact same position but rather close to the pre-defined point. This can explain the differences between the measurements of the certifying company and the crawler at, for example, Ring B P13, and Ring C

P10 – P12, since the crawler's measurements above and below water show little deviation, making an incorrect measurement less likely. Due to the high number of deviating measurements determined for ring C and three of them occurring at the same position in the dry dock and under water, accidental measurement errors are unlikely. Especially since the values of the crawler taken in the dry dock and under water at these points show little deviation among themselves. The exceptions are points P2 and P10, where the crawler measurements show differences of 0.31 and 0.18 mm, respectively. Thus, it can be assumed that the difference to the certifying company's measurements may be due to highly corroded surfaces requiring crawler measurements to be taken at a slightly different position than indicated on the hull in the previously described radius of 5 cm around the point each time.

The crawler measurement for ring D P4 was only possible when the sensor was submerged under water and not in the dry dock, showing that the water can be an important conductor that aids the measuring process at highly corroded surfaces. Similarly, the representative of the certifying company uses conductive gel to circumvent complications with reading on highly corroded surfaces. This results in a better alignment of the sensor with the surface and enables the reading of the echo signals, without influencing the thickness readings. This suggests that the crawler reading could be improved and the deviation to the measurements of the certifying company reduced when using a conductive gel.

As stated in section 4.1, the range of the sensor mount was limited and did not offer a ready solution for measuring the points on the curvature. When approaching the point sideways in the dry dock by driving on the curvature perpendicular to the ring, the crawler proceeded to slide to the bottom of the ship due to its own weight in air and the experienced gravitational pull. In water, the crawler was able to maintain its position on the curvature due to the reduced weight of the crawler in water. Nevertheless, lack of visibility in the water and the limited orientation of the crawler's front-facing camera resulted in great difficulties when navigating on the curvature. While it was possible to collect data for some of those points on the curvature, their quality comparability remains questionable. Thus, while it is technically possible to measure points on a curved surface, alterations of the sensor mount are required to enable a safe and viable measurement.

5.2. Technical and System Limitations

The crawler system and chosen method of experimentation both display multiple technical limitations, which in turn impact not only the data quality but also the comparison between the crawler readings and those generated by the certifying company. Even though much effort was put into ensuring the measurement of the same points by both methods in the dry dock and under water, it was not always possible to achieve this on the exact same spot due to high corrosion degrees of the chosen surfaces or other interfering factors. Therefore, the sensor head was rearranged around the indicated point until a stable measurement was possible. This may cause differences between the measurements of the certifying company and the crawler at, for example, Ring B P13, Ring C P10 – P12, since the crawler's measurements above and below water show little deviation among themselves, making an incorrect measurement less likely.

As previously discussed, the limited range of the sensor arm caused great technical difficulties in measuring the points situated on the curvature. While these difficulties could easily be solved by redesigning the sensor mount and changing the angle of the camera in the future, it caused significant hindrance during the experiments on site.

Furthermore, for the measurements conducted by the certifying company, conductive gel was applied to the designated point to aid measurement of corroded surfaces and their sensor is a hand-held device that can be manually aligned on the hull surface to generate an ideal reading. At severely corroded areas, the certifying company usually goes so far as to sand down the designated measurements spots to create a smooth surface (which was purposefully avoided during the experiments). In contrast, the sensor on the crawler is controlled by a remote and is limited by the mechanical features of the mount and the connected ball joint. Moreover, while the sensor itself is covered by a thin protective membrane, it does not use any conductive gel between the membrane and the ship hull that would improve thickness readings. Certainly, technology exists that would allow either the application of the conductive gel on the hull under water prior to crawler measurements, attaching an additional arm with a sanding machine or include a thicker and more flexible membrane pad that could demonstrate the same features as the gel. Despite this major difference between the measuring methods, the crawler and Cygnus sensor yielded measurements of good quality.

At points where the readings between the certifying company and the crawler measurements differ greatly, several reasons can be assumed. First, the measurement points identified prior to the measurement process were not ideal for the crawler system and thus prohibited measurements on exactly the same spot. Secondly, the readings of the crawler were repeated three times each in the dry-dock and under water and an average was used for the analysis, while the measurements of the certifying company were taken only once. Thus, they do not account for potential miss-readings or errors.

5.3. Environmental Limitations

The ship hull presented a number of interesting features for the crawler to traverse. While none of these artifacts presented an issue for the crawler in terms of driving across the surface, especially the welding seams and the ship's internal metal walls (spaced in regular intervals for stability and segmenting the inner compartments) demonstrated a difficulty for the measuring process for all three measurement methods. The sensor requires an even surface to transmit and receive the ultrasonic wave and be able to acquire a sensible reading and cannot be placed directly onto a welding seam or point, where the wall connects to an internal wall. While several actions can be taken by the certifying company to cope with uneven surface structures (conductive gel, sanding machine), these particular features cannot be altered and must, therefore, be avoided with the crawler system. Thus, the location of all surface features must be known in advance to present measurements on these spots. The certifying company has the advantage to inspect the hull visually and identify these features prior to the measurement process. For the crawler system, their identification and avoidance are much more difficult, especially under water.

Another difficulty playing into the detection of features by the crawler, especially under water, is the limited visibility. Ship inspection and maintenance takes place in shipyards, where the water is shallow and well traversed, which disperses soil particles in the water column, and are usually polluted with all kinds of substances. Hence, water quality and visibility are often low, making an optical-based camera system for the detection of features, position and damages on the ship hull difficult. These challenges could be overcome with a digital model of the ship hull and included features or obstacles used to navigate the crawler to the appropriate measurement positions on the hull. Similarly, such a model would also allow a simplified tracking of not only areas to inspect but also areas of high risk or points of interest after collision events. All of the information available combined within a model could also enable various simulations and present the starting point for a real-time localization scheme of the crawler on the respective ship hull, opening the doorway to autonomous inspection and measurements. As an alternative to autonomous localization, an observation tool based on a different detection mechanism such as multi-beam echo sounders could be used instead to detect and inspect the surface of a ship hull, regardless of the water quality and dispersed particles in the water.

When comparing the general logistics and method for the crawler to the certifying company’s measurement process, it becomes apparent that the method and robotic system require improvement before presenting a valid alternative to replace the thickness measurements conducted by the certifying company. In addition, the method would need to undergo the certification process of the ship certification organization before it could be accepted as measurement method. Nevertheless, the chosen approach shows that the overall quality of the measurements is feasible for thickness measurements, and thus should be developed further in the future.

5.4. Existing Concepts and Industry Applications

In recent years, the interest for autonomous robotic survey and inspection of marine infrastructure and transport vessels has increased significantly. Hence, various approaches exist that use different robotic systems and observation tools for a diverse field of applications. These applications range from hull cleaning, *Song and Cui (2020),* and inspection, *Hong et al. (2019), Ventikos et al. (2018), Bogue (2018), Kurc et al. (2019),* to more complex tasks of thickness measurements, *Enjikalayil Abdulkader et al. (2020),* and even autonomous welding, *Kermorgant (2018).*

Depending on the task and respective requirements, some systems and tools are more suitable than others. For the detection of damaged areas after grounding events for example, remote operated vehicles (ROVs) with a sonar, *Wang et al. (2019),* or stereo vision, *Hong et al. (2019),* are an appropriate choice, as these systems can be employed on the spot without requiring dry-docking. In addition, an ROV can cover a large hull area quickly and identify surface structures and shapes. This is especially practical when the exact area of grounding or contact is unknown. In contrast, a crawler-based system can traverse almost the entire area of the ship hull once the ship is in the dry dock. Thus, water levels and submersion of the ship do not play a role when aiming to inspect a diverse range of points on a ship hull. Furthermore, a crawler system is not impacted by possible waves and current flows under water and thus reduces the amount of energy required since it does not have to steer against external forces and correct its position as ROVs have to, *Gabi et al. (2020)*. Examples for crawler-based inspection and measurement methods are presented by the MARC system using a low-cost monocular camera for visual, *Milella et al. (2017),* and a lightweight crawler using a video camera for visual inspection of ship hulls, *Eich et al. (2014),* for on-land applications. One of the only crawler systems for ship hull thickness measurements available was proposed by *Enjikalayil Abdulkader et al. (2020)* called Sparrow, using a similar technique of ultrasonic measurement and magnetic wheels as the VISION crawler to adhere to and measure thickness of ship hulls. A short comparison of the two systems is displayed in Table I. While the two crawler systems present similar masses and dimensions, differences exist that create distinct contrasts between the two systems. One major advantage of the crawler system used within the VISION project is that it can be used above as well as under water. Thus, it is not limited to the use in the dry dock like the other crawler or to use under water like ROVs. Dry-docking is an expensive undertaking and poses risks to workers and surveyors on sight, demanding the crawler's connection to an additional safety rope, making maneuvering more complicated. Other advantages of the VISION crawler are that it has only three wheels, one of which omni-directional, thereby increasing its maneuverability and decreasing its turn radius, making it very suitable for the navigation and manipulation in tight areas difficult to access. While it is able to travel with a speed of up to 0.2 m/s, the Sparrow crawler demonstrates a higher maximum velocity of about 0.6 m/s. Furthermore, the latter displays a larger thickness measurement range of 0.08 to 635 mm, while even the 2.25 MHz probe for the Cygnus sensor only displays a range of 2 to 250 mm. Still, this range was deemed sufficient for the application of ship hull thickness measurements. While the camera on the Sparrow crawler is mounted on the front in a similar position as the VISION crawler, its thickness sensor is attached in the center underneath the robot's body, making it impossible to observe the sensor before and during the measurement activities. In contrast, the mount holding the sensor on the VISION crawler is also attached in the front, enabling the use of the front-facing camera to check the sensors position and orientation during the measurement process. This way, errors associated with the position of the crawler or potential damage to the sensor membrane can be observed and corrected much faster. Yet, the Sparrow crawler presents a certain level of autonomy and does provide the opportunity to log the measured thickness together with the current position of the robot, making the tracking and documentation much simpler. This presents only one of the features to be added to the VISION crawler during further development and improvement, aiming to create a fully autonomous and reliable inspection and thickness measurement procedure. In addition, the VISION crawler system presents the opportunity of exchanging the sensor mount by several different add-ons such as a pressure washer, vacuum head, and dozer attachment readily available and even custom-made tools, making it a very diverse system, applicable for many tasks and activities.

Table I: Available crawler systems, giving dimensions, measurement characteristics and speed of the Sparrow crawler introduced by *Enjikalayil Abdulkader et al. (2020)* with the one introduced within this study (VISION crawler).

	Sparrow Crawler	**VISION Crawler**
Mass [kg]	14	16.6 (excl. sensor + mount)
Dimensions (LxWxH) [mm]	400 x 300 x 100	710 x 406 x 228
Type of Adhesion	Magnetic	magnetic
No. of Wheels	4	3
Maximum Speed [m/s]	0.6	0.2
Camera Specifications	Wi-Fi HD 1080p	700 TVL 0.0001 lux
Thickness Sensor	Olympus 38DL PLUS ultrasonic thickness gauge	Cygnus ROV mini mountable thickness gauge
Sensor Range [mm]	0.08 – 635	2 – 250
Areas of Application	On land	On land, under water

6. Conclusion

The experiments performed within this project have shown that the crawler system can be used to determine the thickness of ship hulls and deliver satisfactory results. It may not replace the measurements taken by the certifying company as they are faster, and the crawler system does not entirely prevent the need for dry docking of the ship since it must undergo further maintenance and inspections on the hull as well as inside for its certification. Furthermore, the introduced method and robotic system requires technical development and improvement before presenting a valid alternative to thickness measurements like they are currently conducted.

Nevertheless, it proves to be a great alternative for dry docking after grounding events or inspections of critical areas and should therefore be developed further. Thanks to the modularity of the system, new approaches can be implemented and added, presenting a diverse and interchangeable tool, adaptable according to customer needs. Especially within the maritime industry, other interesting applications would include inspecting not only ship hulls but other structures like harbor infrastructure, pipes or wind turbine shafts as well using different types of sensors and scanning equipment, surveying chemical tanks, which is otherwise very costly, risky, and time-consuming, or re-applying anti-fouling coatings.

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Survey on Biofouling Management and Anti-fouling Systems

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Abstract

In September 2021, BIMCO conducted a biofouling survey to gain an insight into how shipowners and operators are managing biofouling and in-water cleaning as well as learn from their first-hand experiences of using anti-fouling systems (AFS). The survey collected information on biofouling management from entities that had a direct link to ships and AFS. Responses from 53 companies representing 5,668 ships have been analysed.

1. Introduction

BIMCO conducted a biofouling survey among shipping companies (both members and non-members) during a four-week period starting in September 2021. The aim of the survey was to collect information on biofouling management directly from entities that had a direct link to ships and AFS. The survey results are listed below.

2. Survey

The responses from fifty-three companies with a direct link to ships and AFS were analysed in detail. These 53 companies represented 5668 ships, which accounts for 8% of the world merchant fleet. (Note: The Seafarer Workforce Report calculated the world merchant fleet at 74505 ships in international trade. The number does not include ships operating on domestic voyages and tugs less than 300 GT.)

Out of the 53 companies, 43 identified themselves as being a ship owner or operator, 9 as a ship manager, and 1 as a trading company, Fig.1. Fig.2. shows the geographical spread of the respondents.

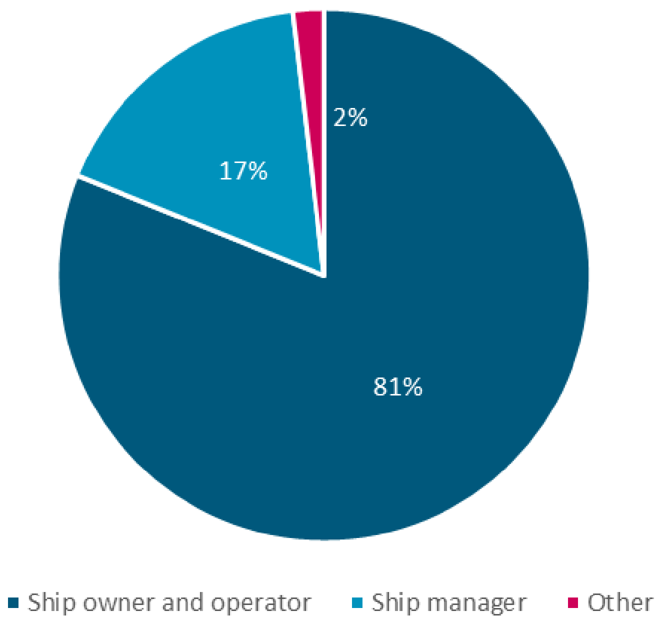

Fig.1: Type of participants

42 of the 53 companies (79%) reported that biofouling management was implemented onboard their ships. The remaining 11 companies reported that no biofouling management had been implemented onboard. This can be attributed to the fact that the guidelines are voluntary in nature and not easy to follow. Also, another contributing factor could be the poor infrastructure in many ports such as the lack of high quality in-water inspection and cleaning services.

Fig.2: Geographical composition of survey respondents (HQ location)

Participants were asked about their experience with biofouling management and the AFS used on their ships. As every participant was asked to give details of up to 3 AFS on board their ships, the survey received information on 88 AFS. Although some were repeated, the AFS have not been grouped into specific brands and/or types because each AFS is considered a separate and distinct system as they were applied onto different ships operating in different conditions.

The average lifetime of the AFSs was found to be 4.92 years.

67 of the 88 submissions claimed a lifetime of 5 years, while rest claimed a lifetime of either 2, 2.5 3,7, 10 or 20 years. The AFS that claimed 2.5- and 3-year lifetime were used on ships which follow a 2.5 yearly dry-dock cycle, Fig.3.

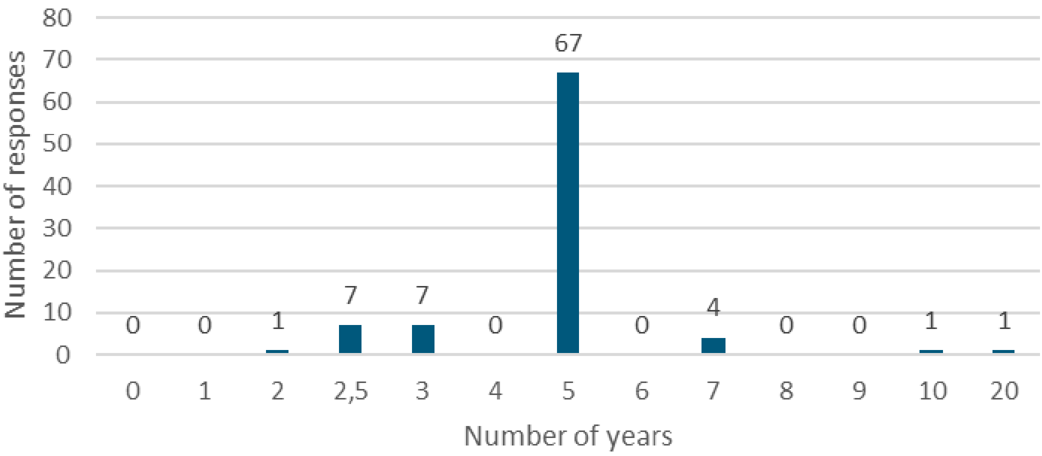

Fig.3: Claimed lifetime of anti-fouling systems

The survey also asked about the effectiveness of the AFS. Here, the effectiveness of AFS is described as its ability to prevent or control the attachment of unwanted organisms on the ship's submerged surfaces, including the hull and niche areas. The question focussed on whether or not the AFS had fulfilled their claimed lifetime, any deviation from which was noted by the users of the AFS. Fig.4 provides details on the outcome.

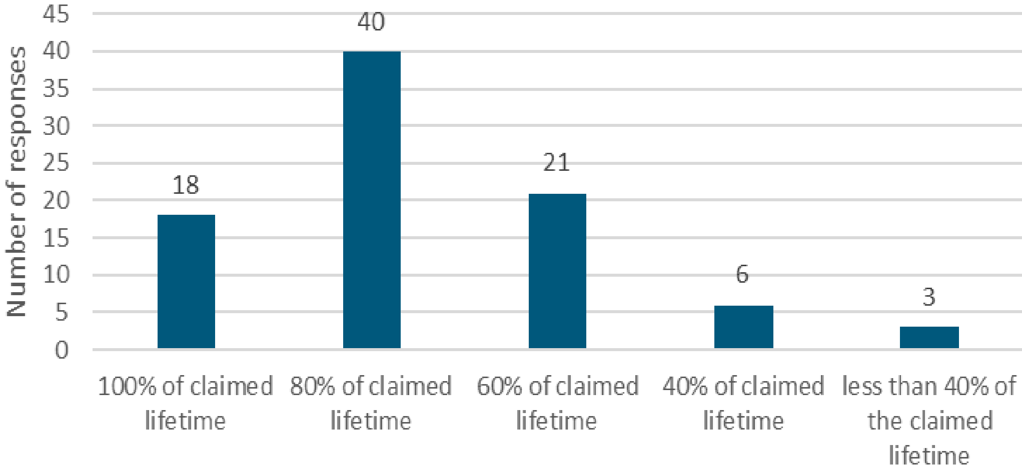

Fig.4: Percentage of lifetime during which the AFS was effective

As can be seen from Fig.4, 90% of the AFS surveyed lasted 60% or more of their claimed lifetime and 66% of the responses stated that the AFS lasted more than the 80% of the claimed lifetime.

From the survey results, it seems that three AFS may have failed for unknown reasons as they were effective for less than 40% of the claimed lifetime. The reason for the failure of an AFS can be anything from low quality of the product itself or bad application in a shipyard to the ship having prolonged idle periods or damage happening to the surface during cleaning or cleaning at too frequent intervals.

In this case, it is believed, that the AFSs may have failed due to other reasons than just a bad quality product. This hypothesis is built on the fact that other respondents reported that the AFS in question was performing much better.

For an AFS to last long, several factors must be in place:

a) The AFS manufacturer's required conditions should be optimal regarding application of the AFS in the shipyard including the temperature, humidity, weather conditions and standard of workmanship.

b) The ship should be operating according to its planned profile, which amongst others includes the geographical area, the water salinity, speed and idle periods.

c) The AFS should not suffer any physical damage eg by tugs, fenders during port stay etc.

d) Cleaning should be carried out with care and only when needed. Cleaning will have an impact on the surface of the AFS as it will remove or roughen its top layer. Therefore, the frequency and quality of cleaning play an important role in maintaining the effectiveness of the AFS. Too frequent cleaning and/or use of an inappropriate method of cleaning may lead to an impairment of the AFS, which will reduce its effectiveness and ability to last as long as predicted by the paint manufacturer. (Note: Hard coatings are excluded as hard coatings are not meant to be anti-fouling coatings and do not actively avoid the attachment of biofouling on it.)

Therefore, when an AFS fails for any reason other than poor quality, the factors contributing to the failure need to be carefully assessed and corrected to avoid future failures.

3. Methods used to assess biofouling growth

42 respondents replied to the question in the survey about the methods used to decide whether an inspection and/or cleaning should be carried out. Fig.5 shows the answers.

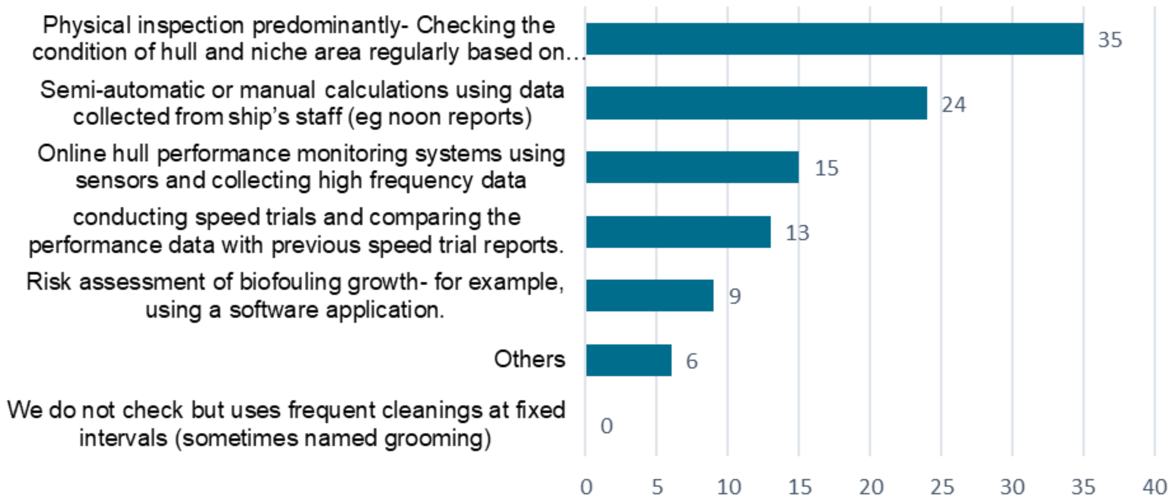

Fig.5: Responses to used methods to assess the condition of biofouling

This part of the questionnaire was not visible to the respondents, who said “No” to using biofouling management. The most popular method was a physical inspection. The questionnaire did not ask for details about the inspections. The next three most popular methods are semi-automatic or manual calculations using data collected from ship’s staff (eg noon reports), online hull performance monitoring systems, as well as conducting speed trials to compare the performance against the energy consumption of the ship. These methods mainly calculate the fuel consumption and compare it with the speed of the ship under given conditions, including cargo quantity, trim etc whilst making allowances for the prevailing weather and sea conditions including water current. The result will indicate an estimated amount of biofouling growth on the ship’s hull.

Some of the answers in the “others” category were:

- “Some ships have been at anchorage for long time, waiting to load or discharge cargo (>30 days) that's why it has been necessary to carry out under water cleaning and propeller polishing”
- “Port requirements”
- “Depends on idle days, and trading patterns internationally”
- “Under water inspection based on earliest indication of rising fuel oil consumption in main engine”

Several respondents use more than just one method to assess the growth of biofouling, Fig.6.

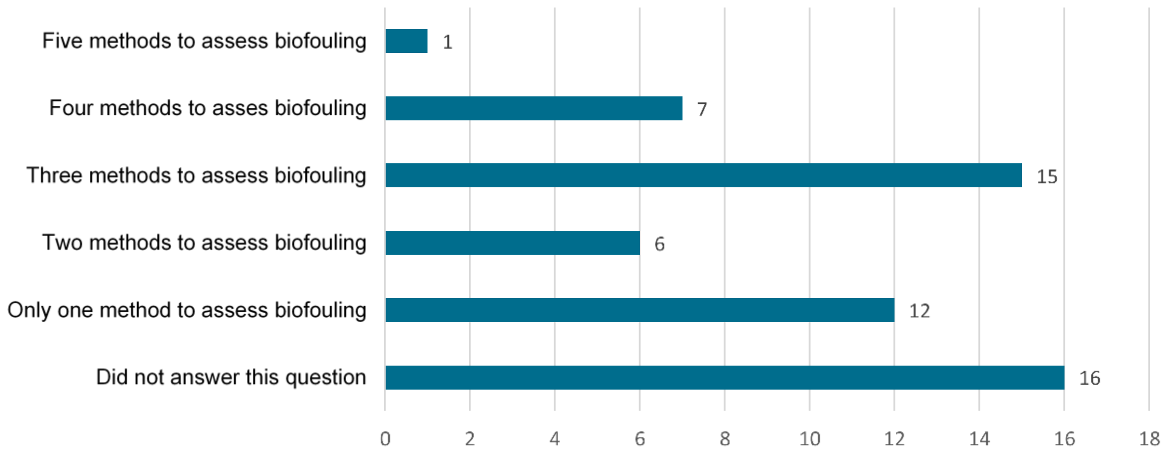

Fig.6: Number of biofouling assessment methods used by respondents

4. Cleaning of a ship's hull

The survey gathered information on the frequency of cleaning (either in-water or out of water cleaning).

A build-up of biofouling on a ship's hull results in hull drag, which has a direct and negative impact on the performance of the ship in terms of loss of speed. To compensate for this loss of speed, the ship must increase its power, which results in higher fuel consumption. The only way to reduce this financial impact is to remove the biofouling by cleaning the ship's hull. Therefore, stakeholders have a direct financial incentive to ensure that biofouling is removed before the growth becomes significant.

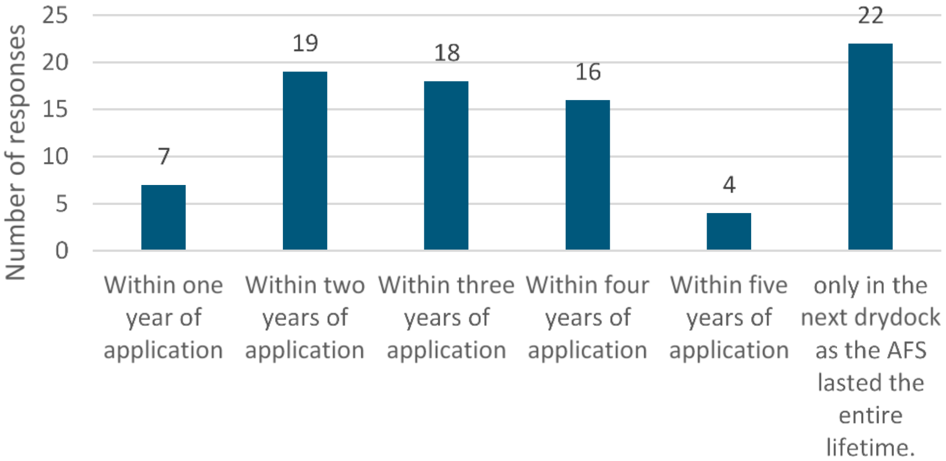

Fig.7: Cleaning for the first time after dry-dock

Fig.7 shows this data. The largest group of 22 AFS (26%) were so effective that biofouling growth was only found when the ships entered the drydock after completing their dry-dock cycle. The majority of cleaning is conducted between second and fourth years of ship in service. Only 7 (8%) of 86 responses claimed that the AFS needed a cleaning within the first year of application. This included non-toxic paints that, by design, need to be cleaned frequently during their lifetime.

On average, the AFS needed to be cleaned less than twice (1.84 times) during a period of five years, Fig.8. 18 AFS required no cleaning in five years but a majority of 50 needed one or two cleanings in 5 years whilst 14 were cleaned three times during that period. One AFS needed to be cleaned 5 times in 5 years, while one more AFS needed to be cleaned 10 times. These seem to be caused by an AFS failure. One AFS, which was cleaned 20 times in 5 years, was a hard coating without toxic properties. Such hard coatings are designed to be cleaned frequently to remove the biofouling growth and to maintain a smooth hull.

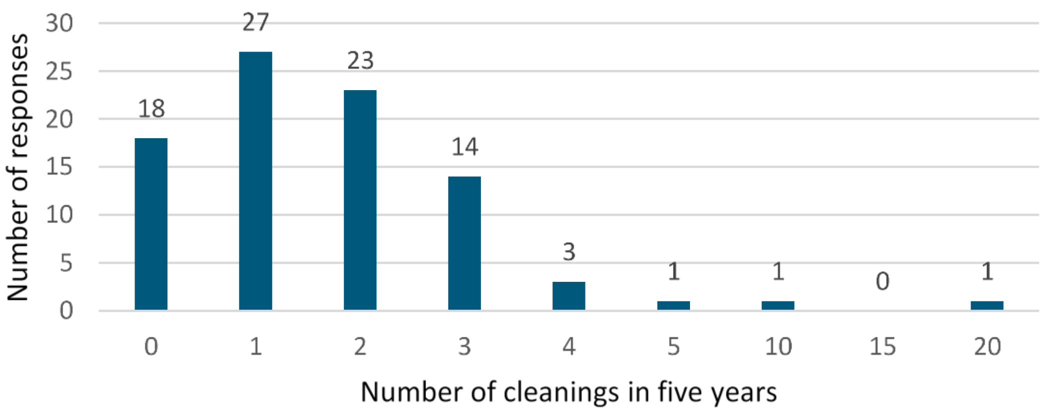

Fig.8: Number of cleanings in 5 years

Furthermore, in most trades involving time charter, the ship is cleaned prior to handover of the ship between the charterer and the owner. This is also the case in offshore trade even for ships (offshore boats) the continue to work in the same area. Between the old and charter, the ship will often have a long idle period that leads to the growth of biofouling. In most cases, these ships are cleaned every time there is a change of charterer, even if the charter party has lasted only a few months.

5. Challenges in the survey

While the survey managed to gather some good insights into how shipowners and operators conduct biofouling management, there were some challenges in answering the questionnaire. It is not easy to generalise answers for a large fleet especially if the ships have different working profiles. For example, it is hard to accurately estimate the effective lifetime of a particular AFS, which is used on different ships operating in different trading routes and geographical conditions, all of which affects its lifespan.

Furthermore, not every company follows the popular 5-yearly dry-dock cycles. There are companies that dock their ships every 2.5 years. This adds another level of complexity when estimating the average lifetime or effective lifetime of AFS. Despite the challenges in gathering and analysing the data, the survey provides some interesting insights into the biofouling management practices currently being followed.

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Replacing Dry-Dock or UWILD Hull Inspections with ROV Visual Inspections

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Abstract

This paper describes how the use of Remotely Operated Vehicles (ROVs) are utilized for vessel inspection for: (1) Evaluating Physical Integrity - There were 49 large class ships lost and 2,703 shipping incidents in 2021 alone. With physical damage being the leading cause of incidents (40%). Additionally, ROVs can be used as a tool for ship owners to instantly inspect for damage, paint status, and other areas requiring maintenance. (2) Improving Port Security - Seizures of cocaine aboard commercial ships and private vessels world-wide more than tripled over the past three years, to 73.2 metric tons in 2019 from 22.4 metric tons in 2017. ROVs are ideal for underwater contraband inspections on a moment's notice. (3) Uncovering Invasive Species - Approximately 42% of threatened or endangered species are at risk due to invasive species, many of which are carried over on shipping vessels.

1. Introduction to Remotely Operated Vehicles for Vessel Inspections

Remotely Operated Vehicles (ROVs) are unoccupied, highly maneuverable underwater robots that can be used to explore underwater depths while being operated by a person at the water's surface, *NOAA (2019*). Protecting the integrity of a ship's hull is extremely important to keep a vessel at peak performance. In addition to negatively impacting speed and fuel efficiency, a damaged hull can be harmful to the ship, crew, cargo, and surrounding marine life. While regular hull inspections are a necessity for optimal vessel performance, they can be difficult. In addition to being expensive, dry docking takes ships out of commission for extended periods of time. Hiring divers for UWILD inspections not only requires substantial time and money, but also potentially puts people into dangerous situations. With ROVs providing an efficient method of hull inspection, vessels can be consistently monitored to optimize maintenance schedules, maximize performance, and limit environmental impacts.

2. Dry Dock Surveys

Fig.1: Cargo vessel dry-docking

To abide by SOLAS requirements, merchant vessels and cargo ships to perform a complete hull survey an average of once every 2.5 years, with intermediate surveys every 36 months. Any passenger vessel is subject to annual inspections, with at least two occurring by dry dock every five years. Depending on the size of the vessel, location, nature of required repairs, etc., estimated cost of each dry dock inspection can cost upwards of $1 million USD for larger ships. This forces a substantial repeating cost, and vessel owners are subject to guesswork at ideal times to conduct surveys.

3. UWILD Surveys

Underwater Inspections in Lieu of Dry Docking (UWILD) inspections are an alternative to traditional dry-docking methods of vessel inspections. During a UWILD, commercial divers will enter the water to conduct visual inspections without taking the ship out of service. This effectively reduces downtime, travel time to docking ports, and can potentially cut costs. While SOLAS still requires dry docks to be performed, UWILDs can alleviate these issues for intermediate surveys or for three of five passenger vessel inspections. Additionally, UWILDs may be performed in conjunction with dry-docking to allow optimized repairs or repainting before major issues or degradation of performance from biofouling can occur.

4. The Core Areas of Inspection and Repair

One of the main causes for inflated costs of dry-docking is the nature of the repairs needed. Allowing minor concerns to compound into major issues will not only affect the performance of the ship, but heavily increase required repair costs during required inspections. Some common submerged assets that are subject to repair include sea chests, hull exteriors, sacrificial anodes, and propellers/steering gear, *Wankhede (2019).* Accumulation of biofouling, damage from running aground, or general wear and tear and cause significant inefficiencies or even create a dangerous work environment if left unattended. One of the difficulties vessel owners' faces is a lack of understanding of their submerged assets due to difficulties performing quick visual inspections.

4.1. Biofouling

Biofouling refers to the accumulation of marine organisms on a submerged asset. If larger organisms such as mussels, barnacles, or soft corals accumulate as 'macrofouling', the additional drag can result in excessive fuel consumption. According to a recent study from the Acquisition Directorate Research & Development Center, the cost associated with biofouling in the United States (U.S.) was estimated to be as much as $120B per year in added fuel costs from added drag, *Heaslip (2021).*

Additionally, biofouling can result in the transportation of invasive species, which carries a wide variety of negative environmental impacts, https://www.nwf.org/Educational-Resources/Wildlife-Guide/Threats-to-Wildlife/Invasive-Species. For example, "when freighters load up and empty ballast water from local sources, they risk introducing invasive species to their destination. Scientists believe that these ballast tanks brought the zebra mussels, native to southern Russia and the Ukraine, to the Great Lakes", *NN (2019).*

4.2. Damage

Physical damage can occur overtime with general wear and tear, or suddenly with an abrupt contact with the seafloor, physical protrusion, or other vessel. Historically, there has been no method of conducting a quick internal inspection to evaluate for damages while the ship remains in service. Since protocol dictates a visual inspection after any collisions, this resulted in excess dry-docking, adding travel time to ports, downtime, and large inspection costs; all on the suspicion of a required repair which may or may not be needed.

4.3. Vessel Security

With drug seizures are on an upward trend in the U.S. throughout the 2010s, it has become apparent that ports are being targeted for the smuggling of illegal substances. While the GAO, https://www.gao.gov/, recommended three courses of action for the CBP to improve port security, another method to limit the entry of illicit substances is to locate them at the source. In some circumstances, the vessel crew can be completely unaware of illegal drugs or weapons being stowed away. With no method of conveniently conducting routine external inspections, it becomes possible for smugglers to store contraband without being detected by the onboard crew.

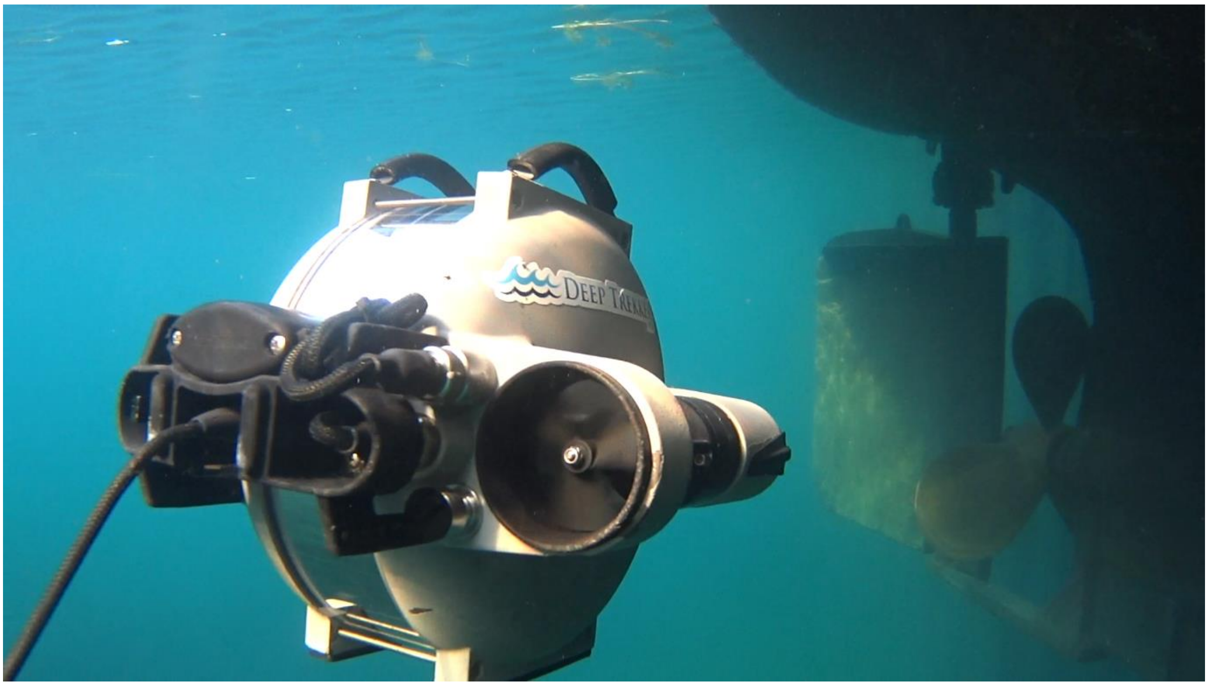

Fig.2: ROV inspecting a ship propeller

5. Remote Operated Vehicles for Intermediate and Ongoing Visual Inspections

In 2002, an adjustment was made in relation to SOLAS requirements of visual merchant and passenger ship inspections (The Federal Register), https://www.ecfr.gov/current/title-46/chapter-I/subchapter-T/part-176, which allowed approved remotely operated vehicles (ROVs) to be used. This change marked a major advancement in empowering both vessel owners as well as commercial dive teams to utilize a much safer and quicker method for effective ship inspections. Advancements in ROV technologies over the past few decades have transformed what were once large and extremely high-cost devices into compact inspection machines capable of a wide range of maritime tasks.

5.1. Conduct & Record inspections

ROVs are equipped with the ability to record video and save images instantly to either SD cards or external computers/hard drives. Capturing and maintaining consistent video recordings or snapshots of key features allows for more thorough evaluation, since the evaluating team will have complete control over what is recorded in comparison to a contracted dive team. Rotating camera heads allow operators to adjust camera angles rather than adjust the vehicle pitch, allowing the ROV to simply forward for a seamless video of different assets. By using an approved ROV to conduct intermediate visual inspections, vessel owners can limit their paid inspections to the minimum legal dry-dock requirements.

Additionally, having an ROV aboard enables ship crews to conduct consistent internal inspections for performance optimization. Rather than relying on the information gathered during required inspections every 1-2.5 years, ship crews and quickly deploy the ROV for external inspections for biofouling, hull, or propeller damage, and monitor degradation of sacrificial anodes. ROVs are also compact and maneuverable enough to enter ballast tanks, sea chests, and can be decontaminated for potable water storage tanks. With updated information on critical assets, ship crews can make informed decisions on scheduling dry-dock repairs.

5.2. Emergency Response

If a vessel is part of any physical collision, an emergency inspection is needed. This is to ensure that the ship is still reliable to be aboard and does not compromise the safety of the crew. Traditionally, ships would be required to navigate to the nearest dry-docking port immediately for a visual inspection. This yields a high cost and renders the vessel completely useless for an extended period.

With the introduction of ROVs, ship crews can quickly deploy the vehicle to survey for damage in mild to moderate currents. Requiring no certifications to operate, any qualified crew member can use the ROV to inspect for damage and evaluate the integrity of the hull. This limits dry-docking to only necessary situations, while simultaneously putting no crew members in danger for an underwater inspection.

5.3. Thickness Testing

Dealing with corrosion is an integral part of ship upkeep. Conducting regular thickness tests is the key to optimizing maintenance schedules and minimizing vessel downtime. Along with sonar, ROVs can also integrate with ultrasonic thickness gauges. This enables them to evaluate the thickness of steel on tanks, hulls, and other metal surfaces. The probe simply presses on the surface to provide effective measurements even through paint coatings or marine growth.

5.4. Sonar Scans

Maritime environments can make obtaining clear visuals difficult, particularly at ports where frequent movement can stir up silt from the bottom. While most ROVs come standard with high quality lighting, turbid conditions can render camera visuals useless. In these instances, ROVs can easily be equipped with imaging sonars to provide clear perspective even through the murkiest environments.

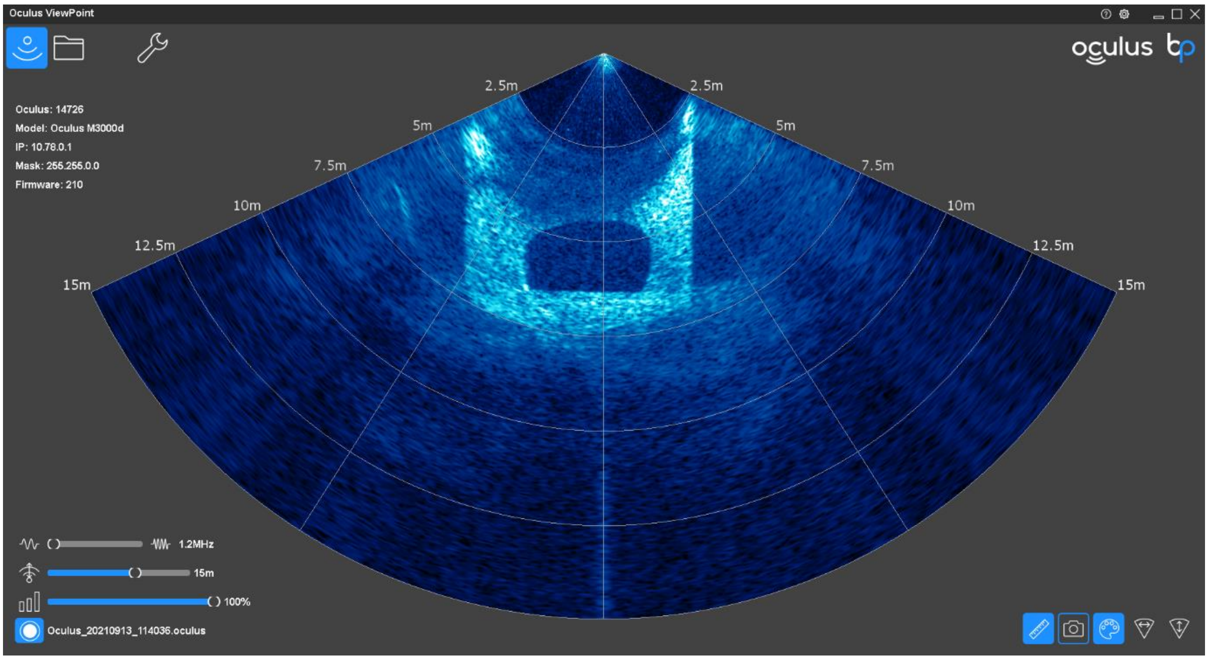

Fig.3: Sample Sonar Scan During an ROV Inspection

5.5. Minimize Risks to Divers

The most important benefit of utilizing an ROV for hull inspections, is the limitation of danger for divers during UWILDs. Diving under a large vessel can put divers in extremely precarious positions. Even when a ship is anchored, it still retains the ability to adjust positions with the current. If a diver is underneath conducting an inspection, a shift can result in a direct collision with the diver. On top of the specific dangers of navigating under ships, divers are also at risk of the regular concerns of pressurization during diving. If ship owners are required to have divers enter the water, accompanying them with an ROV enables a direct communication line between them and the topside team for an additional safety precaution.

6. Case Study: Foss Maritime, *Deep Trekker (2020)*

Foss Maritime Company is based in Seattle, WA, and offers a complete range of maritime transportation and logistics services. Along with its independent subsidiaries, Foss maintains a fleet of hundreds of tugs and barges throughout the United States. Foss is recognized for its state-of-the-art vessels, experienced and dedicated crews, knowledgeable customer service staff and world-class engineers. In addition to transportation and maritime logistics, Foss also provides engineering and shipbuilding services to assist customers throughout the entire life cycle of a project including analysing vessel and equipment requirements for a specific job, to designing a new build or vessel modification through to production and proper outfitting of a vessel.

The Foss Shipyard encourages employees to focus on continuous improvement and business development opportunities. As part of an approved Continuous Improvement Initiative, Foss purchased a Deep Trekker ROV to reduce the costs of using divers for diagnosis of damage response and equipment failure inspections, blocking/pre-drydocking checks, pre-operation/charter vessel surveys, quality assurance information among other potential options such as UWILD external specialist certification for basic barge inspections.

The predicted savings was $68,500 for the first year and $87,500 annually thereafter. However, after tracking the first year of ROV use, Foss realized an astounding actual and measurable impact of saving/earnings of a total of $135,650, which was double original predictions (not including immeasurable costs such as losing a tow job due to waiting on divers or potential cost of increased equipment damage due to inadequate underwater information).

6.1. Previous Inspection Challenges

In addition to alleviating diver costs, Foss also notes that external vendors can impact overall project timelines due to the dependence on fitting into their schedules of availability and also having to wait until the dive team can all organize themselves to the same time and place.

Also, due to safety concerns of having divers in the water, sometimes there are delays ensuring that the vessel is in a condition that is stable and safe enough for dive operations. Since the ROV can be operated by one person, it is deployed MUCH faster than divers and has way more schedule flexibility as well as operational flexibility since diver health is not a concern.

6.2. Daily ROV Functions

The Foss Shipyard began to use the ROV on almost a weekly basis, whether it was called in to perform block checks during a drydocking, inspecting the hull and running gear of moored vessels coming off-hire or ramping up for work, or providing helpful information on equipment failure. The ROV was light enough to be manually carried from pier-to-pier or office-to-pier by one person and did not require a shore power connection, so it was easy to transport to the vessel location, which is important when dealing with working vessels.

The ROV operator would fill out a Job Safety Analysis form and a Pre-Dive survey before operating the ROV to ensure operational safety and awareness before beginning an inspection. The operator would then splash the ROV as close as possible to the vessel inspection site and work with the dockmaster or vessel owner to ensure proper inspection and that photo and video data was captured for reporting purposes.

The ROV is easy to handle and lift in and out of the water. Once the inspection was complete the ROV operator would bring the vehicle back into the office for storage and battery charging then download the data to a computer and develop a dive report noting hull and equipment condition and pointing to any irregularities. The report was then emailed to interested parties.

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Discussions on Global Biofouling Tracking of Ships

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Abstract

The technologies of using under water drones to survey fouling degree of ships has evolved greatly in recent years. IMO imposed on all ships in 2011 to send GPS signals each 15 min to a central data base, Automatic Identification System (AIS) which has evolved into an essential tool in ship management and monitoring. A similar idea can be developed with drone biofouling surveys. If all ships arriving in a port were surveyed and standardized data transmitted to a central open to the public data base it could become a powerful data source for ports to identify higher risk vessels, enable ship operators to know real time the condition of the hulls to take timely and planned action, enable Charters to monitor the hull condition of chartered vessel, provide hull fouling control systems to live real time data to evaluate their systems and products.

1. Introduction

PPR 9/INF 24, *GFP (2022)*, is an inch thick lengthy document with a lot of details on the current state of the market regarding in-water cleaning (IWC) a primary tool used for optimizing the hull performance of ships between shipyards. It highlights the uncertainties and difficulties facing ship operators with various and differing rules, requirements and regulations governing IWC.

With the IMO Carbon Intensity Index regulation coming into force the tolerance for biofouling on ships hulls will be significantly reduced. The reason being that biofouling significantly increases the hull viscous resistance and by that fuel usage and Green House Gas (GHG) emissions, Fig.1.

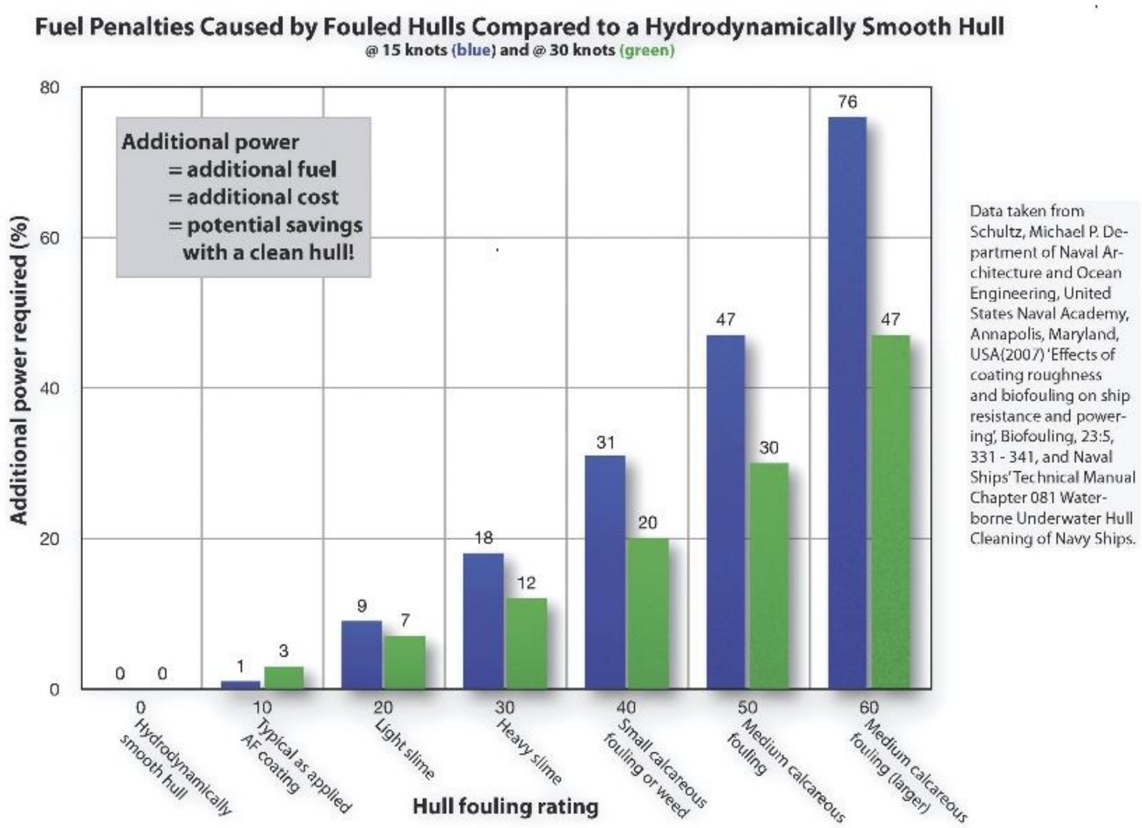


Fig.1: Fuel penalties caused by fouling, Source: Dr. M. Schultz

As the degree of hull biofouling increases, so does added power needed to propel the ship forward. Fig.1 also shows that the slower the vessel is, the more negative the effect of biofouling and the more important that the hull is clean.

To manage the biofouling on ship hulls, we need data. Data on the degree of biofouling in real time will help us optimize the time for corrective actions, such as in water hull cleaning (IWC). Among the beneficiaries of such a global biofouling survey system are also:

- Ports which can evaluate the risk of spread of invasive species before a ship arrives in the port,
- Academia in getting much more real-life data to analyse against other parameters (chlorophyl content, temperature …) and develop predictive tools,
- Paint companies getting earlier and more frequent data on the performance of their antifouling systems, etc.

2. Current State

The GloFouling Partnership (GFP) was launched in December 2018 with the intention to build capacity for implementation of the 2011 Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species (Biofouling Guidelines) in developing countries. The intended deliverables are reports and Best Practice Guidelines (BPG).

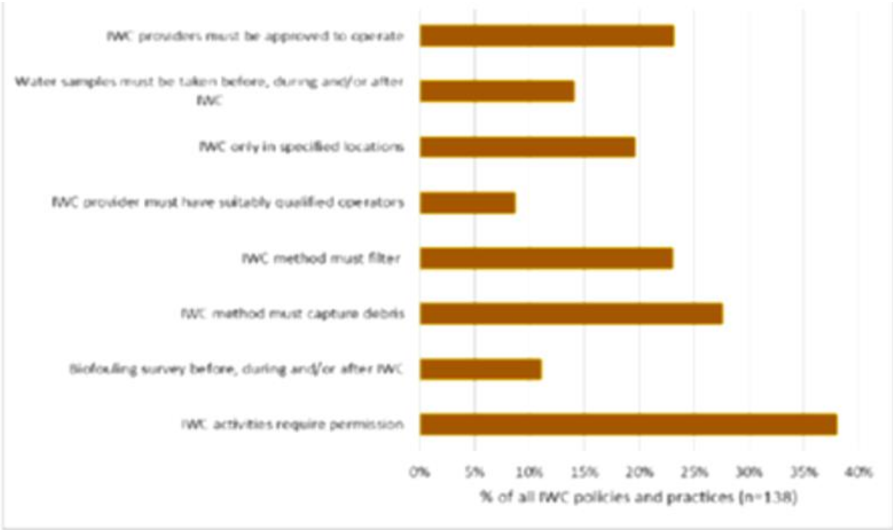
GFP work was following a collaborative approach involving as many different parts of the marine industry as possible. The resulting PPR 9/INF 24 report was published on January 28th, 2022. The primary author of this 129-page document was Susie Kropman, independent consultant. Comments and input were provided by Lilia Khodjet, John Alonso, and members of the Global Industry Alliance (GIA) for Marine Biosafety. Key conclusions were:

- Without an overarching international regulation or convention on Biofouling Management, inconsistencies will continue.
- Uncertainty surrounding In-water Cleaning (IWC) policy results in inconsistent conditions being applied by authorities.
- The performance of anti-fouling systems varies.
- Inconsistency in Biofouling and IWC policies creates a major challenge for the shipping industry.
- Most importantly, it describes the <u>chaos</u> we have regarding Biofouling Management in scattered and inconsistent rules and regulations around the world!

A few snapshots from the report follow. Note that there is much more data in this report than presented in this paper and reading the full report is highly recommended.

The PPR 9/INF 24 report describes:

- current International Guidelines and Recommendations
- IMO Biofouling Guidelines
- AFS Convention
- INTERTANKO's antifouling management guidelines
- IOGP/IPIECA guidance for the off-shore industry
- BIMCO's IWC with capture guidelines
- Regional, national, sub-national biofouling management and IWC policies regulations
- barriers, challenges, and their impact



IWC providers are required to have **approval to operate** in 23% of all identified provisions.

Fig.2: Key features of all identified IWC provisions

Of 29 publicly available identified IWC provisions, Fig.2, 10 require (or recommend) independent expert approval of IWC system. There is, however, no internationally agreed standard for testing and approving such systems in their ability to prevent or minimize contamination.

Of the publicly available IWC provisions only the BIMCO IWC standard and approval procedure for in-water cleaning with capture, and procedures developed by the Flemish ports for hull and propeller cleaning provide detailed testing procedures. The Flemish procedures are the only one identifying specific independent testing bodies for water sample analysis. All 9 other that have provisions that require independent approval of the IWC systems, including the BIMCO standard, do not specify the independent expert or approval body. This lack of identified expert organizations limits the ability of decision makers to make this a requirement and by that limit their confidence in the environmental performance of the IWC systems themselves.

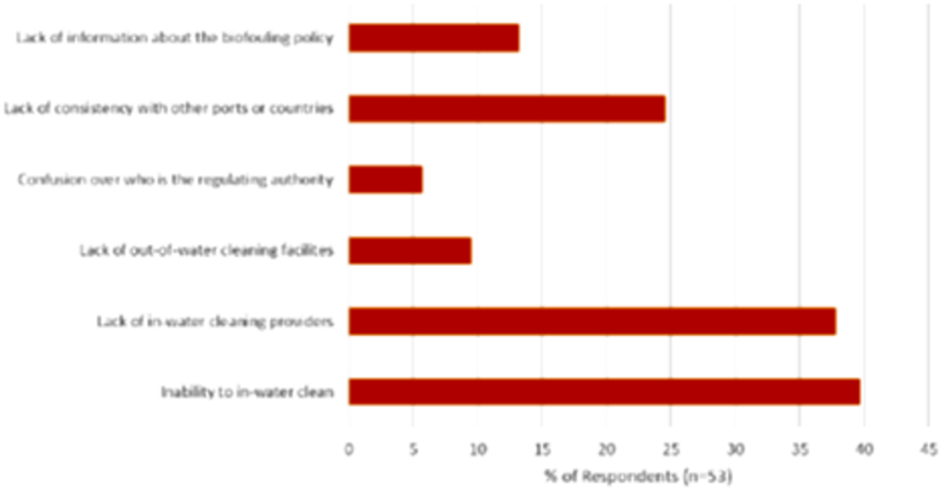


Fig.3: Challenges facing ship owners and operators in complying with biofouling policy

More than a third of the 53 shipowners and operators noted the inability (39%) to clean when needed and a lack of IWC service providers (38%) where needed as the main challenges they face to comply with biofouling policy, Fig.3. Shipowners and operators also identified two main challenges when trying to comply with the various IWC policies: Insufficient and ineffective communication (33%) and lack of consistency with other ports and estuaries (31%), Fig.4.

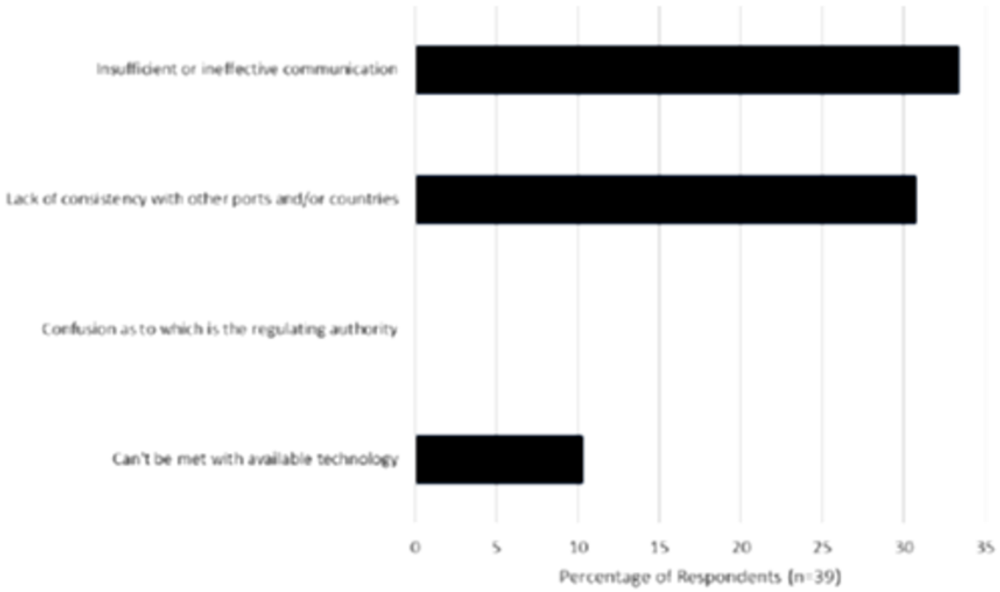


Fig.4: Challenges for owners and operators in complying with IWC policies

This confusion is disincentivizing hull cleaning and clean hull management. Shipowners and operators want and need consistency and predictability to facilitate managing clean hulls to reduce GHG emissions.

The updated IMO Biofouling Guidelines are expected to address some issues surrounding IWC activities. However, the amendments are not likely to sufficiently assist government authorities in facilitating or regulating IWC. The amendments are not expected to provide a standard for IWC; approval procedures for IWC systems or providers that assure both biological and contamination risks are minimized, or identify independent experts able to undertake approval work.

In the absence of internationally agreed standards, IWC policies risk either being ineffective at mitigating risk or having the effect that no ships proactively engage in cleaning in those locations. This impacts the ship owners' and operators' ability to execute what most likely will be a critical component of their biofouling management regime, Fig.5.

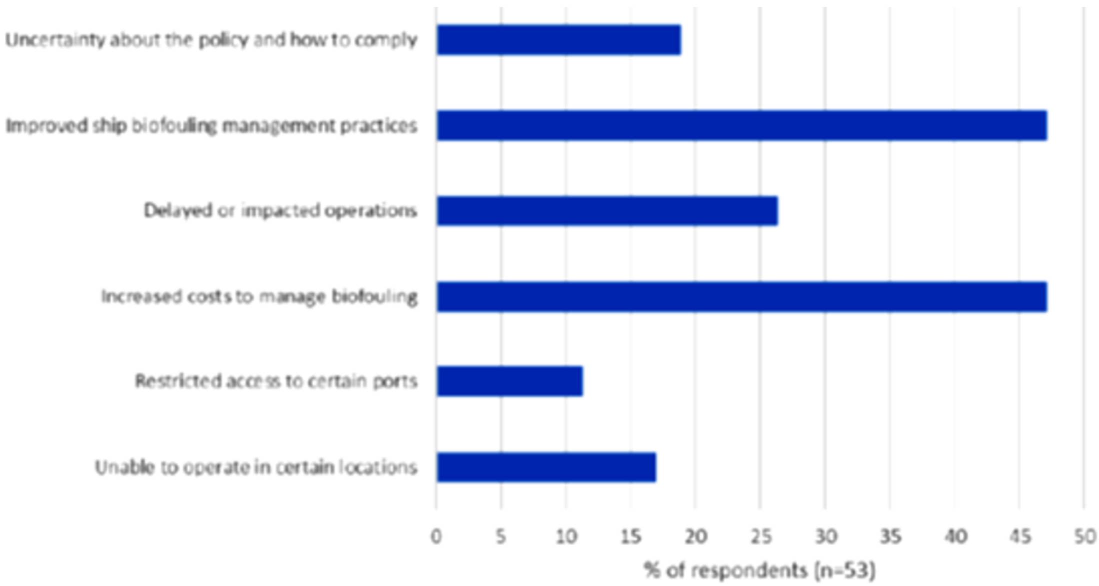


Fig.5: Impacts of biofouling policies on owners and operators

Managing biofouling comes at a cost for the marine industry. 43% of shipping industry stakeholders said facing increased cost managing biofouling in accordance with their policies and practices, Fig.6. That means that they go beyond what is required and pay. These costs include new documentation (biofouling management plans that mean something), in-water inspections and in-water cleaning as deemed necessary. Owners and operators do not have trees in the backyard growing golden apples that can be used to pay for added costs. It must be paid for from the income of the vessels. This means all costs must be passed on the food chain or it is not a sustainable situation.

It must be the responsibility of all of us to maintain an environmentally and economically sustainable marine industry.

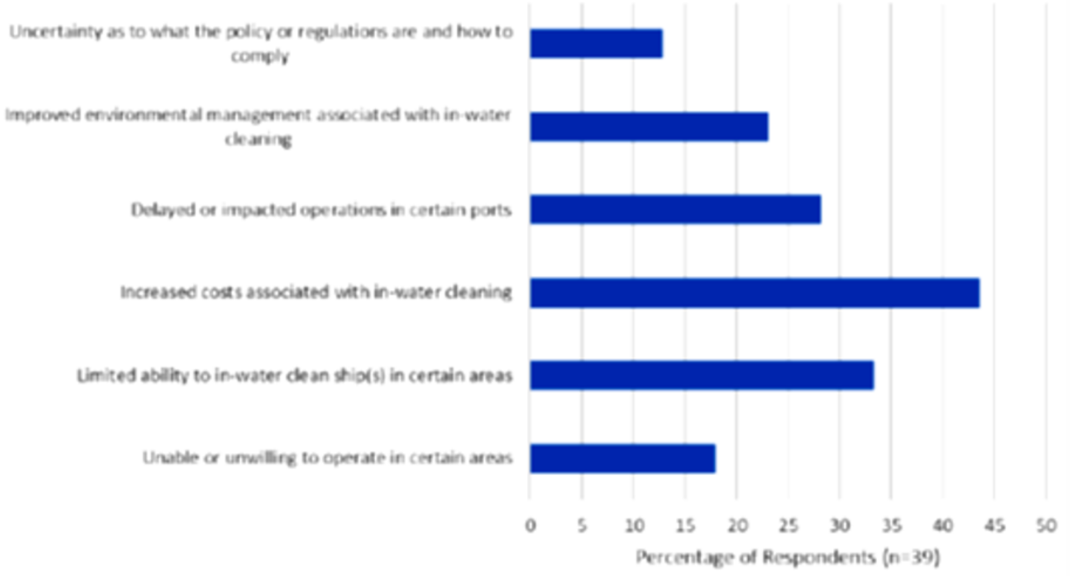


Fig.6: Impacts of IWC policies on owners and operators

The uncertainty about policies and regulations, delayed or impacted operations, increased cost associated with IWC, limitations to conduct IWC in certain ports, even being unable to cater to certain ports was raised as issues facing the owners and operators.

IWC providers also face increased cost to comply with requirements for local environmental reasons, Fig.7. We are not arguing that such local environmental concerns do not have merit. We understand these concerns. 45% of the IWC providers identified increased cost as an impact on their operations.

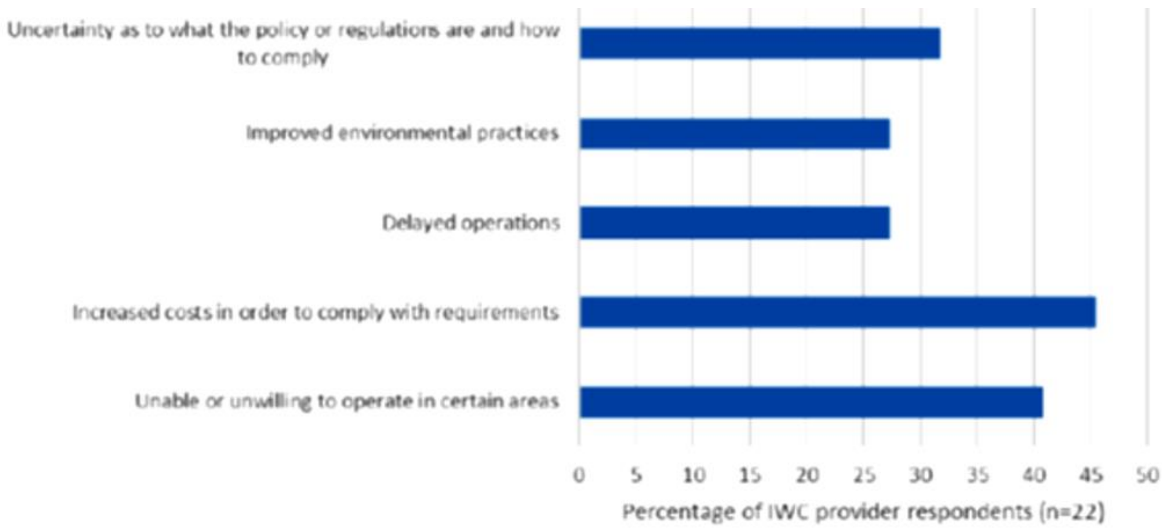


Fig.7: Impacts of IWC policies on IWC providers

There is a need for internationally agreed independent verification of IWC systems that makes sense and is globally implemented.

Delayed or impacted operations as the result of biofouling management policies was reported, possibly linked to new mandatory biofouling requirements in in places like California, New Zealand and Australia:

- 40% of ships inspected in California from 1st of August 2018 to 31st July 2019 were found non-compliant and given a 60-days grace period to come into compliance.
- In New Zeeland 17% of ships inspected failed.

These are significant numbers.

40% of IWC providers were unwilling to or unable to operate in certain areas due to IWC policies in place limiting the IWC availability. 17% of owners and operators report they are unable to operate in certain locations based on local biofouling policies.

There is much more information in this document. The concluding message is that we need order in this chaos.

3. Challenges

Key recommendations are:

1. Complete review of Biofouling Guidelines to minimize variations in the local port/state regulations, particularly on IWC guidance.
2. Consider mandatory international instrument based on the revised Biofouling Guidelines. The performance of the non-mandatory guidelines has proven to be ineffective especially in addressing IWC. With 19 regional and subnational policies and practices identified in the report and 27 others under development in the next 5 years, there is a great risk of wide inconsistencies and confusion. Existing polices and regulation vary as examples on the type of fouling and anti-fouling system, handling of waste, etc. Many authorities have water quality regulations that limit the amount of contaminants and substances in their waters. In relation to IWC with capture (see *BIMCO (2021)* standard) key features in of these regulations also vary, particularly in relation to capture rate, filtration, sampling and documentary requirements and the need for approval of IWC systems. San Francisco Bay has five water districts that do not agree fully.
3. Develop an internationally agreed IWC performance standard. Uncertainties surrounding IWC derived at least to a significant degree from the lack of standardization drives ports/states to take the precautionary approach placing onerous requirements on IWC, if allowed at all. The most comprehensive biofouling management policies are those of California and New Zealand. Both are mandatory and have documentary, reporting and verification requirements included, but vary in approach.
4. Comprehensive Biofouling Management policies are not widespread and those that do implement comprehensive policies are not consistent. Uncertainties caused by this and a lack of identified independent expert approval bodies cause confusion.
5. With 40% of all ships that enter drydock worldwide have > 10% hard fouling on their hulls, *NN (2020a)*, the situation is not satisfactory. We need to facilitate IWC worldwide to reduce the overall fouling extent on ships.

4. Communication

AAMP have a TEG532X correspondense group with more than 100 active participants worldwide openly discussing risks from Biofouling in the Marine world. Members comes from many sides; regulatory, paint suppliers, IWC providers, academia, consultants, Owners and Operators, etc. The group is tasked with discussing biofouling risk in the marine only. Not with agreeing on anything, nor making reports, etc. Just tasked with discussing various aspects surrounding biofouling in the marine.

The founding principle is to make as many of the different persons working in silos around the world listen to each other respectfully. This hoping that everyone will learn from each other, and maybe more harmonized regulations and rule will precipitate.

6. Suggested Solution to help with biofouling management

With good data we can manage better. Without good data we cannot manage. A global biofouling tracking system in the public domain could come a long way to alleviate the lack of data.

The dream is about a system of globally collected biofouling information on all ships in all ports sent to a central public database. Meaning each ship (above a certain size) is surveyed each time it enters or leaves a port providing data on the amount and general type of fouling present. With this data updated each time the ship enters a port or estuary we get data on how the fouling develops and grows. The method used in this dream is using drone technology to survey all ships arriving in ports with a standardized reporting system for data consistency collected in a database open to the public.

The benefits from this approach are multiple:

- Ports will have real life data to assess risks that each ship pose in terms of the spread of invasive species.
- Owners have real-life data and can plan action to lower cost and operational disturbances.
- Paint manufacturers can track their products real life – help with research for optimization and product improvements.
- Academia can use data to study biofouling evolution on ships, etc.

A group at AAMP, the TR21517 are looking at the state of the art of the drone and reporting technologies for developing a global biofouling system as described.

Acknowledgements

We thank Solène Guéré for her valuable discussion on this paper, especially her insights into drone in-water inspection.

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How to Properly Clean Swiss Cheese: The Challenges and Realities of Comprehensive In-Water Hull Cleaning and Inspection

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Abstract

Historically, ship in-water cleaning has concentrated upon reducing drag to improve fuel economy. In-water cleaning must now also address biofouling so as to manage biosecurity risks. Ironically, places on a ship which attract and retain the most biofouling are also the ones most difficult to access for effective cleaning and inspection. To be truly effective in attenuating biofouling risks, in-water cleaning needs to ensure that these niche spaces are comprehensively cleaned, or otherwise treated. This presentation will review the standards, equipment and techniques that should be considered to fully and verifiably remove biofouling by in-water methods.

1. Introduction

Driven in parallel by an intent to limit potential biosecurity hazards in accordance with evolving national rules as well as the more established regulatory imperative to improve ship energy efficiency performance, having a ship free of, or with as little biofouling as practicable, is now considered a desirable ship condition, and certainly a subject of greater attention than previously. Given that fouling control coatings (i.e. anti-fouling coatings [AFCs] and fouling release coatings [FRCs]) do not always perform optimally or effectively over their intended life, may be damaged, or that some ship fittings are not normally so painted, ship hull cleaning has become an issue of resurgent focus of the shipping industry. While drydocking is arguably the best way of cleaning a ship's hull, its costs, implications for ship availability and operations, impracticalities and the limited availability of suitable facilities in optimal locations mean that for most of their working lives, any regular hull cleaning of a ship will be conducted as an in-water activity.

While 'hull cleaning' may appear at face value to address both ship operating efficiency and the marine biosecurity management objectives, in reality one only overlays the other to some extent. Having a 'clean ship' for the purposes of optimising hydrodynamic performance and energy efficiency and the subsequent reduction of greenhouse gas emissions will very rarely result in the simultaneous and serendipitous outcome of having a 'clean ship' for the purposes of biosecurity controls. Conversely, while a 'clean ship' in the context of biosecurity objectives is more likely to have the parallel outcome of also being 'clean' for energy efficiency purposes, this outcome cannot always be assumed. For example, a ship operating solely in a regional area may have her niche spaces cleaned to remove accumulated biofouling acquired in a previous location and considered to present a biosecurity hazard to the new location, while an inspection assesses that fouling on the hull proper represents no biosecurity threat and hence does not need to be removed. It is critical, therefore, for ship operators and biosecurity regulators not to be lulled into any false assumption that a verified in-water clean of a ship will always present as an outcome of a ship that is both optimised for energy efficiency and poses minimal marine biosecurity hazard.

This is not a 'scientific paper', per se, but rather a distillation of the observations and experiences of the author in over 600 ship biofouling inspections, risk reviews and cleaning programs. This paper does not consider or address in-water cleaning and capture systems nor the regulatory aspects of ship biofouling management and risk evaluation, except in an incidental sense, but rather focuses on the technical challenges and limitations inherent to comprehensive underwater cleaning and survey of ships.

2. Why is a Ship Like Swiss Cheese?

Much like Swiss cheese, below the waterline most ships present hull voids and cavities, with these consequently susceptible to biofouling while concurrently being difficult to access for cleaning and inspection. Perfunctory visual examination of the exterior surfaces of any ship can be decidedly deceptive in terms of determining the full extent of biofouling vulnerabilities and areas and features prone to the recruitment and accumulation of biofouling organisms. Even many ship technical diagrams, such as general arrangement (GA) drawings and docking plans, fail to fully represent all of a ship's hull cavities and voids. In effect, these 'Swiss cheese holes' in ships represent biofouling niches. Axiomatically, the more difficult it is to find some of these biofouling niches, typically the more problematic they are to access for cleaning and survey, especially when conducted in-water by divers or remote vehicles.

Biofouling niches are variously defined by different agencies and correspondents, but a useful definition is that given in the *IMO (2011)* biofouling guidelines, namely as:

"... areas on a ship that may be more susceptible to biofouling due to different hydrodynamic forces, susceptibility to coating system wear or damage, or being inadequately, or not, painted, e.g., sea chests, bow thrusters, propeller shafts, inlet gratings, dry-dock support strips, etc."

Not all biofouling niches are difficult to clean by orthodox methods, with examples being block marks and hull markings. Typical biofouling niches which fall into the cohort of difficult to access and clean include: seachests; box coolers; keel coolers; ropeguards; tunnel thrusters; retractable azimuth thrusters; azipod mountings; retractable stabiliser housings; stern rollers; some sacrificial anodes; overboard discharge apertures; and moonpools. Other, more arcane examples may include features such as free-flood sponsons, suction-breaking tunnels, free-flood equipment spaces, or perforated bilge keels. Many of the in-water 'clean and capture' systems and performance standards which are required to be employed in various jurisdictions are almost invariably also equally difficult to apply to these fittings and voids. This compounds the cleaning problem while simultaneously exacerbating nascent biosecurity risks.

With the possible exception of some non-motorised 'dumb barges', few vessels are devoid of these underwater void spaces, nooks and crannies, and by extension few are bereft of the sorts of niche spaces which attract colonisation by biofouling and which require focused cleaning effort. The size of a ship provides no indication at all of the number, character and complexity of its biofouling niches. Some ships, including some of the biggest afloat such as 250 000 t bulk carriers for example, have few of these void spaces, but some are invariably present. By way of contrast, relatively small, typically specialised work vessels, can be replete with biofouling niches, literally peppered with cavities and other enclosed spaces below the waterline which are conducive to biofouling while simultaneously compounding the difficulties of in-water cleaning and inspection. To this end, it is somewhat ironic that those are the same ships which are often characteristically engaged in slow speed activities of extended duration in coastal and littoral areas, before moving on to some new assignment in some distant area. In other words, the ships which often have an extensive number and array of difficult to access biofouling niches are also the ones most likely to accumulate biofouling of biosecurity concern, and then to convey that accumulated biofouling assemblage to some novel location, accentuating and amplifying biosecurity hazards at all phases of the risk transfer continuum.

Biofouling niches are virtually impossible to totally avoid in the design and build of most ships. Nevertheless, thoughtful prior consideration and planning can variously eliminate some niches or otherwise improve design features to facilitate access for cleaning and inspection, for both in-water and drydock purposes. Conversely, poor design decisions with regard to biofouling niches inevitably result in the perpetuation of these sub-optimal features for the entire life of a ship.

3. Why Clean a Ship In-Water?

Any review of current market activities and associated advertising, edicts and guidance from the IMO and recurrent themes in the technical literature render it clearly evident that ship in-water cleaning techniques and protocols are in vogue and a matter of topical interest. Much of this is underpinned by the need to achieve energy optimisation and the associated greenhouse gas emissions reductions. Recent and emergent regulations compel ship operators, for both new and existing vessels, to meet their energy efficiency and carbon intensity benchmarks via the EEDI, EEXI and CII metrics (respectively: Energy Efficiency Design Index for new ships; Energy Efficiency eXisting ship Index, for ships in service; and Carbon Intensity Indicator).

One of the compulsory mechanisms for ship operators to demonstratively meet these targets is via the Ship Energy Efficiency Management Plan (SEEMP). The IMO's guidelines for the structure and content of a ship's energy efficiency plan specifically address hull cleaning, advocating that hull cleanliness and procedures to retain a clean hull be featured in a vessel's SEEMP, namely, *IMO (2016)*, p.9:

"Hull Maintenance

Hull resistance can be optimized by new technology-coating systems, possibly in combination with cleaning intervals. Regular in-water inspection of the condition of the hull is recommended.

Propeller cleaning and polishing or even appropriate coating may significantly increase fuel efficiency.

The need for ships to maintain efficiency through in-water hull cleaning should be recognized and facilitated by port States.

Generally, the smoother the hull, the better the fuel efficiency."

Even a heavy slime layer on a hull can increase ship fuel consumption by the order of 10%, while small calcareous fouling or weed may result in a 20% penalty, *Schultz et al. (2011)*. It is perfectly understandable that, historically, ship in-water cleaning has concentrated upon reducing drag to improve fuel economy, with the associated benefits for operating costs and profitability. The prevailing fixation with ship energy efficiency factors accentuates and entrenches these established practices and attitudes. Nowhere in the IMO's standard SEEMP template are the biosecurity aspects of in-water cleaning mentioned or acknowledged, nor the concomitant benefits to the environment which may be realised by cleaning the whole of the ship thoroughly beyond the efficiency gains from reducing hull roughness.

In-water cleaning, and for that matter drydock cleaning as well, must now also address biofouling so as to manage biosecurity risks. Ironically, the niches on a ship which attract and retain the most biofouling are also the places most difficult to access for effective cleaning and inspection. This difficulty is acknowledged in the IMO biofouling management guidelines (author's emphases), *IMO (2011)*, p.11:

"Dive and remotely operated vehicle (ROV) surveys can be practical options for <u>in-water inspections</u> although they do <u>have limitations regarding</u> visibility and available dive time compared with the area to be inspected, and <u>difficulties with effectively accessing many biofouling prone niches</u>."

It must be recognised that it is entirely possible to conduct a ship in-water hull clean, with associated validation inspection, and to report and record such without actually doing anything at all about the biosecurity threats posed by biofouling in a ship's niche spaces. Exacerbating this inattention to cleaning of niches is that fact that they have minimal, if any, bearing upon ship hydrodynamic efficiency, and hence provide no benefit if one's cleaning objective is improved energy efficiency and reduced exhaust emissions. More than once the author has stood beneath a drydocked ship where the yard foreman has insisted that the ship is 'clean', where the hull plate has indeed been cleaned but seachests and thruster tunnels have not been opened, let alone actually had accumulated biofouling removed. There is a general absence of awareness and clear comprehension of these matters in the wider shipping industry, although this is changing with a broadening appreciation of the nexus between biofouling and biosecurity. As things stand, a documented in-water clean of a ship may generate a totally misplaced sense of security that a ship's biofouling-mediated biosecurity risks have been addressed.

It is evident that to be truly effective in attenuating the ecological risks arising from biofouling, in-water cleaning needs to ensure that niche spaces are comprehensively cleaned, or otherwise treated, even when there is no operating efficiency imperative or dividend. To do so requires both recognition of the critical role of biofouling niches in terms of biosecurity risks, as well as reliable differentiation of in-water cleans of the 'hull' (ie. the external faces) as opposed to one of the hull and niches. Such awareness and discrimination are not unambiguously manifest in the maritime industry. The Clean Hull Initiative, https://bellona.org/projects/clean-hull-initiative, for example, is focused upon ship hydro-dynamic efficiency - there is no consideration evident of niches which do not influence hull roughness. While a laudable initiative, adherence to the CHI precepts may result in a misapprehension that a 'clean ship' is one with a managed biosecurity risk profile. Conversely, the BIMCO/ICS in-water cleaning standard, *BIMCO/ICS (2021)*, p.2, does address niches, but this is more from the stance of ensuring that material cleaned from these locations is effectively captured according to the promulgated standard:

"The Industry standard helps to ensure that the in-water cleaning of a ship's hull, and niche areas including the propeller, can be carried out safely, efficiently and in an environmentally sustainable way."

While a very valuable development, as can be seen from the text above the BIMCO/ICS standard does not specifically address the need to clean niches for the purposes of biosecurity risk control, nor to delineate if any particular ship in-water cleaning activity was for the purpose of hydrodynamic efficiency gains or biosecurity management. Thus, a ship could be cleaned in accordance with the BIMCO/ICS standard, but this will not of itself ensure that a ship's biofouling niches are cleaned such that all biofouling is removed or otherwise neutralised.

4. What Types of Niches Are Particularly Hard to Clean and Why?

It is critical to have a very good understanding of the location and form of all underwater niches on a ship subject to in-water cleaning. This is to ensure the proper planning for, conduct and verification of the ship cleaning program. As previously noted, ship's diagrams, such as GAs and docking plans, very rarely include all biofouling-significant niches. Whereas cleaning and inspection in a drydock is more likely to provide for the 'luxury' of effective and essentially unobstructed views of a ship, and thus the ability to locate and examine otherwise unknown biofouling niches, no such latitude is afforded by in-water inspections. Except in exceptional circumstances, 'unknown' biofouling niche areas and fittings will not be identified at the time of an in-water work program, let alone cleaned and inspected, undermining the level of confidence which may be realised as to the efficacy of the entire clean. In fact, in some conditions, even niche fittings with a known exact location on the ship can be difficult to find by divers or remote vehicles. Using the Swiss cheese analogy, this is akin to not knowing that a specific hole exists in the cheese, much less being able to certify that it has been cleaned and checked.

Not all biofouling niches are necessarily difficult to access for cleaning and inspection. For example, block marks, areas around the bow subject to anchor cable abrasion and seachest grates - or at least their external faces - are readily accessible for maintenance and survey. Other niche fittings are similarly openly accessible but may be difficult to clean in some circumstances, primarily dependent upon the tools and techniques being used. Examples include padeyes, overboard discharge apertures, the backs of sacrificial anodes, and the gaps between stabilisers and the hull, where divers with hand tools, for example, can readily undertake successful cleaning, but where automated brush or water jet cleaning systems are unlikely to be able to scrub effectively.

Some niches areas can only be properly cleaned and verified if able to be opened underwater. These include seachests, tunnel thrusters and other free-flood spaces. Some, such as thruster tunnels, often have designs, if only by good providence as opposed to conscious design choices, which permit some level of diver access, or access for specialist tools, notwithstanding diver safety considerations. Other niche fittings, however, are invariably of a character which precludes effective access while in-water, for either cleaning or inspection. These include items such as box coolers and the void space beneath stern rollers. In most circumstances these two features are also exceptionally difficult to clean effectively in drydock.

Seachests present an interesting case. Often, by dint of the layout and extent of the seachest cavity in relation to the size of the intake grates and the spacing between bars, it is not even possible to obtain a reliable view of the seachest interior from the position of an external observer. In most instances, the interior faces of the grates and the seachest interiors can neither be cleaned effectively nor checked to be clean unless the seachest is opened. This is readily achievable on some ships, while others may have seachest grates which are welded into place, and hence not easily removed by divers. Others may have small openings which prevent any diver from placing more than outstretched arms into the interior space even if the grate is removed, limiting the likelihood of in-water cleaning being effective.

Ship size is not an indicator of biofouling cleaning difficulty or effort required. Some ships, with a total wetted surface area measured in the tens of thousands of square metres, may have as few as five difficult to access biofouling niches. Conversely, relatively small ships, typically those designed for specialist purposes, may have many dozens of difficult to access biofouling niches.

Complexity of hull form and the number and intricacy of niches exacerbates the difficulties of underwater cleaning and inspection. For effective, verifiable in-water cleaning, these situations call for a wider range and number of more elaborate tools and techniques, consume more time in planning and conduct, and introduce uncertainties as to how long it will take to conclude the cleaning program, with the associated penalties in costs and disruptions to ship's schedule. (This is especially the case in variable or marginal conditions, such as short tidal windows, strong currents, and limited visibility, which can adversely affect the endurance and performance of divers and remote vehicles.) For example, the author was involved in a recent in-water cleaning program for a 90 m ship in response to the detection of a listed marine pest species in the ship's biofouling suite. This cleaning activity took nine days and employed multiple dive teams using a range of specialised equipment. By way of contrast, a 'routine' hull clean of this ship would normally be expected to take less than a day, using one dive team equipped with a standard brushcart. It should also be considered that the greater the number and complexity of biofouling niches which need to be cleaned and checked, likely also the lower level of confidence in the assessed effectiveness and rigour of biosecurity outcomes.

5. How Can In-Water Cleaning and Inspection Be Improved?

The first response to this question should be 'What is the objective of the hull being cleaned?'. If it is purely for the purposes of energy efficiency and operational cost savings, and especially in the absence of any biofouling-mediated biosecurity hazard, then there is probably no need to alter current, common practices. If, however, the intent is to effectively and convincingly improve in-water cleaning and inspection as a vehicle by which ship marine biosecurity risks can be better managed, then the first step should be to clearly enunciate when such an outcome is required. This would then lead to unequivocal differentiation in the planning, conduct, verification, reporting and recording of such activities, minimising, if not eliminating, current ambiguities and uncertainties. This could be effected by delineating ship in-water cleaning activities as either a 'hull and/or propeller clean of external surfaces, for the purposes of energy efficiency', or as a 'full underwater clean, of hull and biofouling niches and voids, for the purposes of marine biosecurity risk control', for example. Perhaps the shorthand titles could be along the lines of 'hull efficiency clean' and 'full underwater biofouling removal', or similar.

Obviously, fully cleaning a hull and its niches in order to reduce biofouling-related risks is going to take more time, cost more, and will likely be more difficult to schedule given the need to engage specialist dive or underwater cleaning teams with tailored equipment. If only a clean to improve fuel efficiency is required, as called for in a ship's SEEMP, then it makes good sense from the perspectives of cost and schedule to only have a clean of the external hull surfaces, essentially of the 'skin' of the ship, rather than invariably undertake an otherwise unnecessary full clean with the associated cost and time penalties. Such a clean of external surfaces only should, of course, be clearly documented as such to avoid any confusion at some later date should the ship's biofouling cleaning record be scrutinised for the purposes of biosecurity evaluation.

In the circumstances where a ship needs to be thoroughly cleaned for the purposes of biosecurity, there exist a number of means by which the may process be improved to ensure greater certainty and transparency of intended outcomes and the communication of such. These span a number of domains, which may be categorised as: administration and regulation; ship design; and in-water cleaning tools and techniques.

5.1. Administration and Regulation

As previously noted, a fundamental change that is required to be recognised and adopted widely in order to instil rigour and confidence at all levels in the ship in-water cleaning continuum is to reliably, consistently and unambiguously delineate whether any particular in-water clean has been conducted to a biosecurity standard or a ship energy efficiency standard. The reasons for this are self-evident and are elaborated upon elsewhere in this paper.

The *BIMCO/ICS (2021)* in-water cleaning standards address this inherent ambiguity to some extent, but arguably are still open to misunderstanding and miscommunication. Improvements could be realised if industry standards were more precise in this regard and those facets concerning hull cleaning in both the IMO energy efficiency and biofouling management guidelines were better aligned with each other.

5.2. Ship Design

Improved ship design standards should be developed and implemented with the intention to recognise and then eliminate or otherwise reduce the number and complexity of biofouling niche fittings and voids. This initiative should augur to limit the extent and complexity of biofouling assemblages on ships in the first instance, in parallel with facilitating access for more effective maintenance, cleaning and inspection, both in drydock and in-water. Of course, any such design endeavours would need to be balanced and harmonised with other ship design imperatives, objectives and rules, and within the constraints of technical and material limitations.

A non-exhaustive selection of possible ship design changes which would be beneficial for biofouling management include the following:

- Tunnel thrusters with grates permitting diver access, as can be achieved with either larger grate openings or a hinged and bolted grate section.
- Azipod mounts with access hatches or ‘soft patches’ enabling access to the void space.
- Seachests with hinged grates, and with grates bolted on instead of being welded.
- Seachests designed so that the grates more closely align with the internal dimensions of the seachest itself, reducing the visual ‘dead space’ for an observer looking through the grate.
- Seachests designed to eliminate or minimise internal features such as brackets and frames, attenuating biofouling vulnerability while also simplifying cleaning and maintenance.
- Ropeguards bolted into place in lieu of being welded on.
- Ropeguards designed with larger inspection ports, to permit better access for inspection and cleaning.
- Flush-mounted sacrificial anodes, eliminating the gap behind the anode.
- Sponsons designed so as not to be of the free-flood type.
- Stern rollers with larger exchange ports at their base to improve access for visual observation and specialised cleaning tools.
- Installation of appropriate marine growth prevention systems (MGPS) in order to minimise biofouling accumulation in difficult to access areas, such that MGPS installed in seachests, for example, offer more comprehensive protection than ones installed in strainer boxes.

Improvements in ship design with the intention of eliminating, minimising and simplifying biofouling niches will work in complement with an effective AFC or FRC. It is also critical that fouling control paint systems selected for any particular ship service be customised, as much as practicably achievable, to the operating areas and service and maintenance profiles of the subject vessel. This may involve the more widespread development and application of hybrid coating systems, where different paints are applied variously as better suited to particular areas and fittings on a ship, rather than the conventional approach of a single coating type.

5.3. In-Water Cleaning Tools and Techniques

The quality of in-water cleaning depends upon many factors, such as: ROV operator or diver/dive team competency and experience; suitability and utility of cleaning tools available, including both automated and hand-held gear; and operating conditions such as currents, visibility and incompatible operations and activities which may preclude full or persistent access. These limitations can never be fully negated, but they can be minimised through proper training and equipment, and by ship operators/owners being consciously aware of the capabilities, or limitations, of any service provider which may be engaged to clean their ship.

Effective in-water cleaning of a ship's biofouling niches, and the verification of such, requires effective prior planning. This is underpinned by a good understanding of the ship in question in the context of biofouling niches, whatever specialist equipment may be needed, and the likely time required to conduct the cleaning, inspect to validate its effectiveness, and allow time for any further remedial actions which may arise in order to demonstrably attain the desired standard, such as those set by various national ship biofouling cleaning regulations.

Common ship in-water cleaning equipment includes power and automated tools such as bruscharts (which may be autonomous, remotely controlled or diver operated), scrapers, wire brushes and hand-held grinders for propeller polishing. More specialised, and less prevalent equipment includes water blasters (particularly ones with long hoses and long, thin nozzles in order to extend an operator's effective reach), as well as simple items such as scrapers with long handles. Well-equipped dive teams also possess the tools necessary to open, and later shut, items such as seachest and thruster grates, and ropeguards.

It must also be considered that being 'clean' for the purposes of biosecurity risk reduction does not necessarily require the physical removal of fouling organisms. Being 'clean' for these purposes fundamentally means biofouling organisms are unable or unlikely to pose a risk of introduction of a new species in a novel geographical location. Dead, remnant fouling, while still present on a ship, presents no such translocation hazard. This presents the option of conducting an in-water biofouling 'clean' with the intent of killing the organisms in situ. This can be achieved by means such as heat treatment, chemical dosing, or asphyxiation or starvation as may occur if isolated for a sufficient period from life sustaining water – as could be realised, for example, by blanking and isolating void spaces. By extension, a well-appointed in-water cleaning outfit should also have the ability, variously, to:

- Blank off seachests and other cavities, such as ropeguards, for the purposes of heat treatment or chemical dosing or similar.
- Employ heating or steaming equipment, including temperature measuring and recording devices, as necessary to verifiably apply heat treatment to areas, such as box coolers, which cannot be accessed underwater for effective physical removal of biofouling.
- Apply suitable chemicals, with the means necessary for their injection into fittings such as ropeguards, as well as any required approvals for their use.

A corresponding requirement with the need to effectively undertake a comprehensive clean of all biofouling niches and fittings on a ship, as well as the external hull surfaces, is the need to be able to check and document such an outcome. This pivots upon the ability to know of and locate all of the relevant niches, and then to capture appropriate video and/or still imagery of sufficient resolution. The difficulties of access to some niche voids and fittings for automated cleaning equipment similarly manifest for automated survey and inspection equipment, which may be very capable when used to check the external surfaces of a hull, but less so for items such as seachests, thruster tunnels, ropeguards, and similar.

For areas where cleaning by physical removal is not an option, some other form of verification of the effectiveness of the alternative treatment is necessary. This will obviously depend upon the tools, techniques and biofouling control concepts employed, and may encompass, for example, temperature monitoring or sampling of biofouling specimens to confirm their expiry.

6. Conclusion

There exists a prevailing misapprehension and dichotomy of what represents an effective underwater clean of a ship and the purposes for doing such. Clearly, there are significant benefits on offer for ship operators to maintain a clean 'skin' on their ships, as well as embryonic regulatory imperatives for doing so. Less obvious and less prevalent is an overlapping need to minimise biofouling-mediated ship biosecurity hazards, and one which is also inconsistent given the different biofouling regulations and expectations of the various national jurisdictions. Imprecise language and vague regulation and standards have resulted in these two superficially similar, but fundamentally different, ship 'clean' states being interchangeable and confused with each other

Comprehensive, IMO-sanctioned SEEMPs include elements devoted to hull cleaning in order to reduce biofouling and hence reduce hull friction, and with good reason to do so. Nevertheless, faithful implementation of the hull and propeller cleaning elements of a SEEMP will in all probability do little to reduce a ship's biofouling-linked biosecurity status. Notwithstanding this absence of any meaningful nexus, a record of regular hull cleaning, by dint of lax and undisciplined terminology, may have the effect of lulling ship owners and operators, and some regulatory agencies, into assuming that the whole of that ship is regularly cleaned and then erroneously conclude that the ship presents a reduced biosecurity threat.

The difference between an in-water cleaning for the purposes of ship fuel efficiency, and the ability of a service provider to only perform such a clean, should be clearly delineated from the more comprehensive in-water clean typically required for the purposes of biosecurity management. This requires focused regulation and standards together with clearly defined and understood nomenclature. Such delineation should be clearly reflected in domains such as underwater services companies' advertising materials, technical literature on in-water hull cleaning systems, biofouling management regulations, and the entries in ship biofouling record books.

In addition to the administrative and regulatory facets, reform is also required in ship design practices and in the tools and techniques employed by in-water cleaning service providers. Improvements in ship in-water cleaning for the purposes of biosecurity management, and unequivocal confidence in such outcomes, can only be realised via wider uptake of the in-water cleaning tools and techniques necessary to provide for greater certainty of effective cleaning of all niches. This needs to be accomplished in concert with the complementary uptake of the in-water inspection tools and techniques necessary for effective and confident survey of those niches.

Suffice it to say that some ship biofouling niches can never be 'fully and verifiably' cleared of biofouling, either in drydock and particularly not by in-water cleaning and inspection methods. Alas, there will always exist some degree of uncertainty requiring balanced risk-based decisions. These uncertainties, and the residual risks, will, however, be attenuated as a result of increasing awareness of these factors and the subsequent limitation of residual doubts and ambiguities, coupled with the wider development and adoption of improved, purpose-designed, if not bespoke, cleaning and survey tools and techniques which such awareness will engender.

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The Jellyfishbot: Easy Robotic Cleaning for Port Water Surfaces

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Abstract

The Jellyfishbot is a compact and robust robot that collects, autonomously or remotely, marine litter (bottles, cans, plastic wrappers, cigarette butts, microplastics, paint particles, etc.) and oils on the surface of water bodies. Ideal for cleaning up the harbours, industrial and touristic areas, the Jellyfishbot is a major tool for the maintenance and the preservation of the water bodies. Acting as close as possible to the source of the pollution; it prevents the dispersion of the pollutants into rivers, seas, and oceans.

1. Introduction

IADYS is an innovative start-up developing artificial intelligence and robotic products in service of the environment, located on the Mediterranean coast near Marseille (Roquefort-la Bédoule). Since its inception in 2016, IADYS has continuously expanded internationally. A first fundraising in June 2021 has allowed the company to speed up the development process and comfort its position especially internationally. IADYS is proud to count significant establishments in the Asia-Pacific area (Japan, Taiwan, Singapore and Australia), in Western Europe (Spain, Germany, Switzerland, United Kingdom, Finland and Greece) and more recently in the UAE.

2. A company committed to environment and human

2.1. An alarming environmental context

Every year, an additional 8-12 million tons of plastic and 2.3 million tons of oils end up in the seas and oceans. In 2017, there was already one ton of plastic for every five tons of fish and, if nothing is done, there will be more plastic than fish by 2050. In addition to this, other forms of pollution are now polluting our oceans (hydrocarbons, metals, green algae, etc.). Numerous regulatory measures have been adopted to prevent the discharge of waste and pollution into the environment, but despite these measures, the quantities discharged are still too great. Carried away by rain, wind or simply discharged through negligence, they end up in inland water bodies, rivers and then the seas and oceans. According to the United Nations Environment Program, about 80% of marine pollution is land-based. It is therefore essential to concentrate efforts to combat pollution as close to the source as possible, i.e., in industrial water bodies, tourist sites, canals and ports. Once waste or pollutants are dispersed at sea, it is almost impossible to recover and treat them.

2.2. Awareness of the fragility of the sea

Passionate about the sea since his childhood, Dr. Nicolas Carlési, IADYS's founder and CEO, practices on a regular basis, nautical and underwater activities such as sailing and scuba diving. It was during these activities and especially during a trip to Sicily that he was struck by the amount of waste in the water (fishing nets, plastics, bottles etc. …). "Few years ago, during holidays in Sicily, I faced marine litter: heaps of plastic waste, bottles, pieces and many fishing nets… I realized that I had no choice but to wake up to the urgency of the situation". Nicolas Carlési has a PhD in Robotics and Artificial Intelligence and decided to act by putting his knowledge and robotic skills to good use in a large-scale project for the protection of the marine environment.

IADYS (Interactive Autonomous DYnamic Systems) was founded in September 2016. The company is at the interface between human activities and the aquatic environment, offering solutions to detect and collect pollutants before they reach the open sea. However, this does not mean that all the company's clients are in coastal areas.

2.3. IADYS, artificial intelligence and robotic innovations dedicated to environment

The innovative start-up IADYS designs, develops and delivers Artificial Intelligence & Robotic innovations. Initially founded in Aubagne, in the south of France near Marseille (13) is now located in Roquefort-la Bédoule and has sixteen employees. The Sea-neT project is the first range of IADYS products and is designed for the aquatic decontamination market, with a set of hardware and software solutions: marine vehicles, on-board intelligence systems… The Jellyfishbot was created for this context: it is a small robot that collects floating waste and oils. Before its launch, the clean-up of the water bodies was done most of the time manually, by means of motorized boats and landing nets, or with fixed mechanized solutions in the form of skimmers for oils or mechanisms that suck up floating waste.

2.4. The Jellyfishbot, a robot to clean-up water bodies

Small very handy robot, the Jellyfishbot, Fig.1, can collect waste and oils on the surface of water bodies, Fig.3. Genuine "Swiss Army Knife", the Jellyfishbot is equipped with a system of slides, a frame and nets with smaller or larger meshes (up to 7 different sizes), to collect different types of pollution in the best possible way. The range includes now upcycled, reusable or disposable nets, which can be adapted according to the enhanced waste management of the user. For oils collection, the Jellyfishbot is combined with disposable nets filled with absorbents that capture slicks, oils and greasy residues in the water. This robot is an efficient and flexible solution for the clean-up of aquatic areas, no matter how extensive and/or difficult to access, particularly for sheltered areas: industrial installations, ports, marinas, shipyards, lakes, canals, but also golf courses, leisure centers and hotel residences.

With about 60 robots adopted equally by marinas (Saint-Tropez, Cannes, Barcelona, Ajaccio, Calvi, La Turballe, Mainz in Germany, Neuchâtel in Switzerland…), commercial ports (le Havre), shipyards (Saint-Nazaire), the efficiency and reliability of the Jellyfishbot are no longer in question. Private companies dedicated to waste collection such as SMA (Monaco Sanitation company) in Monaco, by companies specialized in industrial sites depollution such as SERPOL, and by one private petrochemical company, lately research institutes in France and abroad chose to acquire a robot to depollute, clean or conduct research on microplastics. Finally, several theme parks and leisure centers are beginning to be equipped. For example, the Yokohama Hakkeijima Sea Paradise aquarium uses the robot to maintain their water bodies but also to educate and develop the awareness of their audience regarding coastal preservation.

Fig.1: Jellyfishbot

Fig.2: Bathymetric survey on control display

2.5. A robot very easy to use

Compact, easy to handle and very light, the Jellyfishbot is extremely simple to transport and to set up. It can be operated by one person and passes through all types of doors. It can be operated by only one person. It can tow a net containing up to 80 liters of waste and 30 liters of oils, and covers a cleaning area of 1000 m² per hour at an average speed of 1 kn. Once full, the net is easily removed and replaced without the robot having to leave the water. The operator simply uses a boat hook to remove the frame and net. The maintenance is also simplified, a quick rinse with clear water is enough, and in case of oils depollution, no-rinse products are recommended and available for purchase. The Jellyfishbot can operate up to 8 h and needs only 2 h for recharging. Batteries are removable and can be easily exchanged with another set for continuous use of the robot.

2.6. New features from 2021: a 100% autonomous robot

Since 2018 the Jellyfishbot has been available in a remote-controlled version. In January 2021, IADYS took a new step with an autonomous version of the robot, tested in Cassis harbor. "This is a feature that our customers are very excited about. It's a real efficiency booster for Jellyfishbot operators because they can do other tasks while the robot is cleaning the water", Dr. Nicolas Carlési explains. It's quite simple: it only needs to determine GPS points that shape the area to clean, directly on the remote control's screen. Once programmed, the robot will automatically move to the area to be cleaned and will stay there, avoiding obstacles on its path. Throughout the mission, the user gets remote access to the video on the remote control's built-in screen thanks to the on-board camera. The user can then take over the robot to clean the hard-to-reach areas (such as boat moorings) or bring it back to its starting point, where he can remove and empty the net.

This autonomous version sets the stage for practical applications requiring the cooperation of several robots for handling wider areas or for ongoing maintenance. Clients can also add options such as 5G connectivity, a flashing light to alert people of its presence or accessories such as different types of nets, one of which is 100% upcycled or a transport and launching trolley to improve working conditions.

2.7. New features in 2022: bathymetry and water quality measures

Genuine "Swiss Army Knife", the Jellyfishbot can be equipped with probes and measures the quality of the water (salinity, temperature, turbidity, cyanobacteria, and phytoplankton concentration levels, etc.). The robot can also perform bathymetric surveys down to 10 m in depth, Fig.2, using the sonar for further underwater obstacle avoidance. It allows the users to clean the hard-to-reach areas, in total safety, autonomously or remotely. It facilitates the maintenance and monitoring of aquatic areas.

2.8. Future features in 2023: detection of moving obstacles

IADYS plans to roll out a second level of autonomy in the first quarter of 2023, with the launch of the Advanced Jellyfishbot. Based on the same functions as the previous autonomous robots (onboard camera, GPS, 4G), the next version will operate in an area defined by the operator, fully autonomously, avoiding all moving objects in the intervention area. This version is specially designed for the harbors with higher boat traffic.

3. Positive environmental and societal impacts

IADYS is committed to reducing its impact and that of the Jellyfishbot on the environment. Through an ambitious CSR program, we have identified 7 Sustainable Development Goals, among the 17 established by the UN, on which we have the most impact and on which it is essential to act now. Reflections are carried out at each stage of the robot's design and manufacture to achieve these objectives, and to contribute, at our level, to the global effort of energy transition and protection of the marine environment. As such, IADYS and the Jellyfishbot contribute to:

- UN SDG #3: Good health and well-being
- UN SDG #6: Clean water and sanitation
- UN SDG #8: Decent work and economic growth
- UN SDG #11: Sustainable cities and communities

- UN SDG #13: Climate action
- UN SDG #14: Life below water
- UN SDG #17: Partnerships to achieve the goal

3.1. Improving work conditions

Before the Jellyfishbot was designed, the collection of waste from water bodies was mostly done manually. This was difficult work, with limited efficiency, which exposed staff to the risk of falls, musculoskeletal disorders and health risks due to contact with polluted substances. The robot therefore helps to improve the working conditions of the staff responsible for collecting pollution from water bodies. The drastically reduced workload means that the only operations they must carry out are putting the robots in the water, supervising them in their collection task and replacing the nets as soon as they are full. The safety conditions of the operators are thus significantly improved, as handling is limited, and they are no longer directly exposed to waste and toxic substances. The Jellyfishbot also allows an increase in the skills of the staff in charge of maintaining the water body. The operators now become trained and qualified drone pilots.

3.2. Less waste, more recycling

With the Sea-neT project, IADYS is actively participating in the transition towards a circular economy by providing new solutions for the collection, reuse or recovery of marine waste. Thanks to the collections made with the Jellyfishbot, the project contributes to the reduction of waste discharged into the water. The Jellyfishbot allows for more frequent and efficient waste collection, especially on water bodies near urban areas or economic activity zones, preventing this waste from being dispersed into the sea.

IADYS is in partnership with environmental associations that are setting up circular economy channels to recycle the marine plastic waste collected by the Jellyfishbot. “We raise our clients' awareness of the second life of the waste collected by the Jellyfishbot so that it can be recovered and reused/repurposed by these associations. Thus, all the plastic collected, once sorted and recycled, will be transformed into new objects such as filament for 3D printing which could even be used for our own production” explains Dr. Nicolas Carlési.

3.3. A tool for environmental monitoring and protection

The Jellyfishbot can be used for monitoring, inspection and maintenance of water distribution basins and canals, notably by carrying out bathymetric surveys, measuring water quality, the quantity of cyanobacteria and phytoplankton, and by collecting invasive species (duckweed) that can proliferate in these areas. IADYS is developing new functions for detecting and measuring environmental quality: presence of micro/macro-waste, hydrocarbons, measurement of water quality (temperature, salinity, turbidity, oxygen, cyanobacteria, phytoplankton).

Fig.3: Environmental monitoring


Fig.4: Educational role

These functions will help to change practices in terms of monitoring water quality and the presence of plastic waste and hydrocarbons in water, facilitated by autonomous robots, in order to prevent the discharge and dispersion of pollution in the marine environment. Awareness campaigns on the problem of waste in aquatic areas also lead to changes in practices to limit the pressure on the environment.

3.4. Attention to natural resources

IADYS is actively involved in the transition to a circular economy and in limiting the resources used and the waste produced. Design studies aim to use as many recycled and/or recyclable materials as possible in the manufacture of robots and equipment for the pollution control system. For example, since 2020, IADYS has been marketing a new macro-waste collection net for the Jellyfishbot, designed from end-of-life fishing nets and Dacron fabric, recovered by a partner company.

Fully electric, the Jellyfishbot does not consume fossil fuels, unlike alternatives available on the market to perform the same tasks. It is powered by LiFePO4 batteries and therefore produces no air pollution. The robots are very energy efficient as a single two-hour recharge of the batteries allows for 6 to 8 hours of operation. LiFePO4 batteries have a service life of around seven years in daily use, which corresponds to around 2000 charge/discharge cycles. Their long life means that they can be replaced less frequently and therefore consume fewer resources. The IADYS technical team also recovers and reuses/revalues defective robot parts. In general, IADYS is working hard with its suppliers to ensure that they follow the same environmental approach and offer solutions for managing the entire life cycle of products.

3.5. Conservation or restauration of biodiversity

By contributing to the collection of waste before it is dispersed in the open sea, the Jellyfishbot contributes very positively to the preservation of biodiversity in aquatic ecosystems. It is indeed indisputable that the biodiversity of marine and aquatic areas is directly dependent on water quality. The degradation of plastics and the dissolution of hydrocarbons degrade ecosystems, and their residues are ingested by the smallest organisms before being dispersed throughout the food chain. It is therefore essential to drastically reduce the amount of waste arriving in the oceans, especially as these materials have extremely long degradation cycles. The use of the Jellyfishbot therefore contributes to the preservation or restoration of biodiversity.

3.6. An educational role

IADYS is furthering its commitment to environmental preservation. The Jellyfishbot is an excellent awareness-raising tool for children, tourists, and citizens, Fig.4. Its color attracts attention, its handling is intuitive and extremely playful, which facilitates access to this technology for all types of public.

A Way Forward for In-water Proactive Cleaning

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Abstract

Biofouling on ships' underwater hulls is a problem in need of a solution. It accounts for an estimated 9 to 10% of world fleet Green House Gas (GHG) emissions and represents an important vector for invasive aquatic species. In-water Proactive Cleaning using remotely operated or autonomous sub-sea robotics is a new and potentially definitive approach to keeping ships' underwater hulls unfouled. To be truly proactive, one must be allowed to do it everywhere, however. This paper will summarize policy status with regard to proactive cleaning, identify main stakeholders and their respective interests and recommend a way forward.

1. Introduction

Biofouling on a ship's underwater hull has a negative effect on the environment and the cost of operating the ship. It increases frictional resistance of the hull and decreases propeller efficiency, leading to higher fuel consumption and increased emissions of pollutants to air. Biofouling on a ship's hull can also serve as a vector for the spread of aquatic invasive species.

According to the IMO, around 2.9% of the world's Greenhouse Gas (GHG) emissions stems from marine shipping activities, *IMO (2021a).* As much as 9-10% of these emissions is the result of biofouling on ship hulls causing an increase in resistance, *IMO (2015).* Therefore, combating biofouling can save roughly 0.3% of the global GHG emissions. Depending on ship type and bunker prices, fuel typically accounts for 50-70% of the cost of operating a ship. Given IMO's estimate of 9-10% of the fuel cost being a result of biofouling on ship hulls, combating biofouling can reduce the operating cost by around 5-6%.

Biofouling is considered as one of the most common mechanisms for the introduction of aquatic invasive species (including pathogen bacteria, microbes, small invertebrates, algae, eggs, cysts, and larvae of various species). The European Union (EU), for example, estimates biofouling on ships hulls account for around 21% of introduction of aquatic invasive species in the seas around the EU since records began in 1949, *EMSA (2021).* Biofouling has been identified as a potential means of transfer for 87% of New Zealand's non-indigenous marine species (NIMS), *Kospartov et al. (2008),* and more than 85% of NIMS in the waters of Hawaii, *Eldredge and Carlton (2002).*

Marine biofouling is typically classified in four stages of development, as shown in Fig.1. When a surface is submerged in seawater, an organic polymer film forms within minutes. During the first 24 hours, this layer allows bacteria to adhere, and they will form a biofilm (or slime layer). This stage is commonly referred to as microfouling. Within a week, algae and other single-cell organisms will have attached on the slime layer. After 2-3 weeks, organisms such as tubeworms, barnacles, etc. have attached. These organisms are known as macrofouling, *Davis and Williamson (1995).*

Increasing fouling will increase a ship hull's roughness accordingly and thereby also the total required shaft power to generate thrust to move a ship though water. Depending on hull design and operating profile, microfouling can result in an increase in shaft power of up to 20%. Macrofouling increase roughness and thereby required power even further, from an increase of 35% for small calcareous fouling or weed and up to 86% change in required shaft power for heavy calcareous fouling, *Schultz (2007).* As long as fouling is limited to microfouling, the biosecurity risk is generally considered low. When macrofouling is present on the hull, on ships traveling in between eco-systems, the risk of transfer of aquatic invasive species is sufficient to be of concern, *Georgiades and Kluza (2017).*

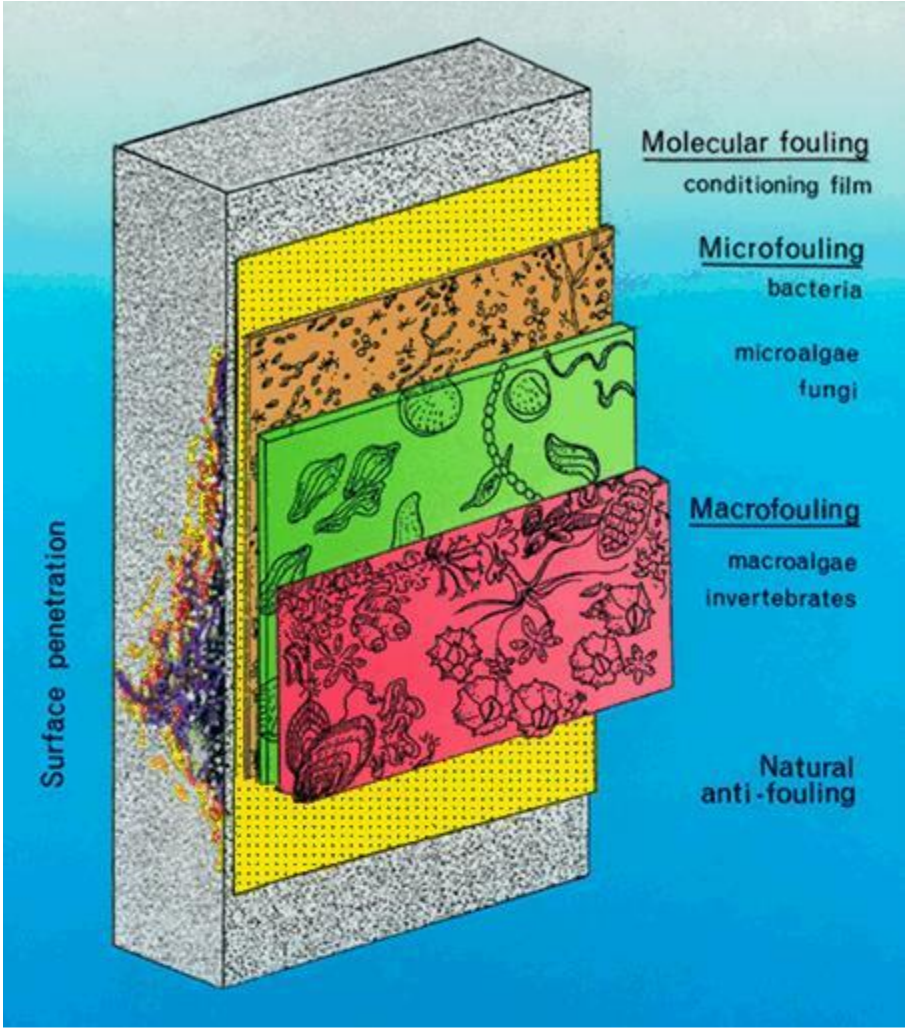

Fig.1: The four main stages of biofouling and their surface penetration, *Davis and Williamson (1995)*

Measures to combat biofouling are known as anti-fouling systems (AFS). AFS can generally be divided into two categories; prevention and removal. The most common preventive AFS today is anti-fouling paints or coatings. These coatings usually contain one or more biocides, which are released into the sea during the coating's life span. Another preventive approach is the use of fouling release coatings, which surface properties makes fouling adhesion difficult. These coatings typically require the ship to hold higher speeds to ensure the effect of self-cleaning. Biofouling removal (or cleaning) is done mechanically and can be done during the ship's dry dock or in-water (typically referred to as in-water cleaning (IWC)).

Inherent risks during fouling removal are erosion or damage to the coating and release of aquatic invasive species to the local marine environment. Fig.1 illustrates that biofouling at a late stage has a deep surface penetration. The risk of damaging the hull coating during cleaning is generally higher the more advanced the attached fouling. Erosion or damage to the coating can lead to excessive release of biocides and/or coating particles being released into the local marine environment. Furthermore, it can deteriorate the anti-fouling properties of the coating, leading to a potential increased risk of fouling during further operations.

IWC on macrofouling can cause release of aquatic invasive species to the local marine environment. To combat this, many technologies include mechanisms to capture the organic debris removed from the hull. Requirements for biofouling capture vary between different ports and port states. Some countries have no requirements for capture, while others have strict requirements, i.e. 90% capture or higher. Quantifying the accumulated and removed biomass is challenging. No standard methods exist to quantify and document the amount of biomass removed or to verify capture rates. The recently published BIMCO standard for IWC requires that 90% by mass of captured debris shall be separated/ treated but does not specify what share of total debris shall be captured in the first place, *BIMCO (2021).*

Proactive cleaning, also referred to as hull grooming, preemptive or preventative IWC, is a new tool in the biofouling management toolbox. Proactive cleaning is still at an early stage of development and according to the Clean Hull Initiative (CHI), proactive cleaning involves cleaning at a sufficiently high frequency, to ensure removal of any biofouling before it becomes a problem, *Oftedahl and Skarbø (2021).* In order for the proactive cleaning to be effective, the biofouling must be removed before it causes a measurable reduction in hull performance and corresponding increases in both carbon intensity (grams of CO_2 emitted per ton-mile) and fuel cost. It must also be removed "before it reaches macrofouling stage and before it represents a risk of transfer of invasive species. Finally, it must be removed before any later removal damage or erode the hull coating and thereby also contaminate the water column, *Oftedahl and Skarbø (2021).*

CHI argues that conventional antifouling paints cannot (yet) offer fully reliable protection against fouling on ships in the most challenging operations, *Oftedahl and Skarbø (2021)*. Examples cited of what can make operations challenging from a biofouling management perspective are:

- extended idling periods
- major changes in ship's operating profile (e.g. a major increase or decrease in sea-water temperature or operating speed)
- unplanned extensions of dry-docking intervals

Proactive cleaning is, at the current technology boundary, the only solution that can reliably keep the hull clean in such situations.

Along the same lines, Florida Institute of Technology defines hull grooming as the "gentle, habitual and frequent mechanical maintenance of a ship's hull in order to keep it free from fouling and particulate debris", *Tribou and Swain (2015).*

The technology provider that appears to have come furthest in bringing a proactive cleaning solution to the market is Jotun. As of August 2022, Jotun reports being in the final verification stage of their latest innovation for proactive cleaning. Other companies have indicated they are working on proactive cleaning solutions including SeaRobotics, iKnowHow/Scrufy and Armach Robotics.

This paper will summarize policy status with regard to proactive cleaning, identify main stakeholders and their respective interests, and recommend a way forward.

2. Policy status

2.1. Biofouling management regulations and in-water cleaning policies

The regulatory landscape on IWC and biofouling management in general is complex. Most jurisdictions globally lack explicit (and implicit) regulations for in-water cleaning. There is no international agreement on what a comprehensive IWC policy should contain, and policies vary greatly between different jurisdictions. With no internationally agreed IWC standard, system testing procedures and a lack of independent expert approval bodies, authorities attempting to mitigate environmental risks from in-water cleaning may be reluctant to approve IWC operations, based on the precautionary approach, *IMO (2022).*

Some jurisdictions have regulations, standards and/or practices for biofouling, but this is in general not widespread. In 2011, IMO published guidelines on biofouling management on ships, *IMO (2011).* However, these guidelines are by nature not mandatory, and have been criticized for not being specific enough. Even the jurisdictions with most comprehensive biofouling management policies, such as New Zealand and the state of California (United States), are both consistent with the 2011 IMO Biofouling Guidelines, but with differences in approach. Currently, at least 19 regional, national and sub-national biofouling policies and practices are already in place, with at least 27 policies intended to be developed in the next five years, *IMO (2022)*. A report commissioned by the Global Industry Alliance (GIA) for Marine Biosafety concluded that without an overarching international regulation or convention on biofouling management, inconsistencies between jurisdictions would continue to occur. These inconsistencies and thereby lack of standardized biofouling management practices, increase complexity and create a major challenge for the shipping industry when attempting to manage biofouling proactively, *IMO (2022)*.

Jurisdiction of hull cleaning activities can fall under several regulatory authorities. Typically, it is up to the port authority to determine whether a hull cleaning operation can be carried out in a port or at an anchorage. However, if there exist one or more regulatory agencies with jurisdiction of i.e. biosecurity and/or water quality, they would typically have to approve the operation and/or in some cases issue a permit. Some port authorities have their own IWC/biofouling policies, independent of the local, regional and/or national public regulatory bodies. Some jurisdictions have a case-by-case approval for IWC operations. Typically, the approval is based on a biosecurity risk assessment of the vessel in question, where the assessment is based on anti-fouling system, previous trade, previous cleaning operations, cleaning method to be used, etc. Other countries have a permit system, where IWC operators are required to be registered and approved and the equipment or cleaning systems certified according to certain requirements. Many authorities have water quality regulations or guidelines that limit the types and quantities of contaminants and substances in their waters.

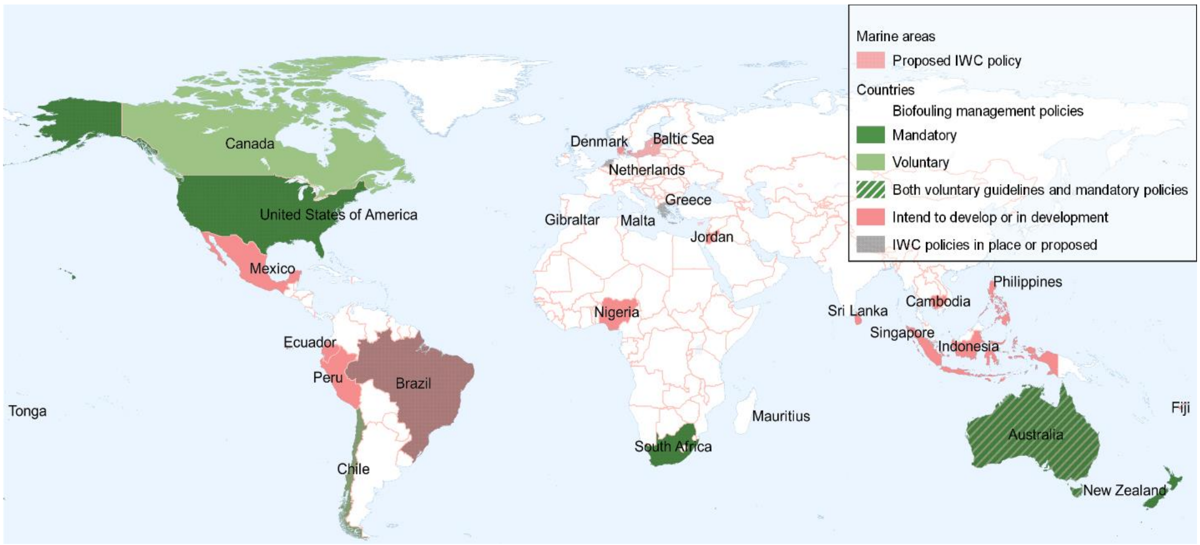

Fig.2: Current and proposed public biofouling management policies and IWC policies, *IMO (2022)*

2.2. Proactive cleaning

Proactive cleaning regulations are also at an early stage. Jotun experiences that proactive cleaning is allowed on a piloting basis in several ports and at several anchorages worldwide, including ports within EU, US, Panama, New Zealand, Australia, Japan, South Korea, Singapore, Taiwan, India and South Africa.

References to proactive cleaning are made in draft Biofouling Management Guideline from *IMO (2021b)*, in a proposed new Vessel Incidental Discharge Act from the Environmental Protection Agency in the US, *EPA (2020)*, in Australia's proposed new In-Water Cleaning (minimum) Standard, *DAWE (2021)*, and in Canada's draft Voluntary Guidance for Relevant authorities on In-water Cleaning of Vessels, *TC (2021)*.

In the draft revised Biofouling Guideline from IMO, proactive cleaning, including hull grooming, is defined as “a protective measure to prevent or minimize newly attached microfouling”, *IMO (2021b)*, p.15. It includes methods for frequent and gentle wiping of the hull or by use of hydrodynamic forces and, as long as compatible with the hull coating used, is recommended once the bio fouling in the relevant area reaches the light microfouling stage (p.22). Microfouling is described as a precursor to macrofouling caused by bacteria, fungi, microalgae and other microscopic organisms, such as diatoms that create a biofilm also called a slime layer. The microfouling is defined as light when the slime layer is less than 5 mm (p.14). The technology used to undertake proactive cleaning should not damage the hull coating and avoid release of harmful waste substances (p.23). Proactive cleaning can be done without capture if it does not damage the hull coating and as long as the biofouling in the relevant area is limited to light microfouling (p.5).

In a draft new Vessel Incidental Discharge Act the US Environmental Protection Agency uses the term “Preventative in-water cleaning” and defines it as “the frequent, gentle cleaning of the vessel hull and appendages to prevent the growth of biofouling organisms, with minimal impacts to the antifouling system”, *EPA (2020)*, p.67868. According to the agency, “preventative cleaning has been shown to effectively reduce biofouling without significantly increasing biocide loading into the aquatic environment”. Macrofouling requires more abrasive removal techniques, which may damage the antifouling coating, resulting in a higher tendency for subsequent biofouling as well as a larger pulse of biocides and particles into the aquatic environment. Additionally, macrofouling (FR >20) is composed of more diverse and mature organisms and, depending on geographic origin, may present a greater risk of discharging ANS than a slime layer, *EPA (2020)*, p.67868). EPA therefore proposes to prohibit in-water cleaning of biofouling beyond microfouling, except when the fouling is local in origin and cleaning does not result in the substantial removal of a biocidal antifouling coating, as indicated by a plume or cloud of paint; or when an in-water cleaning and capture system is used that is designed and operated to capture coatings and biofouling organisms; filter biofouling organisms from the effluent, and minimize the release of biocides, *EPA (2020)*, p.67868). EPA expects that regular cleaning of microfouling, in combination with the potential for cleaning of macrofouling with in-water cleaning and capture systems, currently represents best available technology, *EPA (2020)*, p. 67868.

In a proposed new Australian in-water cleaning (minimum) standard, the Australian Department of Agriculture, Water and the Environment (DAWE) uses the term “hull grooming” and describes it as “[p]roactive, regular and light cleaning of a vessel hull coating to remove slime or prevent the establishment of biofouling”, *DAWE (2021)*, p.12. According to DAWE, hull grooming can be done without collection given a set of requirements are met, notably including removal of the fouling before it reaches the macrofouling stage and without damaging the hull coating, *DAWE (2021)*, p.8.

In its draft Voluntary guidance for relevant authorities on in-water cleaning of vessels, the Canadian Ministry of Transport (Transport Canada), does not use the term proactive cleaning or similar. Transport Canada recommends opening up for in-water cleaning without capture in the event that the fouling to be removed consists only of microfouling or is of local origin, however, *TC (2021)*, p.13.

Although the terms used differs, it appears to be broad alignment on some main attributes of an underlying proactive cleaning concept: Removing biofouling before it reaches macrofouling stage and without causing damage to the hull coating, with no need for collection of debris.

3. Stakeholders and stakeholder interests

The most important stakeholders with an interest in proactive cleaning are shipowners/operators, their interest organizations as well as port and anchorage administrators, providers of hull cleaning services, hull coating providers, IMO, and other regulatory bodies. Other regulatory bodies can be further sub-divided into environmental regulators, health and safety regulators and security regulators.

Considering only benefits upon which proactive cleaning has a bearing, shipowners/operators and their interest organizations are expected to be most interested in:

- having cost and energy efficient ships and reducing overall environmental footprint
- maintaining universal access to ports and anchorages
- a level playing field and the same rules applying everywhere
- having the flexibility to choose between different tools in the biofouling management toolbox

Proactive cleaning, if it remains voluntary and the same rules apply everywhere, appears compatible with all these interests. If proactive cleaning can live up to its promise of keeping the hull always clean, it can represent a substantial contribution towards having energy efficient ships and also help deliver on other sustainability related requirements.

The most important interests of port and anchorage administrators are expected to be to:

- allow the efficient operation of the port or anchorage
- reduce the environmental footprint per call or stay
- ensure safety of personnel and other assets
- minimize administrative complexity and costs

Proactive cleaning, if sufficiently regulated, appears compatible with these most important interests. Individual port and anchorage administrators, given their interest in minimizing environmental footprint per port call within their own port, may prefer that proactive cleaning is being done elsewhere. As a group, however, port and anchorage administrators are expected to find it in their shared interest that proactive cleaning is mandatory everywhere.

Hull cleaning service providers are expected to be most interested in:

- having the flexibility to offer different tools in the biofouling management toolbox
- a level playing field and the same rules applying everywhere

Some providers offer proactive cleaning services, other reactive cleaning with collection. Seen as a group, they are therefore expected to be interested in proactive cleaning being permitted but voluntary.

Hull coating providers are also expected to be most interested in:

- having the flexibility to offer different tools in the biofouling management toolbox
- a level playing field and the same rules applying everywhere

As the cleaning service providers, some of the Hull coating providers have coatings that are already compatible with proactive cleaning, while others do not. One provider, Jotun, is offering its own proactive cleaning solution while other providers have partnered up with providers of reactive cleaning with collection services. As a group, hull coating providers are expected to be interested in proactive cleaning being permitted but voluntary.

The most important interests of the IMO are expected to be to:

- ensure a level playing field and that the same rules apply everywhere
- improve the environmental footprint of the world fleet (with a particular focus on reducing carbon emissions)
- ensure the safety and security of vessels and crews

Proactive cleaning, as long as sufficiently and uniformly regulated, appears compatible with all of these interests. It can also contribute positively towards improving the world fleet environmental footprint and IMO, as long as technology is generally available and costs are reasonable, may therefore also find it in its interest that proactive cleaning is being done everywhere/is made mandatory.

Environmental regulators are expected to be most interested in:

- reducing emissions to air
- reducing emissions to sea (metals, paint particles and organic matter)
- reducing risk of transfer of invasive species (improve biosecurity)

Proactive cleaning, if sufficiently regulated, appears compatible with and can contribute positively towards all these interests. Environmental regulators are expected to see it in their interest that proactive cleaning is done everywhere/is mandatory.

Health and safety regulators are expected to mostly be interested in:

- the health and safety of personnel in the port including port workers, ship crews, service personnel and, where relevant, divers.

Note that proactive cleaning in principle can be done with either divers or remotely operated equipment. Either way, sufficiently regulated, it should be possible to bring health and safety risks to an acceptable level.

Security regulators are expected to be interested in:

- minimizing security related threats including cyber, terrorism, sabotage, and espionage.

Note that in particularly sensitive areas security regulators may even want to block activities that do not pose a direct threat, but that result in an increase in overall complexity. In locations where this is not an issue, if sufficiently regulated, it should be possible to bring also security related risks to an acceptable level.

In summary, it appears all identified stakeholders share an interest in sufficient regulation of proactive cleaning. Stakeholders would also likely agree, or at least not object to, a level playing field and the same regulations applying everywhere.

Stakeholders are likely to differ on whether proactive cleaning should be voluntary or mandatory, however. Ship owners and operators and their interest organizations as well as hull cleaning service providers are likely to see it in their interest that proactive cleaning remains voluntary. Environmental regulators are likely to take the opposite view. Port and anchorage administrators as well as the IMO are likely to either be neutral on the issue or lean towards proactive cleaning becoming mandatory. Remaining stakeholders are likely to be neutral.

4. Recommended way forward

As summarized above; all identified stakeholders are likely to share an interest in sufficient regulation of proactive cleaning so as to ensure environmental risks, occupational health and safety risks as well as security risks are brought to an acceptable level. Identified stakeholders would also likely agree, or at least not object to, a level playing field and the same regulations applying everywhere. An obvious recommendation is therefore for stakeholders to work towards sufficient and globally harmonized regulation of proactive cleaning.

As also summarized above, stakeholders are likely to differ on whether proactive cleaning should be mandatory or voluntary.

However, some environmental regulators are likely to act unilaterally. This has already happened in New Zealand where it is now required that "[t]he operator or person in charge of any vessel must take all reasonable and practicable steps to ensure that when the vessel enters New Zealand territory, it is free of regulated pests and substantially free of biosecurity contamination", *MPI (2018)*, p.12).

If such unilateral regulations become more prevalent, there will be fewer and fewer places to clean reactively. On some routes proactive cleaning may be the only viable option. Given the interest of IMO and other stakeholders in a level playing field and the same rules applying everywhere, the best way forward may then be to make proactive cleaning mandatory.

In preparation for such an eventuality, the obvious recommendation is again for stakeholders to work towards sufficient and globally harmonized regulation of proactive cleaning.

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Effects of Repetitive Underwater Cleaning Operations on Two Fouling Release Coatings

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Abstract

Nowadays controlled underwater hull cleaning operations are opening a new chapter in the shipping industry, and although the fouling control coatings available in the market are not designed to undergo a cleaning process, some studies have proved that gentle cleaning (proactive cleaning) on newly developed thin biofouling is beneficial. In order to evaluate the fouling control coating resistance to mechanical stress, tests that simulate in-water cleaning operations and subsequent surface characterization are required. This study aims to investigate the effect of repetitive cleaning operations on biofouling accumulation, on two different thin fouling release coatings, immersed in the sea under static conditions, during the summer season in the North Sea. The two coatings responded differently to the cleaning process, one was biofouling free after cleaning, while the second paint was showing less effective biofouling removal. Importantly, surface roughness was not significantly impacted when before and after cleaning conditions were assessed. It is fundamental to address the appropriate cleaning setup to the type of fouling pressure and fouling control coating.

1. Introduction

Tightening regulation on biocides for marine antifouling applications has led to renewed interest in novel strategies to fight marine organisms from settling on submerged structures, *Bressy et al. (2010), Abioye et al. (2019), Hopkins et al. (2021).* Nowadays biofouling management strategies are represented by different approaches that are designed to meet the best efficacy and the environmental safety, *Davidson et al. (2016), Scianni et al. (2021).*

With the constant release of toxic compounds from antifouling surfaces, marine organisms in search for a suitable place to settle and develop, are discouraged, physiologically altered or killed. Some of these substances are effective but with the downside of affecting other non-target organisms and representing a source of pollution for the oceans, *Inoue et al. (2004), Qiu et al. (2022)*. Silicone based coatings were developed with the intent of facilitating the release of biofouling without releasing toxic compounds, by having a low surface energy and relatively low elastic modulus, biofouling can be removed by the shear force of the water flowing during sailing time, *Di Fino (2015), Lin et al. (2022*). Fouling control coatings do not always guarantee protection for a full service period, therefore affecting ship performance, fuel consumption and related environmental problems due the greenhouse gases emission (GHG), *Buhaug et al. (2009), Schultz et al. (2011)*. Increased hull unevenness as a result from fouling, has led to mechanical fouling removal from the hull as a drastic measure to decrease the friction. Stiff brushes are often used to remove hard fouling in order to make the ship sailing in better conditions. Such hard cleaning methods can add potential damages to the paint system or the hull structures and pose environmental hazard by the spreading of non-indigenous organisms, *Davidson et al. (2009), Tamburri et al. (2020).* Moreover, worn-out antifouling coating systems are expected to refoul faster.

Proactive cleaning methods were designed to operate more frequently in order to remove biofouling during the first development stage of biofouling. However, it is critical to demonstrate the real impact of cleaning methods on different fouling control coatings. Different parameters need to be considered to find the best match between cleaning devices, fouling rate and coating systems, *Oliveira and Granhag (2020)*. It is now believed that the gentle action of soft brushes could remove early-stage biofouling organisms, leave the fouling control coating intact and, possibly, help increase the service life of the coating system. In this regard, *Swain et al. (2022)* demonstrated that grooming, *Tribou and Swain (2015),* i.e. proactive cleaning, is beneficial for both silicone and self-polish coatings (SPC).

Different methodologies and risks of in-water cleaning technologies were analysed for different combinations of paints and cleaning methods, *Morrisey and Woods (2015)*, and it was concluded that it is crucial to match the right variables of type of coatings, cleaning methodologies and biofouling. Reduced ships performance can also be related to mismanagement of underwater cleaning operations, *Morrisey and Woods (2015)*.

In the present study, the fouling control efficacy of two silicone-based coatings were investigated during underwater cleaning operations. The silicone-based coatings were assessed in static conditions against biofouling accumulation. A static immersion test of coated panels is actually a worst-case scenario from fouling pressure point of view: it simulates a vessel that never sails. This method might give more insight into the cleanability of heavy fouled panels. The cleaning operations were carried out by a proactive in-water grooming method where soft brushes (mounted on a cleaning drone) were periodically used to remove biofouling and the coating performance was assessed over time during the Dutch summer.

2. Material and methods

2.1 Panels

The raft for static panel exposure is located in the harbour of Den Helder. The exposure conditions are representative for a North-European sea and described as coastal water with high biofouling intensity during the biofouling season, lasting from March till October. In the harbour natural tidal currents occur that vary between 0 and 2 knots. Location of the raft is at a distance less than 100 m from the shore and water depth under the raft is at least 8 m, Fig.1.

Fig.1: Raft exposure facility of Endures in the harbour of Den Helder, The Netherlands

For the underwater cleaning tests, six aluminium panels measuring 170 x 30 x 0.5 cm were coated with an epoxy primer. Subsequently, three panels were coated with hard fouling release paint Slips® Dolphin^{TM} and three with a soft silicone-based paint, Fig.2. The soft silicone fouling release paint was chosen from a product available on the market. The topcoat was applied with a dry film thickness of 25 µm. Slips® Dolphin^{TM} is a fouling release paint composed of 70% of silicone and 30% of surface-active polymers (SAPS) that gives high stiffness properties, the topcoat thickness was 45 µm. These panels will be referred to as experimental panels throughout this paper.

Further six polyvinylchloride (PVC) panels 30 x 25 cm were employed to monitor the biofouling accumulation serving as controls, two were lightly sanded and left uncoated, two coated with hard silicone paint (Slips® Dolphin^{TM}) and two with the soft silicone paint, similar to the test setup described in the ECHA Guidance on the Biocidal Products Regulation PT21 antifouling products. The small control panels were mounted at two different depths (30 and 70 cm) and not touched during the test period, Fig.2.

Fig.2: Coated panels mounted on metal frames. Yellow coatings are foul-release, blue coatings are Slips.

Elongated panels are used for the cleaning operations (experimental panels), square coatings are the controls (i.e. not cleaned throughout the test period). Biofouling accumulation was tested by exposing panels in static immersion at the raft testing facility. Panels were mounted vertically on composite racks and immersed in the sea, Fig.1). The sea temperature was varying between 21 and 24°C.

Cleaning operations were performed every 8-10 days (depending on weather conditions) for a total of two months. Pictures were first taken underwater before cleaning operations in order to estimate the biofouling development. Subsequently the cleaning drone was laid on the panels and guided over the entire coated panel by using a remote control equipped with an LCD screen connected to the drone's camera. The robot was cleaning the panels vertically and horizontally, for a maximum of two passages per direction. Barnacles found on Slips panels before the drone cleaning, if not effectively detached during this process, as an additional step, the barnacles were manually removed with a soft abrasive sponge.

2.2 Drone

The underwater cleaning robot (Keelcrab™) equipped with nylon inset counter-rotating centre brushes, was used to clean the panels. The movement of the drone is provided by rubber wheels brushes driven by tracks that allow manoeuvring in all directions. The brushes used were 60 mm diameter and 300 mm long. Bristles were 0.35 mm diameter, with a density of 50 /cm^2. The robot suction effect was generated by a thruster connected to a pump motor, applying a vertical force to the coating of 15.7 N when static position and 12.7 when moving/cleaning. The cleaning speed was about 2 m^2 per minute.

2.3 Biofouling assessment

Coverage of biofouling was first monitored on the experimental panels by immersing a camera in the sea before performing the cleaning operation. After the cleaning operations were concluded, panels were lifted out of the sea, biofouling was assessed, and pictures taken as comparison before-after. The control panels were not subject to cleaning, were photographed when the racks were lifted out of the sea.

2.4 Surface characterization

Coating thickness was measured before the immersion in seawater and at the end of the tests after the cleaning operations. Measurements were carried out with Elcometer digital coating thickness gauge. Roughness values were measured with Taylor & Hobson Surtronic Duo reader, measurements were performed before the immersion in seawater, after the cleaning operations and at the end of the tests. On slips panels where some biofouling was not completely removed by the cleaning robot, an area was cleaned by hand to allow the gauge of roughness reader.

3. Results

3.1 Coating properties

Surface characterization of panels was performed before the immersion in seawater and after the end of the cleaning operations, including roughness, thickness, and wettability, Table I. Roughness R*t* (difference between the maximum height value and the minimum height value within the Evaluation Length) measured on each panels, for Slips paint was 6.3±2 µm before cleaning and 13.1±3 µm after, for the soft silicone paint between 6.5±4 µm before cleaning and 10±8 µm after. R*a*, (arithmetical mean height within length), measurements for Slips were 0.21±0.1 µm before cleaning and 0.68±0.2 µm after cleaning, for the soft silicone paint was 0.22±0.1 µm before cleaning and 0.59±0.2 µm after cleaning, Fig.3. Static analysis for roughness measurements was performed considering data collected after every cleaning process. A two-tailed t-test was performed and no statistical difference in R*a* values was found when comparing T0 and T49 (end point) for both Silicone and Slips, P=0.086 and P=0.220, respectively.

Table I: Coating properties

Measured Properties	Silicone before cleaning	Silicone after cleaning	Slips before cleaning	Slips after cleaning
Thickness top layer	20 - 30 µm	-	46.6 ± 5 µm	-
Thickness paint system	286 ±32 µm	346 ±5 µm	346 ±26 µm	375 ±94 µm
Contact angle	97.6°	98°	74.4°	72°
Roughness R*t*	6.5 ±5 µm	10.06 ±8 µm	6.3 ±2 µm	13.1 ±3 µm
Roughness R*a*	0.22 ±0.1 µm	0.59 ±0.2 µm	0.21 ±0.1 µm	0.68 ±0.2 µm

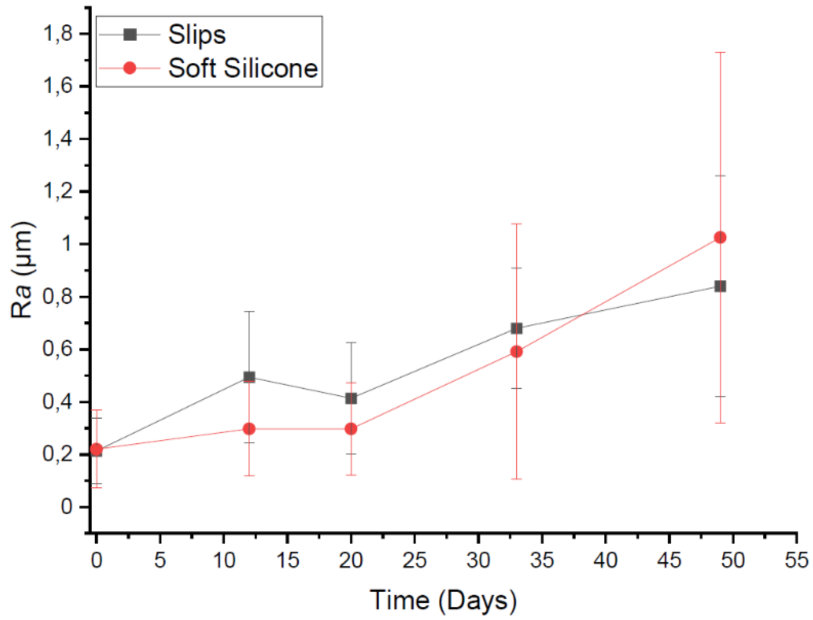


Fig.3: Roughness (Ra) values for Slips and soft silicone paints during a 49 days' immersion

Thickness of the paint system was 346 ±3 µm before cleaning and 375±9 µm after cleaning for Slips paint. For the soft silicone paint it was 28±3 µm before cleaning and 346±5 µm after. The contact angle contact angle measured were 74° before immersion in seawater and 72° after the last cleaning operation for Slips. For the soft silicone paint it was 97.6° before immersion in seawater and 98° after.

3.2 Biofouling

Coated and uncoated panels were immersed in seawater for 7 weeks and 5 cleaning operations were performed. Water temperature was between 21 and 24° C. The first cleaning operation was carried out after 12 days from immersion in seawater. Fouling coverage on Slips and soft silicone coated experimental panels was 51 and 55% respectively, represented by biofilm and green algae, after cleaning the biofouling coverage decreased to 30 and 3%, respectively, Figs.4 and 5. The uncleaned control panels coated with slip were covered by 56% with brown and green algae, while the soft silicone was 35% covered with biofilm and brown algae, Fig.6. The experimental panels were manually gently cleaned of any remaining biofouling not removed by the drone.

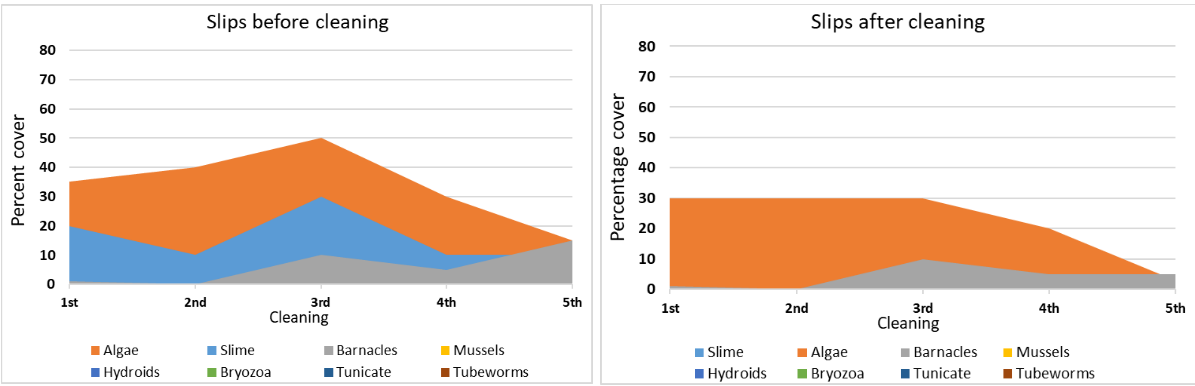


Fig.4: Percentage of biofouling coverage on Slips coating before (left) and after (right) cleaning

Fouling coverage for the second cleaning operation was assessed after 20 days from immersion in seawater, Slips and soft silicone coated experimental panels was 50 and 62% respectively. After cleaning the biofouling coverage decreased to 30 and 3%. The uncoated PVC panels were 90% covered by biofouling. The uncleaned control panels coated with Slip paint were covered by 68% by brown and green algae, while the soft silicone paint was covered by 64%.

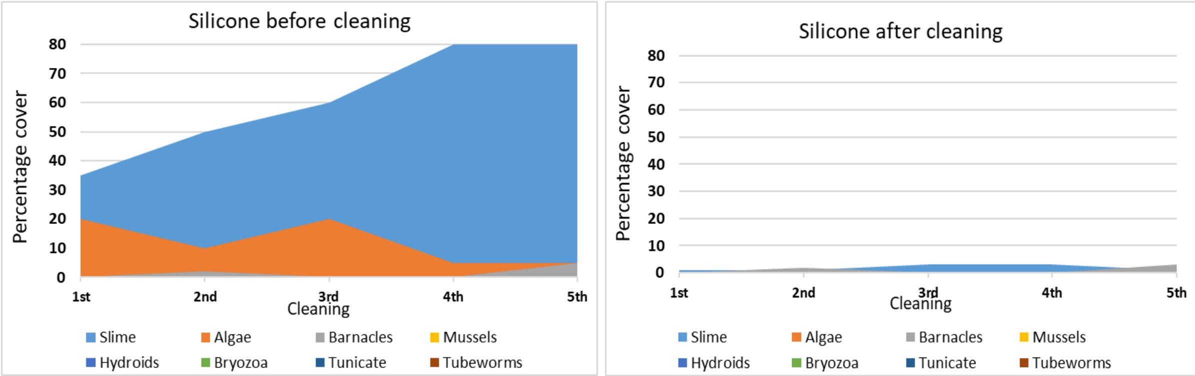


Fig.5: Percentage of biofouling coverage on soft silicone coating before (left) and after (right) cleaning

For the third cleaning operation (33 days immersed in seawater), fouling coverage on experimental coated panels was assessed. The total surface occupied by biofouling was 80 and 90% for the soft silicone and Slips paints, while after cleaning the fouling coverage reduced to 40 and 3% respectively. The uncoated PVC control panels were 95% covered by biofouling. The uncleaned control panels coated with Slip paint were covered by 87% by brown and green algae, while the soft silicone paint was covered by 76%.

After 41 days of immersion in seawater the fouling coverage on experimental panels was 45 and 85% for Slip and Soft silicone coatings, after the cleaning operation the coverage percentages decreased to 25 and 1% respectively. The uncleaned control panels coated with Slip paint were covered by 84% compared to the control panels coated with soft silicone paint that was covered by 82%.

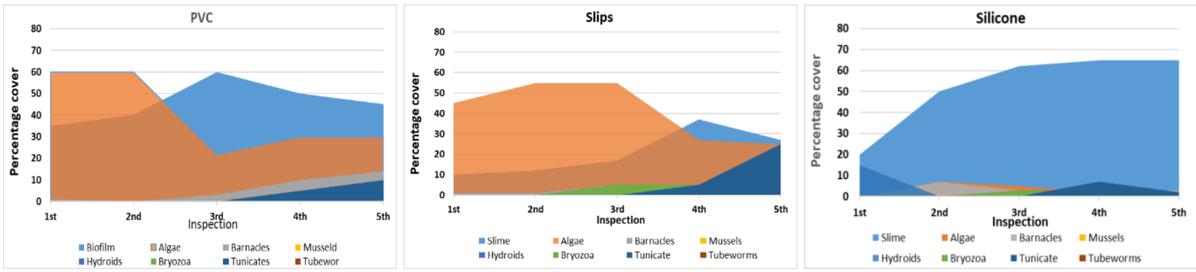


Fig.6: Percentage of biofouling coverage on PVC (left), Slips (center) and soft silicone paint (right)

Uncoated and uncleaned PVC panels were 100% covered by biofouling organisms. The biofouling organisms were overlapping on each other creating a high complex living system that was not allowing a precise identification.

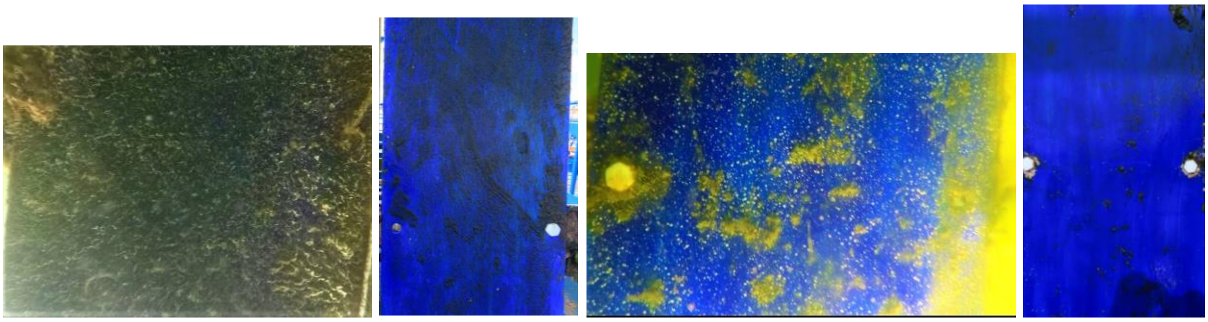


Fig.7: Fouling coverage on Slips paint before (left) and after (center left) the first cleaning and before (center right) and after (right) the fifth cleaning operation

The fifth and last cleaning operation was carried out after the second week of August. The biofouling coverage on Slips, Fig.7, and soft silicone was 40% and 90%, respectively, after cleaning the percentage decreased to 8% and 3%, Fig.8.

The uncleaned control panels coated with Slip paint were covered by 100% compared to the panels coated with soft silicone paint that was covered by 76%. Uncoated and uncleaned PVC panels were 100% covered by biofouling organisms, Fig. 9.

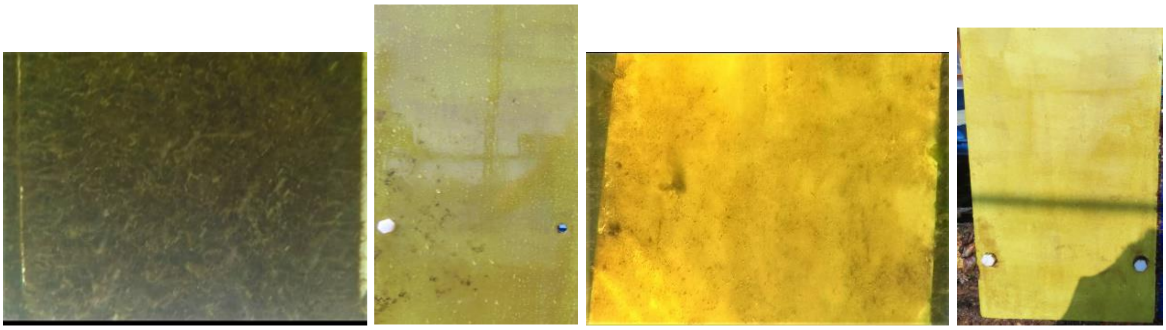
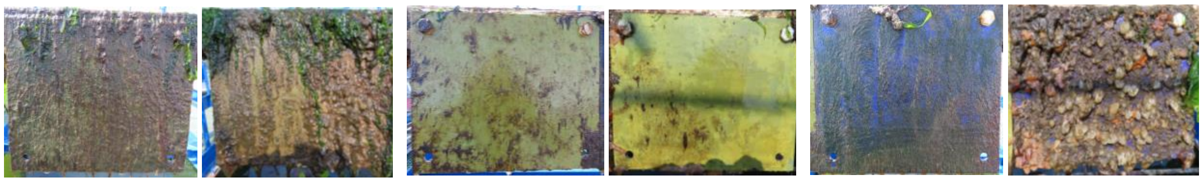


Fig.8: Fouling coverage on soft silicone paint before (left) and after (left center) the first cleaning operation and before (right center) and after (right) the fifth cleaning operation



PVC Soft silicone Slips

Fig.9: Biofouling coverage of control panels immersed in seawater: left images represent inspection after 12 days and right images immersions after 49 days (end point).

4. Discussion

The central aim of this study was to determine the performance of fouling release properties of two different silicone-based coatings following underwater cleaning operations conducted by a drone equipped with brushes. Surface characteristics, mechanical resistance to abrasion and fouling response were assessed during two months of immersion in seawater and 5 cleaning operations.

The expectation was that surface properties of silicone-based coating integrity would not be significantly affected by repetitive cleaning operation performed with brushes, *Swain et al. (2022)*, and that there would be a positive effect on the fouling control performance of these coatings, *Tribou and Swain (2010*). Two different silicone-based coatings with different rigidity and thickness were cleaned regularly during the North Sea high fouling season. During each inspection performed, before cleaning operations, both hard silicone (Slips) and soft silicone coating were found with a high biofouling coverage, mostly by slime, algae, and barnacles. The cleaning drone was capable of completely cleaning the settled organisms from the soft silicone coating after each cleaning operation, with only few juvenile barnacles remaining following the last cleaning. On the Slips coating, the biofouling covering the surface after the cleaning operation decreased substantially, hydroids and slime were completely removed, contrary, green algae and barnacles were still attached. Such organisms were removed with a sponge from the surfaces. However, a lower percentage of barnacles were found re-settled every time an inspection was performed. Only the number of juvenile barnacles were increasing with time, probably due to the remaining parts of calcareous bases, not completely removed, that attracted new recruits potentially due to settlement-inducing protein complex (SIPC), *Dreanno et al. (2006a,b*). The green algae predominance on Slips paint was explainable with the intense solar radiation of the summer sunny days; when the drone failed to remove them, sponges were used, however, the algae were punctually growing back. Only after the third inspection, the algae coverage was lower (with constant light intensity) and easier to remove by the drone. Although soft brushes were used to clean the panels, biofilm was always completely removed from both silicone paints, contrary to other findings that even with different cleaning frequency the most tenacious biofilm was not completely removed, *Hearin et al*.

(2016). Certainly the environmental and exposure conditions and potentially the biofilm diversity were different and not directly comparable as highlighted by *Hearin et al. (2015)*.

The small, uncleaned panels were showing high fouling coverage on Slips paint compared to the soft silicone that showed mostly biofilm and some algae. After six weeks the total area was occupied by fouling development that reached a high diversity and thickness. Such rich fouling was easily to remove by hands, leaving the surface almost completely clean, a quick cleaning with a soft sponge restored the panels.

Generally fouling pressure on the experimental, i.e. cleaned, panels decreased with time and the cleaning operations were greatly facilitated, agreeing with *Tribou and Swain (2010)*, *Tribou and Swain (2017)* and *Swain et al. (2022)* who demonstrated that grooming operation with different rotating brushes was helping the paint remaining relatively free of fouling. It is probable that the cleaning frequency plays an important role in this context *Hearin et al. (2016)*, found that the highest frequent cleaning (three times per week) initially was able to prevent macrofouling. Cleaning at the lowest frequency (every week and every two weeks) was found to be the least effective operation. *Oliveira and Granhag (2020)* found beneficial the planned underwater cleaning with water jet setup on both SPC and fouling release coatings, but his study was carried out in the Baltic Sea where the biofouling pressure might be lower.

The low macrofouling settlement on the soft silicone paint was in line with *Hearin et al. (2016)*, where on a different silicone coating, barnacles hardly settled compared to the ungroomed panels, only a really low number was found after 6 weeks of immersion, likewise this test. On Slips paint the percentage and size of barnacles was higher and found after two weeks of immersion. Macrofouling not removed on this coating might be related to the soft brushes used in this test, stiffer nylon bristles or horizontally rotating brushes might be more effective in contrasting algae and barnacles development.

The coating surfaces were in a good condition, no visual damages and scratches were found on both paints, the soft brushes used for cleaning and the rubber wheels that were turning in different directions during cleaning were not affecting the coatings. On Slips paint an abrasive sponge was used manually to remove algae and barnacles without altering the surface characterization. The results of roughness, contact angle and thickness measurements confirmed that no surface alteration was found on both coatings. Hearing et al. 2015 tested the International Paint fouling release coating Intersleek 900, and only after 12 months of weekly grooming found 5% of damage.

Although grooming seems to not generate environmental risks (e.g. release of biological material in the environment), tests/studies that would potentially enable system approval should be subject to appropriate validation, *Scianni and Georgiades (2019)*, all the in-water cleaning systems need predictive verification testing to regulatory success of emerging biofouling policies, *Tamburri et al. (2021)*.

With these preliminary results it is possible to conclude that by selecting commercially available cleaning tools and fouling control coatings, biofouling can be maintained at lower levels and possibly improve the ship's speed performance. However before forming a clearer picture on the underwater hull cleaning methods and assess any potential impacts, more tests and developments need to be performed, which can be carried out with relatively inexpensive methods. It is important to find the right balance between fouling control coating and cleaning method settings to achieve the best cleaning efficiency and coating performance while working towards eliminating any environmental risks.

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First Application and Approval Scheme for IWC on Non-toxic Hard Coatings in Ports of Bremen - Dead End or Challenge?

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Abstract

In the first German guidelines for issuing permits for in-water hull cleaning, the CLEAN project group has stated binding regulations for hull cleaning with the aim of reducing the introduction of pollutants into the waters of the ports of Bremen. The guideline contains fundamental requirements for obtaining approval for underwater cleaning at the port, including information on the biofouling management in practice, fouling stage of the hull and the presence of non-biocidal hard coatings. Verification tools regarding capture/filtration efficacy, degree of abrasion, and biosecurity are going on.

1. Introduction

In the spring 2021 the Water Authority of Bremen and bremenports drafted a guideline for in-water cleaning, and set it into force in July 2021, *Bremen Ports (2021).* This guideline is intended to provide guidance and define the conditions and criteria for the issue of authorization for in-water hull cleaning in the port of Bremen. The nationally applicable legal and technical requirements for water protection must be complied with as a rule. In-water cleaning is classified as use of water resources pursuant to Section 9 Water Resources Act1 [WHG] and requires a permit under water law. The cleaning of hulls with antifouling coatings containing biocides cannot be approved, and cleaning may only be performed on abrasion-resistant, biocide-free underwater coatings.

2. Requirements

Permits under water resources law are applied for by the cleaning company as a rule. The cleaning company should also coordinate the application process if regular cleaning is included within the shipping company's fouling management system. The requirements for the cleaning company and the used technology include: 5 references of previous IWC actions, at least 95% capture rate, a filtration rate of < 50µm.

Prior to the commencement of cleaning and as a condition precedent, the water authority must be notified of the specific cleaning process used on each individual vessel so that it may issue approval after review of the vessel data. These are for the:

- Vessel: Commissions the cleaning company, submission of proof of active fouling management, previous cleaning in a German or European port, submission of the vessel documents (at least 1 week in advance)
- Cleaning company: Application for individual permission for in-water cleaning/to use a cleaning system
- Water authority issues approval for the specific vessel unit in compliance with the conditions of the permit (self-monitoring by the permit holder)

Where a cleaning company meets the above requirements, a permit may be granted on a case-by-case basis after review of the application documents. The first step is to conduct a thorough review of the system's effectiveness. Notification of each vessel that will be cleaned and its subsequent inspection and clearance by the water authority is included in the permit as a condition precedent.

In addition, the following requirements and conditions must be fulfilled at all times by the cleaning company:

- only the previously verified technology is used in accordance with the documents as submitted and examined
- notification of any change in the staff structure/qualification
- contractual commitment to a specific vessel unit (type of vessel, if applicable) that meets the above requirements and is therefore cleaned regularly
- appointment of a competent person on site

3. Cleaning Companies

The cleaning company shall submit the findings of external studies on the effectiveness of their cleaning, capture and treatment systems for different levels of fouling. The deciding factor is effectiveness at the biofilm stage, but also in areas of macrofouling occurring locally on the hull. Until now, antifouling coatings with biocides involving the electrolytic release of copper have been used almost exclusively in niche areas such as sea chests, and in bow and stern thruster tunnels, etc. Experience has shown, however, that macrofouling frequently occurs nevertheless in niche areas. This means that the capture and separation methods used must be capable of treating macrofouling where it occurs. It is equally necessary to assume that the captured fouling is contaminated with pollutants and must be disposed of as hazardous waste. The effectiveness of the technology used shall be validated by reference samples previously generated at suitable points of the vessel.

All examination findings submitted must have been produced by an independent, qualified institute/ laboratory.

Regarding capture and filtration efficacy the following standards shall be achieved:

- Capture of at least 95% of the removed fouling by means of a suction device that is effective on both flat and curved surfaces.
- Filtration or separation of the extracted water containing the fouling so that only organisms < 50µm can pass. The same applies to the retention of coating particles.
- Once filtration/separation is complete, the returning water must be disinfected by means of a downstream UV system (by killing organisms < 50µm). The filter residues must be stored and treated in such a way that no living organisms can escape.

4. Ship Operators

Vessel data concerning the fouling management strategy can be submitted to the approving authority by the shipping company or the cleaning company. The following report templates are accepted in this regard:

- IMO Biofouling Management Plan and Biofouling Record Book
- Marine Invasive Species Program Annual Vessel Reporting Form (AVRF) submission requirements (MISP.IO)
- Australia Vessel Check
- New Zealand Vessel Check
- Best Fouling Management Practice Guide, Baltic Sea
- DHI Vessel Check
- The vessel/shipping company's specific fouling management system
- Requirements according to the BIMCO standard

The above templates provide sufficient preliminary information to assess whether integrated fouling management is maintained for the vessel and whether the hull and niche areas are cleaned regularly. Regular vessel cleaning is a basic condition for issue of a permit to conduct IWC in the ports of Bremen/ Bremerhaven.

All of the above fouling management templates must be submitted to the water authority by the cleaning company with the following contents as core information at least 1 week prior to entry:

(The individual ports specify the precise form for electronic transmission. Entry of the relevant data in the SIS system is a conceivable method.)

- Vessel type (design, hull specifics, niche areas)
- In-water coatings on the hull and niche areas stating all layers, especially if a sealer has been applied to antifouling products containing biocides and this coating has not been removed.

At present, both corrosion protection coatings and special, cleanable hard coatings are used for the regular cleaning of hulls. These are actually: Cleanable hard coatings (CHC) and biocide-free foul release coatings (FRC), but also epoxy-based corrosion protection coatings.

In view of the fact that there are currently no reliable and effective marine growth protection systems (MGPS) for niche areas available on the market, biocidal coatings or biocidal techniques must be used in niche areas until further notice.

- Operating profile, service speed
- Waters navigated in the last 12 months, ports visited, time at sea, time at anchor, duration of stay per port
- Cleaning history for the last 12 months, with submission of documentation for the last 3 cleaning operations (fouling status before and after cleaning)
- Where no documentation is available, video documentation of the fouling status or the absence of fouling on the hull from a sea area with good visibility situated not further away from the port of call than 50 nautical miles, as the North Sea ports do not provide visibility that is adequate to satisfy the documentation quality requirements.

5. Monitoring

The permit holder shall be required to monitor operations on its own responsibility and ensure compliance with the conditions. Of pertinence in this regard is the interaction between the cleaning system and the vessel type, as well as the location of cleaning. In this regard, the effectiveness and good working order of the extraction and separation equipment must be monitored on site during each cleaning operation.

The monitoring requirements include:

- All tests must be carried out by an independent qualified institute/laboratory that is commissioned by the permit holder within the framework of its self-monitoring duties.
- The competent authority shall carry out its own monitoring at the expense of the company if the occasion arises.
- The filtration/separation technology shall be able to filter out the captured fouling up to a spherical particle size of 50 µm. As this will also detect any abrasion of polymer particles from the underwater coating, it is necessary to ensure during the cleaning process that 3 samples are collected from the wastewater flow at the beginning, in the middle and at the end of the cleaning process, which can then be analyzed for organisms and paint particles < 50 µm. Modern methods for microplastic determination, BallastWise® and/or microscopic examinations must be used for this purpose. Random PCR tests may be used to determine the taxonomy.
- 20 l of wastewater shall be collected in a canister from each filtration/separation unit at the beginning, during and before completion of the cleaning and then poured over a plankton net with a mesh size of 50 µm. The water in the net cup shall be examined microscopically or with BallastWise® to determine the number, survival rate and size of aquatic organisms. Moreover, the quantity of organic and non-organic particles and paint particles shall be estimated and their average size measured.

- At the same time, samples of the port water at the ship and samples of the wastewater shall be taken at the beginning, during and before completion of the cleaning to estimate the effectiveness of the capture and separation technology and the TOC content, and the dry weight of the filterable substances shall be determined. The TOC content and the filtered substances (filtrate) obtained from the port water may only exhibit up to 10% deviation.
- The wastewater samples must also be analyzed for copper and/or TBT content if a unit is cleaned that has a sealer under the biocide-free topcoat with antifouling coatings that contain copper or even TBT.
- It is mandatory that cleaning be immediately interrupted in the event that the capture and/or separation system malfunction. Cleaning shall not continue until this malfunction has been rectified.
- Methods such as, e.g.: BallastWise® (www.microwise.eu) shall also be accepted to conduct random checks on the good working order of the capture and separation system.

6. Perspectives

The implementation of the guideline is accompanied with several investigations to overcome obstacles like verification of the efficacy of capture. As in the ports of Bremen the water bodies display a very low visibility, routine optical methods are hard to apply. One method is to adjust in advance the amount of fouling, which have to be removed according to the stage of the fouling community, *Watermann et al. (2022).* Another approach is the initiative to screen the in-water inspection technologies at hand for their use in water bodies of low visibility. In parallel, regular monitoring is going on to determine the efficacy of the filtration rate regarding the size and viability of organisms.

Furthermore, the use and cleaning on non-biocidal hard coatings deserves a holistic fouling management approach including cleaning facilities in all ports of destination. Up to now, only a few shipping companies can fulfil this operational profile.

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Biocide-Free Antifouling Paint / Possible and Effective

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Abstract

This paper describes the development and commercial results seen over seven years with a unique biocide-free, SPC (self-polishing copolymer) antifouling paint. The paper outlines the research, development, testing and real-life applications of this product. The testing done includes application and follow up on various vessels and vessel types. Pre-pandemic monitoring showed excellent, low-friction antifouling performance. Post pandemic results seen on cruise ships indicates that in regular operation the material can provide long-term, biocide free antifouling performance without the need for underwater grooming or cleaning.

1. Introduction

The oceans which account for approximately 70% of the Earth's surface area, have a significant impact on global environmental change, so it is becoming increasingly important to prevent marine pollution and conserve the marine environment. For this reason, in accordance with the International Convention for the Prevention of Pollution from Ships (MARPOL Convention), our role in the world as marine paint maker is to commit for the supply of marine paints that minimise the release into the ocean of oil and toxic substances that have a serious impact on the marine ecosystem.

Current anti-fouling paints mainly adopt a system of release of antifouling components into the sea to prevent biological adhesion to the hull. In the polishing mechanism, the antifouling component i.e., biocide which is slowly released to keep the coating's surface fresh and active. Modifying a combination of self-polishing copolymer and various kinds of biocides, current antifouling technology has been developing continuously to tackle to the ever-changing marine environment. However, the selection of biocides might be limited in future due to stricter regulations designed to help save and protect the marine environment. A recent example is the ban on the use of Cybutryne (Irgarol) as a biocide, *IMO (2021)*. From 1st January 2023, ships shall not apply or re-apply antifouling systems containing Cybutryne and the current hull coating systems containing Cybutryne shall not be exposed in the external coating layer of their hulls or external parts or surfaces.

As further examples, in Canada, copper actives are re-evaluated and approved in 2016. Cuprous oxide is the only registered products allowed to be used. Any products with Copper Pyrithione incorporated in their formulation are not approved in Canada. Copper Pyrithione is one of the most commonly used and successful biocides in the world. In the State of California in the United States, a law about the use of copper containing antifouling paint has been in force since 1st July 2018. This states that only to use coating which copper leaching rates below 9.5 µg/cm^3 can be used for recreational vessel/yachts. As described, regulations on the use of biocides, including copper, are expected to be tightened in the future.

With all this in mind, Nippon Paint Marine have successfully developed a range of new Self Polishing Copolymer antifouling paints with the three main design criteria these being 'low-friction', 'long-term antifouling performance, and 'biocide-free'. Nippon's teams have confirmed the biological repellences and frictional reduction effects of all these types over years of research. Since its commercial introduction to the market in 2017, the product has achieved long-term post-docking results in both test patch applications and in full coating on actual vessels, mainly cruise ships.

2. The approach to the new biocide-free AF technology

A common and conventional biocide-free antifouling system is a foul release coating with non-hydrolysable silicon, *NN (2021)*. As a non-hydrolysate type, this technology does not renew the surface of the paint surface and its high hydrophobicity has a water repellent effect, which prevents biological adhesion by repelling proteins. However, as it is difficult to ensure antifouling properties, silicone rubber-based antifouling coatings have recently been introduced in combination with a biocide. On the other hand, silicone-based coatings are difficult to apply, as the application process requires masking to protect the surrounding area from contamination and the use of specialised application equipment, which increases working time and costs.

Another example is a hard coating which is epoxy basis. Such hard coating will foul relatively quickly, however, they are designed to be subjected to regular in-water cleaning without damaging on the coating. These coatings claim to offer good abrasion resistance and are suitable for trading in ice. However, planning and executing regular in-water cleaning operations can be challenging for ships not operating on a fixed route.

Further methods are ultrasonic technologies, ultraviolet lights, etc. Despite promising results in some cases, these innovations are challenges related to scaleup, maintenance and additional power requirements. In addition, some of these technologies may not yet be suitable for the entire underwater hull.

AQUATERRAS belongs to a completely new category of antifouling technology: hydrolysis SPC-type, biocide-free antifouling paints, which can provide long-term antifouling properties while being biocide-free, thanks to the hydrolysis type that is the axis of our antifouling technology. Thanks to our unique microdomain structure, we have succeeded in achieving almost perfect antifouling properties without the use of any biocide, surpassing the biocide-containing SPC type even in its performance.

Table I: Current Antifouling Categorising

	Biocide incorporated	Biocide-free
Self-Polishing Copolymer	Hydrolysis polymer, conventional SPC type antifouling coating	Hydrolysis polymer with Micro domain structure ‘AQUATERRAS’ (New Technology)
Non-SPC	Silicon type (Foul Release Coating)	• Silicon type (Foul Release Coating) • Hard coating
Other technology	NA	Ultrasonic/ Ultraviolet (UV) lights, etc.

3. Microdomain Structure

AQUATERRAS has been shown to develop antifouling properties that exceed those of current biocide-containing antifouling coatings, despite being biocide-free. This was achieved by taking a hint from the anti-thrombogenic polymers used in artificial blood vessels to prevent blood vessel clotting.

In general artificial materials, it is known that the (positive or negative) charges of adhered cells are arranged in an irregular arrangement, with a bias between positive and negative charges, especially in the areas where the cells are fused, Fig.1, *Okano et al. (1979)*. On the other hand, the anti-thrombogenic polymers are known to prevent platelets from adhering to the inner walls of blood vessels through a structure in which the positive and negative charges are arranged alternately.

Microdomain structures have such an alternating arrangement of hydrophilic and hydrophobic parts and are known to inhibit cell activation compared to the biased, homogeneous surface of general materials. This microdomain structure is applied to the surface of the paint coating to inhibit biological adhesion, thereby ensuring antifouling properties even when the paint film is free of biocide, and also to ensure an incredible long-term antifouling performance by keeping the coating surface fresh through a controlled polishing mechanism. Furthermore, the effect that the hydrophilic domains catch seawater and the smoothness of this antifouling paint coating contribute to a reduction in frictional resistance.

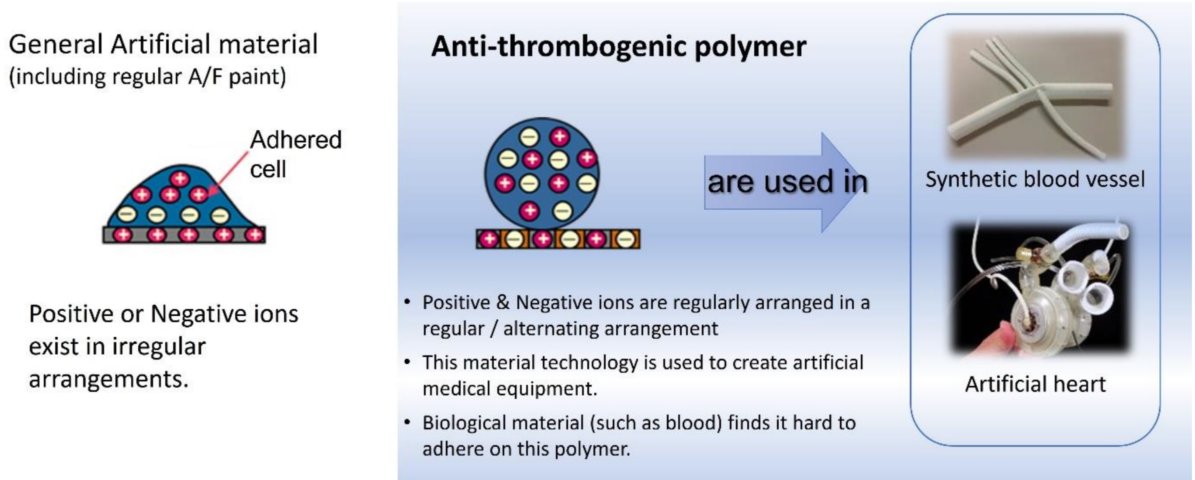


Fig.1: A concept of microdomain structure

4. The study of the advanced antifouling mechanism

Here is the explanation of what we presume concerning the antifouling mechanism of how marine life reacts to the unique microdomains, both hydrophilic and hydrophobic.

In the case of conventional antifouling paint formulated with biocide(s), its coating surface becomes hydrophilic uniformly as a result of its polishing mechanism, then, the antifouling components including biocide are released regularly. In general, domain structure does not form on its coating surface. However, it is difficult to control to keep coating surface always hydrophilic on the entire hull comprehensively during in service. In operation, biocide depletion becomes possible as the polishing rate cannot be controlled precisely. Additional SPC coat thickness provides a safety margin to avoid such a biocide depletion.

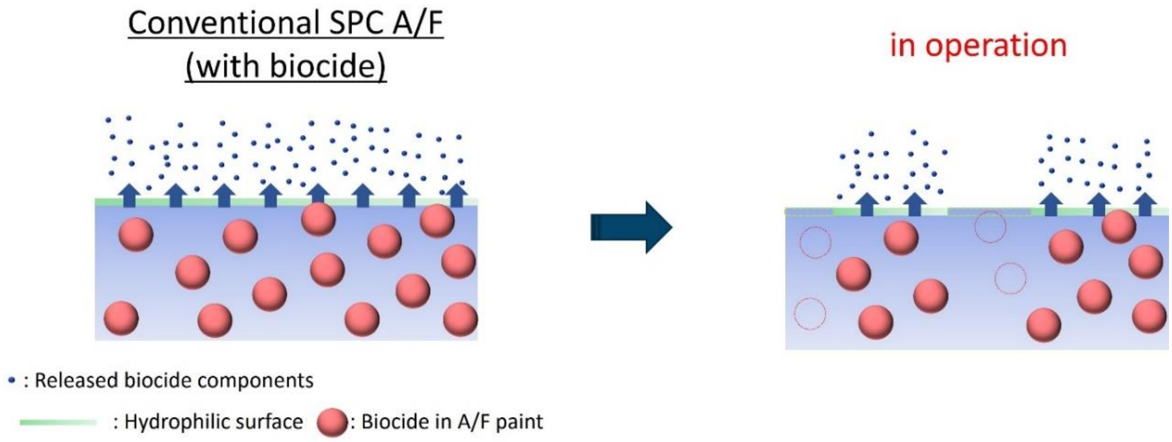


Fig.2: Antifouling mechanism of conventional SPC system

In the case of AQUATERRAS, the Microdomain structure are existing on the coating surface, which is defined by an arrangement of the complex hydrophilic/hydrophobic colonies alternately. These unique colonies are also refreshed and kept active by a polishing mechanism. No other marine coating works this way, and no such object exists in nature. Therefore, when marine life finds the microdomain surface, they are confused and hesitate to try to adhere there because they do not recognise the microdomain surface as a place where they can easily develop.

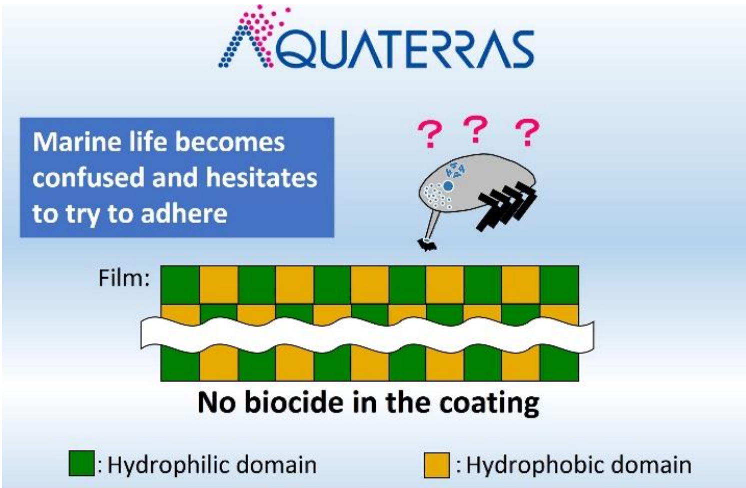


Fig.3: Antifouling Mechanism of AQUATERRAS

5. References of Antifouling Performance with actual ships

5.1. Case in the Indian Ocean

At first, one of the representative cases in the operation of a cruise ship operating in the Indian Ocean is shown. Nippon applied a test patch of AQUATERRAS is on the starboard side of the ship's vertical bottom, at around 30 m^2. The rest of the underwater hull was applied with our biocidal SPC antifouling coating. After the ship's itinerary operating in and around Madagascar for around four months was completed, the ship's general performance had been seriously affected by growth on the hull.

General Parts: (Biocidal SPC)

Test Patch: Excellent condition

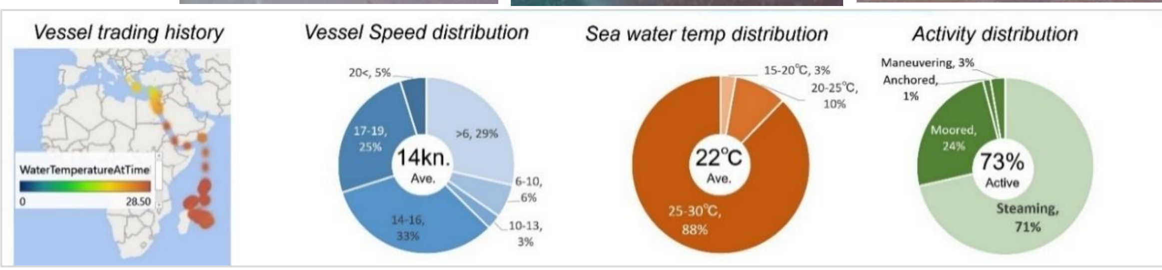


Fig.4: Indian Ocean case (The three pie-charts are shown entire service period for 30 months)

*The average of speed distribution is excluded when vessel is not steaming. Figs.5-7 are the same as well.

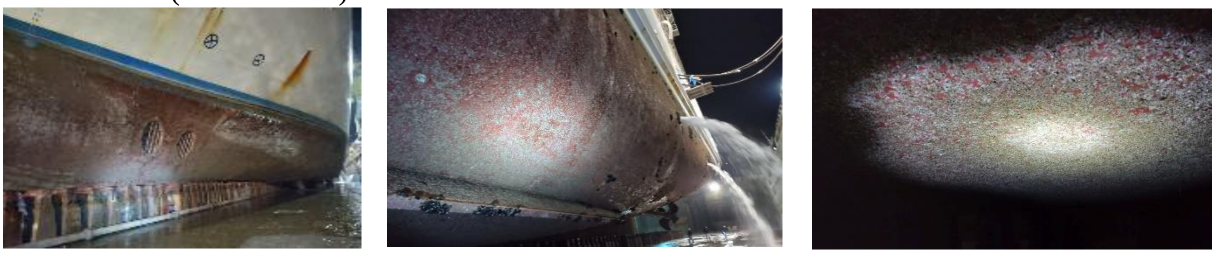
The underwater hull was inspected with an underwater camera, it was found that the moderate to heavy level of marine growth on the general biocidal SPC coating area. We assume that the tropical sea condition was the main cause of serious fouling. On the other hand, the patch of AQUATERRAS has shown nearly perfect condition with no fouling. This outcome has made amazed us and provided one more piece of evidence that AQUATERRAS' performance would work reliably even in intensely biofouling aggressive marine environments.

5.2. Case of long idling off La Spezia, Italy

AQUATERRAS performs well against long idling periods. The 2nd case is also the test patch result of a cruise ship. Due to the unexpected COVID-19 pandemic, the cruising company had no choice but to suspend many voyages cruising for around one and a half years. During the operational pause, almost all cruise ships had anchored for a long period. One cruise ship, having an AQUATERRAS patch on its vertical bottom, stayed in La Spezia in Italy, where is well known place for fish and mussel farming. That means the sea in this area is Phytoplankton-rich hence it is highly likely to be easily grown marine plants and sea animals there. The ship had been in quite a long operational pause mainly in La Spezia for around 20 months in the whole season. It is expected that much marine growth are existing on the whole underwater hull.

In November 2021, when the ship was in-docking, the underwater hull condition has been figured out. The general part where was coated with biocidal SPC antifouling, there were full of barnacles as expected. Surprisingly, the patch of AQUATERRAS still kept good performance with no barnacle and no marine growth. This outcome is one of the best pieces of evidence that AQUATERRAS works well perfectly even in a long idling period in a Phytoplankton-rich place. There is one more case of a long layup.

General Parts (Biocidal SPC): Barnacles in the whole underwater hulls seen



Test Patch: Excellent condition, even after long lay-up for 20 months

(Before washing)

(Before washing)

(After washing)

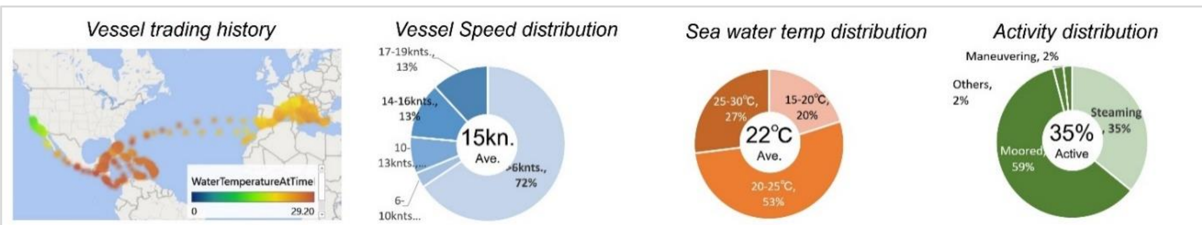


Fig.5: The case of long idling off La Spezia, Italy

5.3. Case of bulk carrier (Full coat)

The reference of AQUATERRAS' perfect condition is not only cruise ships. Here is one reference of Bulk Carrier which is newly built in Imabari Shipyard, one of the most famous ship building yards in the world.

This bulk carrier had been operated mainly in the Pacific Ocean in 56% steaming activity rate under relatively mild sea-temperature condition. There were 2 long idling periods in US (20 and 25 days) while operation. The vessel was docked after 30 months operation, arrival underwater hull condition before washing was perfect on both flat and vertical bottoms, with no fouling and good polishing pattern. This outcome is also one of the pieces of evidence that AQUATERRAS works and useful even such a slow activity vessel like bulk carrier.

General hull condition after 30 months operation

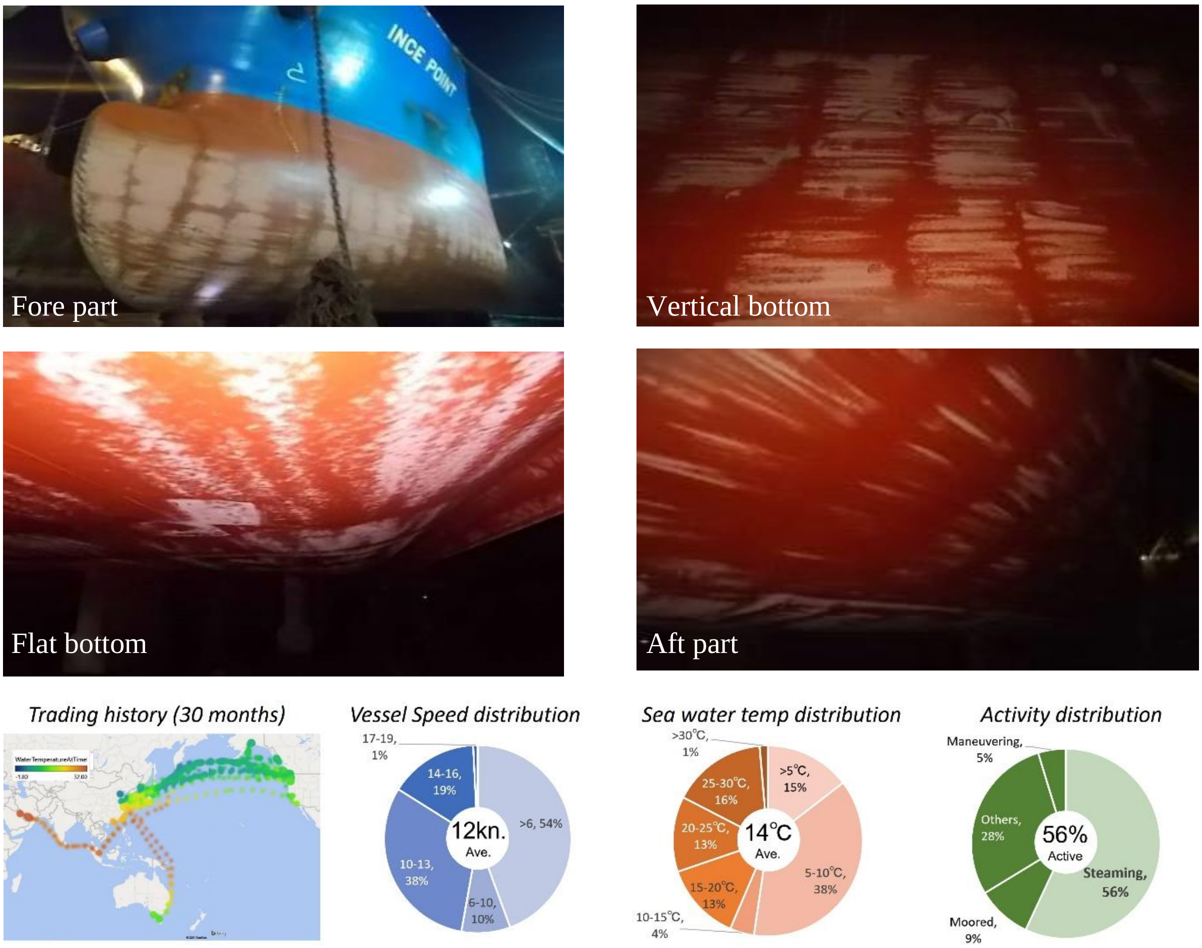


Fig.6: Case of bulk carrier

5.4. Case of operation with long idling in the Caribbean (Full coat)

The perfect performance of AQUATERRAS is observed in the Caribbean area as well. One cruise ship was coated with the full AQUATERRAS system onto its underwater hull just 3 months before the COVID-pandemic began. Thus, the ship was able to operate normally for only 2 months then went into a long operational pause in the Caribbean. While in the pause, the ship's underwater hull condition was inspected twice by divers, the first one after 7 months from undocking, the second one: after 21 months). The divers have witnessed the amazingly perfect performance of AQUATERRAS both times.

The actual visual condition is shown in Fig.7, which is the condition after 21 months with 18 months of operational pause. Investigating the sea condition for 21 months of service from undocking, the ship's activity was only 23% steaming, and the average sea temperature is quite warm, 27°C in total. Furthermore, the Caribbean is known as a significant biofouling area encouraged by the warm sea temperature.

General hull condition after 21 months service with 18 months operational pause

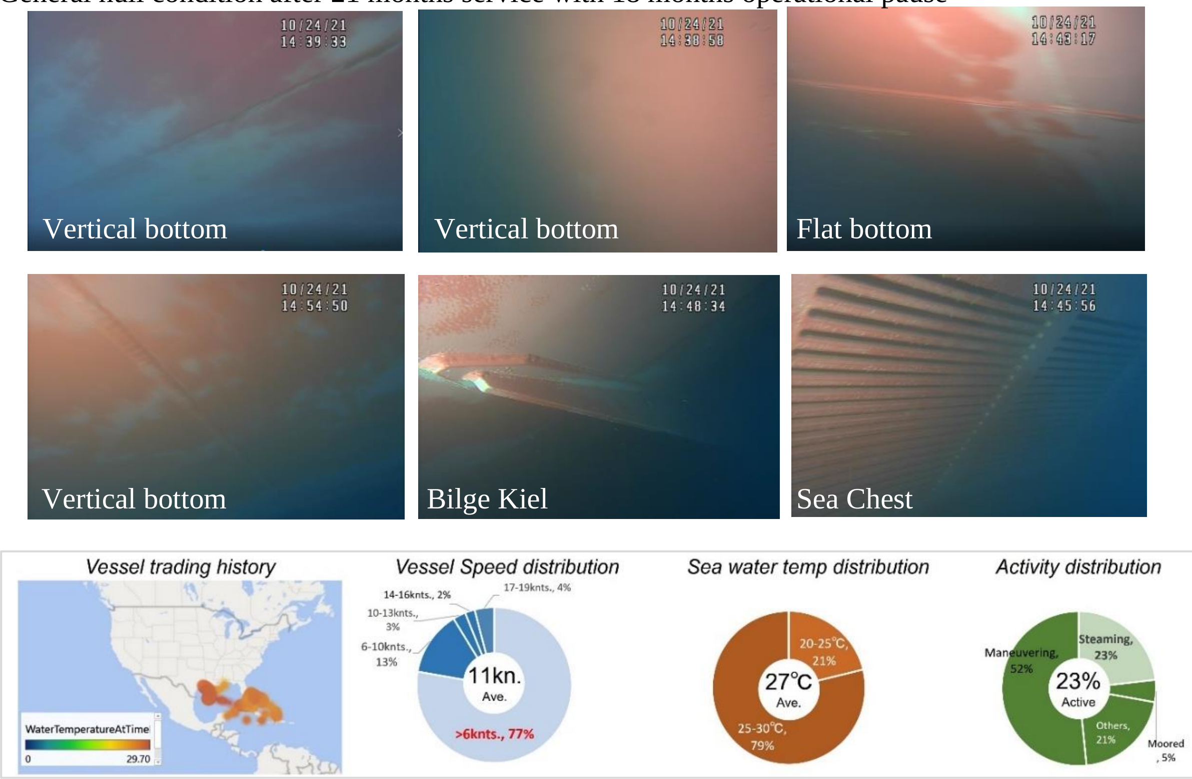


Fig.7: Case of the operation in the Caribbean with a long pause

6. The study of the low friction and the fuel-saving effect, and propulsion analysis

6.1. Fuel consumption test comparing with products

One of the references of the ship's operational analysis test was also conducted to evaluate AQUATERRAS' fuel-saving effect by the method of fixed-points measurement at the same operating route. Thanks to the cooperation of Kobe University, the test was conducted for 4 years with the training vessel for the students of marine science and technology. The underwater hull coating was recoated annually for comparison different 4 antifouling products, conventional SPC paint, LF-Sea, A-LF-Sea, and AQUATERRAS. LF-Sea is the first generation low friction coating and A-LF-Sea is the second generation in our product line-up.

Test methods

- The vessel steams on the fixed route between the No.1 buoy and the No.4 buoy.
- Measures fuel oil consumption and average speed between the 4 fixed points ordering the same distance.
- Calculated annual speed average after filtering error data based on speed and wind factor limitations.

Biography of application

- 1st year: Conventional SPC A/F applied after full blasting.
- 2nd year: LF-Sea directly applied on existing A/F coat.
- 3rd year: A-LF-Sea directly applied on existing LF-Sea.

- 4th year: AQUATERRAS directly applied on existing A-LF-Sea.

The results are shown as the calculated Fuel Oil Consumption that is corrected by average speed data. Standardising the data of conventional SPC as 100%, LF-Sea is found to be about 4% more effective, A-LF-Sea about 7-8% more effective and AQUATERRAS about 10% more effective.

Fig.8: Test route

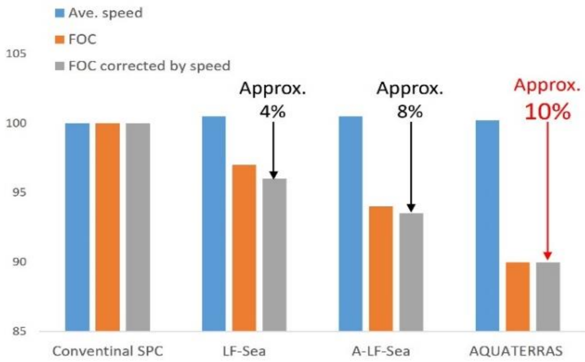


Fig.9: Fuel-saving effect in Nippon's product ranges

6.2. Detailed surface roughness measurement

In general, the smooth surface of underwater antifouling coating is known to contribute to reduce the friction resistance against the sea, hence, it can be contributed to the fuel-saving performance of ship's operation, *Mieno and Matsuda (2013)*. There are a lot of scientific papers and studies about the relationship between underwater hull coating's surface roughness and its frictional resistance. In the study of surface hull roughness, AQUATERRAS has an advantage.

Fig.10 shows the profile of surface roughness measured by a 3D laser analyser. As the surface gets coarse, the profile is shown in yellowish to reddish, and as it gets fine, the profile is shown in light bluish to deep blue. This is one of the pieces of evidence that the advantage of AQUATERRAS' low friction effect compared with conventional SPC A/F coating, should contribute to the fuel-saving performance.

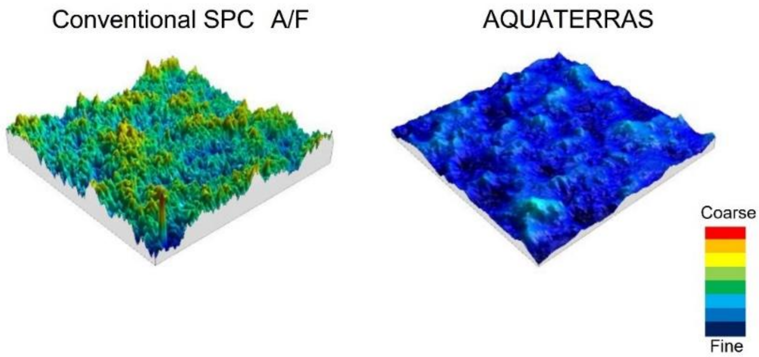


Fig.10: 3D profile of surface roughness comparison

6.3. Ship's performance measurement in Sea-Trial of New Building vessels

Comparing with the contribution to the hull performance on the Sea-Trial in New Building stage, AQUATERRAS showed a superior result to the standard of our low frictional antifouling coating, LF-Sea. Both Sea-Trials were carried out in Imabari Shipbuilding with the newly built Bulk Carriers, and the data analysis was also conducted by them.

In the analysis, collected measurement data were filtered or corrected as follows in order to make the analysed outcome exactly as much as possible.

- Filtered the data that consecutive steaming less than 23 hours
- Filtered the data that the ratio of displacement is less than 95%
- Filtered the irregular vessel speed value that more than 0.1 kn gap comparing the speed calculated with GPS location signal
- Corrected the value of horsepower based on the gap of displacement (draught)

In the result of the curve of Speed-Output, shows that AQUATERRAS can perform well to reduce approx. 4% output when the vessel was steaming at the same speed on both coating ships comparing first-generation low-friction antifouling under the certain condition.

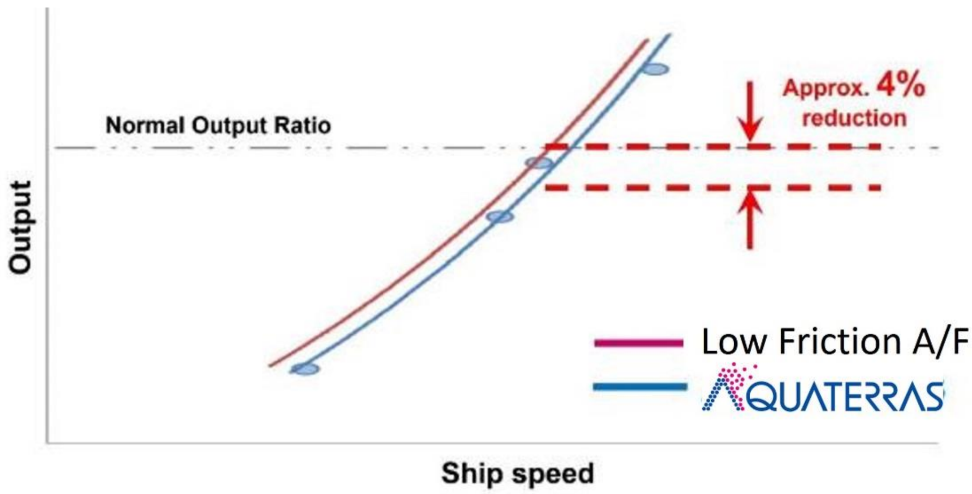


Fig.11: Ship's speed-Output curve comparison

7. Conclusion

Based on extensive testing and the results seen on widespread applications on ships, we have confidence in the possible and effective use of the world's first SPC biocide-free antifouling paint technology.

To comply with recent biofouling management regulation (e.g., in Australia, New Zealand, California, etc.), hull grooming technology may be one of the methods to keep the underwater hull clean. However, AQUATERRAS would be one of the solutions to keep ships' hulls clean, reduce species migration and save fuel, reducing ships emissions at the same time and reducing the biocide impact on the marine environment.

Nobody can easily predict how widely biocide restrictions will be tightened in future. If copper were to be banned worldwide, the selection of antifouling paints would be limited. Without effective antifouling paints the cost to shipowners of higher fuel consumption and increased emissions would drastically affect ship operation. This paper and our presentation could be a valuable reference that SPC antifouling technology and its market still have significant potential to lower the world fleets' running costs and environmental impact even though the bottom paint is biocide-free. The technology is still undergoing further development by Nippon Paint Marine's R&D team to improve its commercial competitiveness.

Also, the test result for output-reduction is proof of the low frictional effect of AQUATERRAS and shows the contribution of fuel saving even in EPL (Engine Power Limitation) operation complying with EEXI and CII annual rating rules.

Acknowledgement

The development of this technology was supported by the Class-NK and the Ministry of Land, Infrastructure, Transport and Tourism in Japan. And the ship's performance measurements in sea-trial period were conducted with the generous cooperation of Imabari Shipbuilding.

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Underwater Cleaning in the Flemish Ports: Lessons Learned and Challenges for the Future

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Abstract

This paper describes the experience of the Flemish ports with regard to underwater cleaning in recent years. Besides following up the tests of new candidates and supervising existing licence holders, there also had to be sufficient attention for new developments. The paper therefore also describes the challenges the ports are facing. These include amongst others the lack of an international standard for underwater cleaning, the challenge of creating a level playing field and the development of port regulations for pro-active cleaning. Besides these challenges, port authorities need to keep an eye on new developments, such as prevention of biofouling by ultrasonic waves, modelling of biofouling growth on ship's hulls and the use of non-toxic, fouling release hull paint.

1. Introduction

Since 2019, the Flemish ports have a common policy on underwater cleaning, more specifically, a policy for reactive cleaning with capture, *Cornelis et al. (2020).* This common policy arose from the commitment as ports to reconcile economic, social and ecological interests in a sustainable manner. As pioneers, the Flemish ports want to give innovative companies a chance to offer a robust solution to the fouling problem that has been troubling shipping for a long time, *Doran (2019), Bertram (2020).* Of course, it is also vital that ports do not ignore their responsibility regarding water quality and the possible spread of alien invasive species.

Key issue is how to maintain the balance between innovation and protection of the aquatic environment. Which framework provides sufficient flexibility and perspective, but at the same time is strict enough to allow proper monitoring and enforcement? And crucial: What is the role of ports in the development and implementation of this framework? At least we hope to inspire other ports, industries and governments. Because we believe we need courageous doers to act now for a better future.

2. Experience in the Flemish ports – What have we learned?

In the meantime, the Flemish ports have almost 4 years of experience with their framework. They still believe in their approach where they also attach great importance to feasibility. However, as expected, there are also many things that can still be improved and some new developments that need to be added.

Since 2019, about 120 hull cleanings and some 280 propeller polishing operations have been carried out in Flemish ports. It is very difficult to make a statement with regard to the number of hull cleaning operations. After a good start in 2019, there were significantly less operations in 2020 and 2021. This may be a consequence of the general crisis brought on by covid-19. In the first half of 2022, we see no change and the number of operations remains below expectations. However, we can report that no less than 42 operations were carried out in the port of Antwerp-Bruges in July 2022.We can only hope that this trend will continue, because when we are honest, the number of shipping companies that actively use these techniques is still relatively limited.

For the propeller polishing operations, it is a different story. In 2020, we saw a good increase, and in 2021 this figure was matched. However, the first half of 2022 is below expectations. Hopefully, we will see a turnaround in the second half of the year.

Some figures are highlighted in Figs.1 and 2. For 2022, only data of the first half of the year are included.

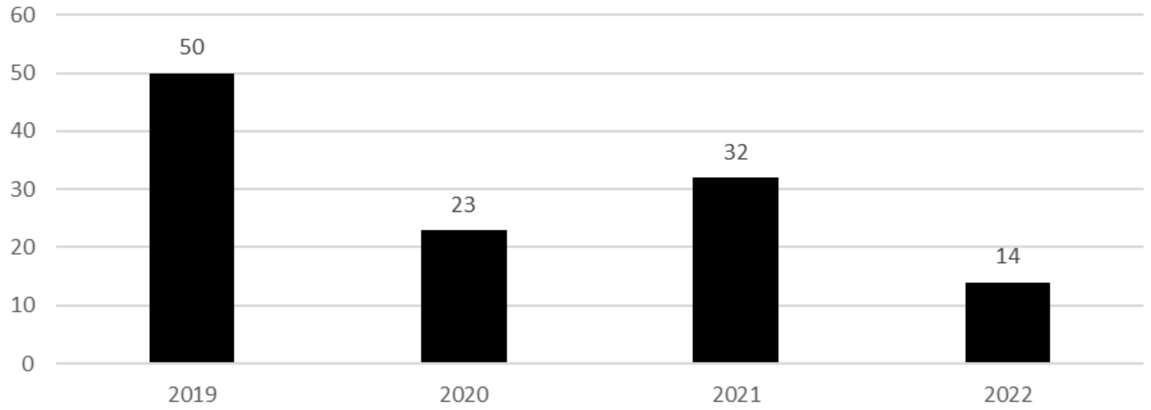

Fig.1: Number of hull cleanings in the Flemish ports per year

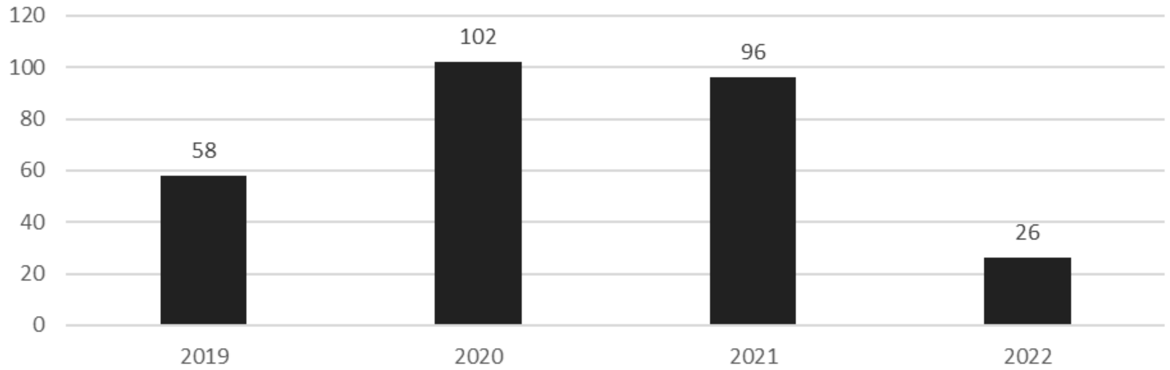

Fig.2: Number of propeller polishing operations in the Flemish ports per year

Another parameter that we consider to be important in the Flemish ports is the interest from the sector. Are there new companies that sign up, do existing companies continue to offer the services or do they expand their services?

It is noticeable that small companies find it difficult to make a name for themselves in the hull cleaning market. Not only is the purchase and development of the equipment a major investment, but the fear of not passing the test and seeing their investment come to nothing is a showstopper. So for the time being, there are still only 2 operators offering these services in the Flemish ports. There are occasional talks with larger players, but so far nothing has led to a concrete case.

A new development is that one of the two companies, when renewing its licence, has also taken up the challenge of cleaning hard fouling, better known as macro-fouling. In the end, they also succeeded in meeting all the requirements. Tables I and II summarize the test results. Despite these good results, we as Flemish ports have already had to issue warnings to this operator. This proves the necessity of continuing to monitor as a regulator.

Table 1: Results of spillage loss (105%) during in-situ test, all results in mg/L

	Average value - baseline	**Average value - sampling**	**Average value - 105%**
Aluminium	0,917	0,953	0,963
Copper	0,063	0,023	0,066
Iron	1,233	1,097	1,295
Nickel	0,009	0,012	0,009
Zinc	0,064	0,060	0,067
Suspended matter	14,333	14,000	15,050

Table II: Results of filter performance during in-situ test, all results in %

	Average
Aluminium	120%
Copper	98%
Iron	107%
Nickel	100%
Zinc	99%
Suspended matter	100%

For propeller polishing, there is a lot of interest from local diving companies. The investment costs are a lot lower than for hull cleaning and that is why many are taking a chance. However, as already reported in 2020, this does not always have a good outcome. Both in terms of suction and filtration performance, we keep finding problems during the test procedure. The idea of increasing the efficiency after a few years has therefore been postponed for a while. However, we are considering imposing a minimum filter standard, for example, the effluent may not contain any particles larger than 0.5 microns.

Specifically, only four firms are licensed at the moment; four others are trying to get their licenses. In comparison with 2020, there is no great increase in the number of companies wishing to offer this service.

3. International standard: Why is this crucial?

The biggest challenge within the subject of underwater cleaning is, according to the Flemish ports, the fragmented policy. Due to the absence of an international standard, there is not only a lack of a level playing field but there is also uncertainty for all parties involved. We often have the feeling: Are we doing the right thing? We are convinced that this also slows down other ports in their commitment to develop regulations for these applications.

As Flemish ports, we support the notion that if the environmental regulations for underwater cleaning are well crafted, more innovation will come, and the environmental impact would be reduced, leading the profitability of the innovating company increases, *Noordstrand (2020)*. By minimising uncertainty, maximising opportunities for innovation and constantly raising the standard, the greatest benefits will be achieved in both environmental and economic terms.

So according to the Flemish ports, in the near future there will be a need to unite the forces of the existing initiatives to publish a fully supported international standard on underwater cleaning. The purpose of this standard should be at least to:

- Define the boundaries of reactive and proactive cleaning in a clear and thoughtful way, taking into account the interests of all stakeholders involved.
- Assure regulatory authorities that no damage is caused to the aquatic environment for which they are responsible. In order to remove all doubt, this requires a well-founded scientific foundation.
- Allow innovative companies to develop their solutions and commercial activities. For this purpose, it is necessary to describe a clear framework for testing and verifying the applications.
- Convince shipowners and operators of the benefits of underwater cleaning and by extension good biofouling management. The benefits gained from following the standard should be documented to inspire others.

4. Pro-active cleaning: The holy grail of mitigation of ship's hull biofouling?

In addition to reactive cleaning -when something is dirty we clean it-, there is now also the development of proactive cleaning -by cleaning we prevent something from becoming dirty-. Since ports want nothing more than to receive the 'cleanest' ships, you would expect them to welcome this new development? However, there are not only advantages but also challenges.

With reactive cleaning, there was always a need to capture what was removed. With proactive cleaning, the intention is precisely to avoid the development of harmful organisms on the hull by means of regular cleaning. In this case, there is no need for capture. As ports, we ask ourselves: where is the line between reactive and proactive cleaning? In other words, to what level is it acceptable to clean a ship's hull without capture? Or is it wrong to state that proactive cleaning is always possible without capture?

Some additional concerns:

- When the boundary between reactive and proactive cleaning has been established, a system must be developed to check the requirements in an objective manner. If this assessment is not carried out correctly, there is a high risk of harm to the local aquatic environment. This method must also be verifiable by the regulatory authorities, otherwise it will be impossible to monitor these operations correctly.
- Besides the release of organisms, regulatory authorities as ports are also concerned about the possible release of biocides and paint particles (seen as microplastics), *IMO (2019)*. These can have an impact on the local marine environment, but also cause local soil pollution. How can we be sure as ports which coatings are suitable for proactive cleaning? And what is the role of the manufacturers of these coatings?

5. New developments: The next step?

The development of hard, non-toxic coatings seems to be an interesting option in combination with proactive cleaning. However, we believe that there is little enthusiasm. The shipping industry needs to be made more aware of the possibilities and advantages. Too often, the easy solution is chosen, the known solution. Innovating has its risks, of course, but also benefits. We hope that in the near future major manufacturers will continue to take responsibility and investigate possible solutions that are both ecologically and economically feasible. For ourselves, but certainly also for the higher authorities, we see the role of supporting new players with promising prospects so that they can earn their place in the market.

A similar story can be seen with ultrasound, which could be used to protect niche areas, *Kelling (2020)*. The technology has been proving its usefulness in industrial installations for quite some time, but has not yet had a breakthrough in shipping. While in the Flemish ports, infringements are regularly observed on the cleaning of sea chests that are overgrown with macro-organisms. What is the reason why this technology cannot break through? Does the impact need to be mapped out more? And, apart from application in niche areas, is there also a possibility of protecting the entire ship's hull in this way? As ports, we are already looking forward to seeing what this technology can offer us in the years to come.

Finally, when we speak of new developments, we must not forget the power of data and computer models. As a port, we believe it is becoming crucial for ship owners to have correct and adequate data at their disposal. At the same time, it will be a challenge to use that data optimally. For example, to link the performance of a ship to its biofouling management. In addition, it will be possible to make predictions about the status of the ship's hull, the coating, the cleaning operations required, etc. Add to this the fact that it is not inconceivable that ports will request this information in the future before admitting a ship and the added value becomes immediately clear.

6. Conclusions

The Flemish ports have gathered a lot of knowledge on underwater cleaning from their position as regulatory authorities. However, they realise all too well that they are only a small piece of the puzzle. There is an urgent need for guidelines and boundaries to enable the further development and rollout of these applications and thus enjoy the many benefits they have to offer. They hope that new players feel inspired and that the interest of major partners is stimulated, because only together can we bring this to a successful conclusion.

Acknowledgments

We thank our colleagues who support us in the operational and administrative follow-up of this project. Special thanks also to Volker Bertram (DNV) for his open questions and useful insights that have contributed to the content of this article.

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Independent Testing of In-water Cleaning Companies

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Abstract

BIMCO has developed an industry standard on in-water cleaning which includes an approval procedure for in-water cleaning companies applying cleaning systems with capture. This approval procedure includes independent testing and verification of compliance with a set of performance criteria. The performance criteria include both criteria for cleaning efficiency as well as criteria for the effectiveness of capturing material being removed during the cleaning. Similar, albeit stricter, performance criteria are also proposed in the latest draft revised IMO guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species (PPR 9/7). This paper discusses the experimental design for testing proposed by the BIMCO approval procedure. Moreover, this paper describes the roles of the different parties involved in testing, such as the independent testing organisation and any approval body. This paper also highlights the practical challenges with testing, in particular with testing of the cleaning system's effectiveness in capturing material being removed during the cleaning.

1. Introduction

BIMCO (2021) describes an industry standard on in-water cleaning with capture, which includes an approval procedure, *BIMCO (2022)*, for in-water cleaning companies applying cleaning systems with capture. The BIMCO industry standard outlines performance-based requirements for in-water cleaning of a ship's hull, propeller and niche areas with capture of the materials that are removed during the process. A minimum of three consecutive cleaning events involving a different ship on each occasion is required for approval of a cleaning company. As per the *BIMCO (2022)* approval procedure, the approval of in-water cleaning companies will be based on an independent testing and assessment of the following criteria:

A. The in-water cleaning process removes at least 90% of macrofouling (i.e., individuals or colonies visible to the human eye).
B. The separation and/or treatment of captured materials during in-water cleaning both: (1) removes at least 90% (by mass) of material from seawater influent and (2) at least 95% of particulate material in effluent water is <10 µm in equivalent spherical diameter (ESD).
C. Local water quality parameters of TSS, in the vicinity of the cleaning unit and at the effluent discharge point from the separation and/or treatment systems, are not elevated above ambient levels during the same time period.
D. When applicable, dissolved and particulate biocides found in anti-fouling coating (AFC) (e.g., copper and zinc), in the vicinity of the cleaning unit and at the effluent discharge point from the separation and/or treatment systems, are not elevated significantly above ambient levels during the same time period.

Performance criterion A evaluates the cleaning efficiency while performance criteria B, C and D evaluate the effectiveness of capturing removed material and the effectiveness of the separation unit for removing captured materials. For the evaluation of compliance with criteria B, C and D, a series of water quality samples should be collected and analysed to quantify impacts of in-water cleaning on local water quality during each approval test similar to what was done by *Tamburri et al. (2020)*.

Compliance with performance criteria A, B and C is required for approval of a cleaning company. Criterion D is not a criterion for approval of a cleaning company, but any results from testing against criterion D are to be reported to local authorities for evaluation.

2. Experimental design for testing

Testing requires the development of a detailed test plan describing the scope of testing, the methods applied for sampling and analysis, and the standard operating procedures (SOP) and quality management system applied by the testing organisation. The test plan must be developed with input from the cleaning company, including stated specifications, limitations and operating procedures to ensure that representative samples are taken but without significantly impacting the cleaning operations. Environment, health and safety plans must also be included to ensure that samples are taken in a safe manner and collected material is disposed suitably.

For testing of compliance with criterion A, i.e., the efficiency of removing macrofouling, a semi-quantitative assessment of the cleaning efficacy should be made to determine the amount of biofouling removed from each of the areas defined during test cleaning events. Using images and/or videos of selected areas selected for testing before and after cleaning, each area should be assessed for percentage coverage and basic type of macrofouling. The areas to be used for the testing should be randomly selected and defined in the test plan. The inspection should be as comprehensive as practicable. The more sub-divided areas that are inspected, the greater the certainty that the biofouling for the target area is realistic.

A methodology must thus be developed for both randomly selecting representative areas used for testing and for objectively evaluating levels of macrofouling prior and after cleaning in order to evaluate whether the cleaning process removed at least 90% of macrofouling. Using a digital assessment tool may be necessary to analyse the images and/or videos.

For testing of compliance with criteria B, C and D, a series of water quality samples should be collected and analysed to quantify impacts of in-water cleaning on local water quality during each approval test. Table I summarises the requirements of the *BIMCO (2022)* approval procedure for the testing of compliance with the mandatory criteria B and C. The same samples may also be evaluated for the presence and concentration relevant biocides to evaluate compliance with criterion D.

Table I: Testing requirements for BIMCO industry standard performance criteria B and C

Criterion	How to sample	Type of sample	Analysis
B – Effectiveness of the separation and/or treatment unit of removing captured materials	Sample collected at two locations: at the inlet (influent) and at the outlet (effluent) of the separation and/or treatment unit	Continuous, time-integrated sample during an in-water cleaning test period of at least one hour	Total suspended solids (TSS), particle size distribution (PSD)
C - Impact on local water quality (Cleaning unit sample)	A sampling hose or submersible pump should be attached to the cleaning unit	Continuous, time-integrated sample during an in-water cleaning test period of at least one hour	Total suspended solids (TSS), particle size distribution (PSD)
C - Impact on local water quality (Background sample)	A pump and hose system should be deployed adjacent or adhered to the test ship (at least 50 metres from cleaning activity) with intake positioned at approximately mid-depth between water line and bilge keel	Continuous, time-integrated sample	Total suspended solids (TSS), particle size distribution (PSD)

Taking representative samples is crucial, and selecting the sample location, installing sample ports and planning the sampling process thus needs careful considerations. Testing organisations which are experienced with taking continues, time-integrated water sample, such as testing organisations performing ballast water analyses, are expected to have the necessary competence and experience for taking representative samples.

For the cleaning unit sample, a suitable intake location and method of mounting the hose or pump must be found and defined in the test plan. The intake location should be where one expects the highest possible concentration of material being removed from the test ship during in-water cleaning and the lowest capturing rate. A computational fluid dynamics assessment may have to be performed to determine this location. Alternatively, samples may be taken from multiple locations on the cleaning unit.

For all samples taken to evaluate compliance with criteria B, C and D, at least 10-20 litres of sample water should be drawn continuously. The container with the 10-20 litres sample should then be uniformly mixed prior to distributing sub-samples for, at minimum, triplicate analyses of each parameter.

Taking a continuous sample of 10-20 litres which is time-integrated over a period of at least one hour requires that a sample port as shown in Fig.1 is installed on the pipes for the influent and effluent water of the separation unit, the pipes with the water from the cleaning unit intake and the pipe with the water from the background sample location.

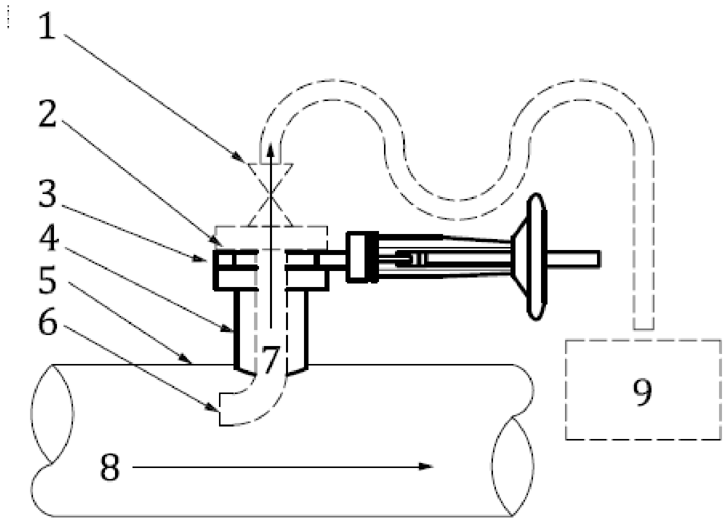

Fig.1: Sample port (figure from *ISO (2019)* adapted to sampling for testing of in-water cleaning companies), with 1 sample collection device valve, 2 sample port access flange, 3 sample port valve, 4 sample port, 5 pipe with influent or effluent water of the separation unit / the cleaning unit / the background sample location, 6 sample probe, 7 sample water flow, 8 influent or effluent water flow, 9 sample container

When selecting the sample port, one must also select a sample probe diameter and sampling flow rate that results in isokinetic sampling conditions. Isokinetic sampling conditions prevent skewed particulate concentration measurements due to inertial effects of particles as they enter the sample probe. Isokinetic conditions prevail when there is no divergence of flow lines around the sample probe. To achieve isokinetic sampling conditions, the sample probe must face directly into the sampled stream in order to minimize or eliminate divergence of the flow lines at the sampler inlet. Moreover, for sampling of ballast water, the IMO sampling guidance *IMO (2008)* concludes that the that flow transitions from the main stream is best for sample port diameters between 1.5 and 2.0 times the isokinetic diameter. The isokinetic sample probe diameter should therefore be determined generally according to the equation $D_{iso} = D_m\ Q_{iso}\ /Q_m$ where D_{iso} and D_m are the diameters of the sample probe opening and the pipe being sampled, respectively; and Q_{iso} and Q_m represent the respective volumetric flow rates through the two pipes.

Samples are to be analysed for total suspended solids (TSS), particle size distribution (PSD) and, if applicable, relevant biocides which may be part of the relevant AFC (e.g., copper and zinc). These analyses are typically performed according to internationally accepted methods, and TSS, PSD and biocide analyses are typically included in the scope of the testing organisation's ISO 17025 accreditation. The analysis of the samples itself is thus not expected to represent a particular challenge to the approval testing of in-water cleaning companies, and many laboratories are expected to have the necessary competence and experience for analysing samples. Nonetheless, there may be some challenges with storing and transporting samples for the PSD analysis. Particles may clump together during transport and storage of the samples, resulting in a PSD that may not be fully representative of the PSD of the influent or effluent water. Given that the performance criteria for removal of particulate material aims mainly at removing particulate material which is larger than 10 µm in equivalent spherical diameter (ESD), any clumping of particulate material of less than 10 µm ESD will thus result in making it more challenging to comply with the performance criteria for effluent water from the separation unit.

3. Independent testing

In accordance with the BIMCO industry standard, all testing of in-water cleaning systems should be conducted by an approval body supported by an independent testing organisation. An approval body audits the cleaning company and issues a certificate of approval. The approval body shall approve the test plan prior to testing and evaluate the test results.

The role of the independent testing organisation is to be defined in the test plan. The *BIMCO (2022)* approval procedure requires that the testing organisation is independent and must at least provide the instructions for sample collection, processing and transportation of samples and carry out the verification of testing of the samples and convey the results of the tests. The BIMCO approval procedure also describes a chain of custody procedure for the collection and delivery of samples for analysis. This potentially allows for the cleaning company to take the samples themselves as per the testing organisation's instructions. However, due to the complexity of the sampling and the importance of having representative samples, we expect testing organisations to prefer collecting the samples themselves or at least survey the sampling, because they are reluctant to assume responsibility for the analysis results when they were not directly involved in the sampling. One can also argue that the independent testing required by the BIMCO industry standard requires that the independent testing organisation collects the samples or at least surveys the sampling given that both independent sampling as well as independent analyses are important aspects of independent testing.

The approval body may be part of the process in various ways, and the BIMCO industry standard acknowledges that while some approval bodies may only need to see the results, others may want to witness the sampling and/or analysis processes. Again, due to the complexity of the sampling and the importance of having representative samples, which includes that samples are taken during a representative period of an in-water cleaning event, DNV, if asked to act as an approval body, would want to survey at least the first of the three tests for a cleaning company. To have independent testing, DNV would also expect the independent testing organisation to collect the samples or at least survey the sampling in the remaining tests.

A survey by the approval body is also necessary for evaluation of the cleaning company's implementation of its cleaning procedures. In addition, the approval body must evaluate the suitability of the cleaning procedures for cleaning different ship types, different niche areas and different levels of biofouling prior to cleaning. The cleaning procedures may be applicable to hull areas and various niche areas and/or propellers. Cleaning efficacy may vary for different target areas due to structural variation, different hydrodynamic forces and susceptibility to AFC wear or damage, or inadequate protection by anti-fouling system (AFS).

For the approval of a cleaning company, the BIMCO Industry Standard requires testing of a minimum of three cleaning events involving a different ship on each occasion. This will result in a verification of the cleaning performance of three cleaning events which may represent some variations in test conditions, such as variations in ship types and hull shapes, propeller types and/or niche areas and levels of biofouling present prior to the cleaning event. However, by conducing only three tests, it is unlikely that all possible variations and conditions are tested. To ensure repetitive robust testing to verify cleaning system performance, the three cleaning events should be similar with respect to target area accessibility, target biofouling type, AFC type and time period of testing. Type and age of AFC has an impact on potential negative effects from cleaning.

A representative set of test ships and target areas should thus be selected to challenge the cleaning equipment within its specifications. The cleaning company should in communication with the approval body select three cleaning events which are representative of the cleaning being carried out by the cleaning company and which provide a suitable variation in test conditions. Moreover, in order to evaluate cleaning efficacy in various target areas, the three tests should include relevant target areas included in the specifications of the cleaning procedures.

4. Review of the IMO guidelines for the control and management of ships' biofouling

Performance criteria for cleaning efficacy and capturing material that is removed through in-water cleaning are also expected to be defined in the revised IMO guidelines for the control and management of ships' biofouling, *IMO (2021)*. An IMO Correspondence Group (CG) has been established and tasked to propose revised guidelines. with the aim to conclude the work and send a report to IMO MEPC in early 2023.

The criteria currently discussed at IMO are similar in nature but stricter than the performance criteria defined by the BIMCO industry standard. As per the latest draft of the IMO guidelines, *IMO (2021)*, the performance criteria for cleaning efficacy are as follows:

1) After completed cleaning, the target area should achieve a biofouling rating ≤1 for the cleaned target area, where a biofouling rating 1 is defined as light microfouling and no presence of macrofouling.
2) Cleaning should avoid damage of coating system, and loss of upper paint layer in accordance with specifications from manufacturer.
3) Cleaning should be conducted by cleaning and maintenance companies following local jurisdictional approval and using relevant international standards and/or accepted industry standards.
4) Cleaning should be in line with occupational health and safety requirements set out by the relevant local authority.
5) Both cleaning in dry dock or by an in-water cleaning technology with capture is recommended, as it will lower the risk of transferring invasive aquatic species and risk of pollution from harmful waste substances.

The performance criteria for capturing defined the latest draft of the IMO guidelines, *IMO (2021)*, are to:

1) capture 99% (by mass) of waste material of the influent to the cleaning system;
2) capture 99% of waste particulate material in size ≥10 μm (in equivalent spherical diameter) of the influent from the cleaning system;
3) concentration of TSS and dissolved harmful waste substances in the surrounding waters should not increase compared to a measurement from ambient water in the same location during the same time period;
4) the discharge/effluent from any in-water cleaning system should not exceed the thresholds for dissolved harmful substances in a measurement from ambient water in the same location during the same time period; and
5) the cleaning systems should not release any visual objects to sea or introduce discoloration of the surrounding water.

The above performance criteria, however, will be subject to further discussions in the IMO CG, and several CG members have expressed concerns that the currently proposed performance criteria are too stringent and difficult to meet with today's best available technologies. The performance criteria, together with the risk assessment to be performed for determination of inspection intervals and minimum inspection intervals, are thus particular topics that the CG will have to consider during the finalization of the work on revising the IMO guidelines for the control and management of ships' biofouling.

The revised IMO guidelines for the control and management of ships' biofouling are not expected to include any provisions for testing and approval of cleaning companies. This will be addressed in separate stand-alone IMO guidelines. Nonetheless, the CG has had some considerations regarding the role of cleaning companies and the role of independent inspection and testing organisations. The CG has so far showed broad support for using independent inspection and testing organisations, which are to be accredited/authorized/licensed by the relevant national authorities, in whose waters the inspection and/or cleaning is to be performed.

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Underwater Localization for Autonomous Inspection of Ship Hulls by Sensor Fusion of Data from a Small-Scale ASV and ROV

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Abstract

Digitalization and the use of unmanned systems are the future backbone of maritime services. Advances in robotics and autonomous surface vehicles are enabling new approaches to ship inspection services in the port of the future. A crucial element in performing an autonomous inspection with an ROV is the underwater localization of the vehicle. This paper introduces the concept of combining the sensors of an overwater and underwater vehicle to determine the relative position of the ROV with respect to the hull of the vessel. Based on an introduction to the concept and its components, the paper will focus on the tests performed for different identified concepts.

1. Introduction

Autonomous waterborne robotic systems are becoming increasingly common in the maritime sector. Waterborne robots are usually classified as Unnamed Surface Vehicles (USVs) and Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), the latter two being submersible. The use of AUVs and ROVs is usually very costly because they are difficult to operate, require special skills, and are often tailored to specific tasks, *Zereik et al. (2018)*. Increased autonomy in ROV operation and the potential to replace ROVs with Autonomous Underwater Vehicles (AUVs) for some operations may constitute a significant improvement in HSE (Health, Safety, Environment) and costs, *Grøtli et al. (2016)*. However, if the autonomy is to be increased here, it is necessary to develop and implement advanced command and control, navigation, motion control and mission control systems to ensure that the vehicles have the high reliability required to perform complex missions, *Zereik et al. (2018)*.

To achieve the higher-level reasoning needed for performing complex tasks, robotic systems require localization capabilities that enable augmenting more complex commands to their higher-level controllers. Localization refers to the capability of understanding the position of robotic systems in their environment. As mobile waterborne robots operate in dynamic and unstructured environments, their ability to accurately map the environment and its changes becomes essential for safe operation. The interest in accurate and robust localization has led to numerous publications on ROV localization and different approaches. *Padial et al. (2014)* use sonar imagery as an automated pilot aid for the localization of an ROV with respect to an a priori bathymetric terrain map. Another method is the use of real-time simultaneous localization and mapping (SLAM). *Meireles et al. (2014)* addresses the development of an underwater visual navigation system for ROVs based on the Real-Time SLAM method using natural landmarks. In contrast to these solutions, this paper will present a solution with a multi-robot system.

2. Underwater Inspection

2.1 Problem Description and Solution

The vessel inspection aims to know the vessel's condition and the location of any damage to the vessel to decide whether a repair is necessary. Specifically, for the ship inspection, it is necessary to know the camera data and the position of the ROV relative to the target ship to synchronize the video stream with the position. The different reference frames and positions required for this are shown in Fig.1.

The desired position to map the video stream with the hull is shown in light blue in Fig.1. The distance of the ROV in the frame of the ship subsequently called $p^{g}_{b/g}$ in the reference frame g of the target vessel.

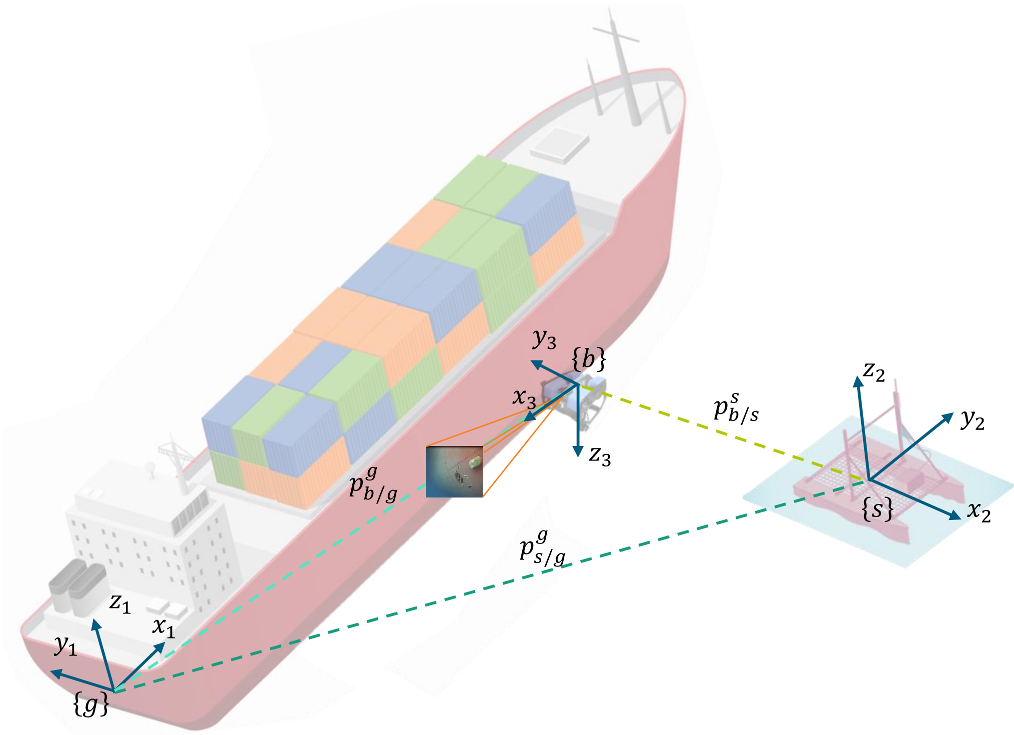

Fig.1: Reference frames for underwater inspection

With conventional systems, there is often the problem that the position of the ROV relative to the target ship is unknown. To solve this problem, the Fraunhofer CML has developed an approach to combine the position of the ROV by fusing the sensors of two robotic systems. A vehicle above water (ASV) is combined with an underwater vehicle (ROV). This offers the advantage that information from sensors such as LIDAR, GNSS, Radar, etc. can be made available to the underwater vehicle. Fig.1 illustrates the approach developed. Instead of determining the relative position of the ROV to the target vessel $p^{g}_{b/g}$The position of the ASV relative to the target vessel $p^{g}_{s/g}$ can be determined and the relative position from the ROV to ASV $p^{s}_{b/s}$. Using these two measured positions, the position of the ROV $p^{g}_{b/g}$relative to the vessel can be estimated as follows:

$$p^{g}_{b/g} = p^{g}_{s/g} + \boldsymbol{R}\, p^{s}_{b/s} \quad (1)$$

The superscript letter indicates the reference frame (g: target vessel, s: ASV, b: ROV). As shown in equation (1), the position of the ROV in the frame of the ASV is transferred using the transformation matrix $\boldsymbol{R}$.

2.2 Inspection procedure

This approach to localization and combining an ASV and ROV allows vessel inspections to be carried out without using a manned vessel. How such services can be offered in the future was shown in the Robotic Vessels as-a-Service (RoboVaaS) project, *Schneider et al. (2020)*. Each step of the inspection procedure is presented in the following. The inspection procedure can be divided into five steps. Steps 3 and 4 are repeated iteratively, depending on the vessel's length. In the first step, the position and length of the target ship are measured. For this purpose, the ASV moves along the ship and records a point cloud with its lidar. With the help of a SLAM approach, the ship's position can be determined.

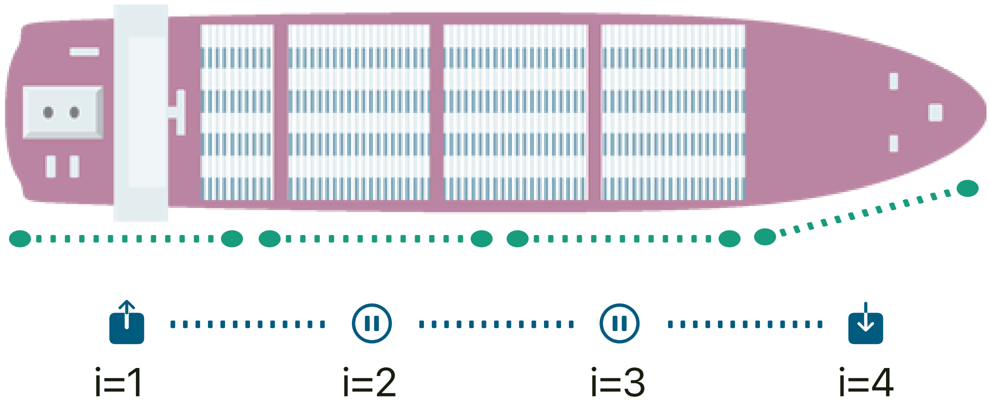

Fig.2: Two-dimensional projection of the path for the execution of a hull inspection

Fig.2 shows a mockup of the 2-dimensional projection of the ship for path planning. Since the distance between ROV and ASV is limited by the cable length, the ship must be divided into i sections $[i \in \mathrm{N}^{+} \mid i \leq I]$ with I total number of individual segments. Here, a nominal path for the ROV is defined as well as a stopping position for the ASV. In Fig.2, the path of the ROV is shown simplified in green and the path of the ASV in blue.

In the second step, the ASV moves to the first stop position (indicated with). Once the waypoint is reached, the vehicle automatically switches to loiter mode and holds the position. While the vessel is holding the position, the launch and recovery system is started and the ROV is lowered into the water. After completing this process, the system switches to the actual inspection mode. Here the position of the ASV is held and the ROV travels along the defined path for the i-th segment. After the ROV reaches the final waypoint of the i-th section, the whole system moves to the next waypoint. The ASV moves to the stop position (represented by) and the ROV moves to the starting point of the $i+1$ patch. This process is repeated interactively until the last segment I is reached. After completing the survey of the last segment I, the ASV holds the position and the LARS system is activated (illustrated by). Here a signal is sent to the winch to start the retraction process. When the ROV reaches the upper position of the A-frame, the tether is retracted and the ROV is placed on the deck again.

3. Research Platform SeaML:SeaLion

To implement the approach described in the previous section, an ASV is required to carry the ROV and launch and recover it automatically. For this purpose, the Fraunhofer CML has developed an ASV that serves for research on autonomous systems and as an interface for other robots. Fig.3 shows the in-house developed ASV named SeaML:SeaLion.

Fig.3: SeaML:SeaLion in the multi-vehicle setup for underwater ship inspection services

The ASV features a catamaran design for improved waterborne stability and a modular layout of the onboard systems and is purely electrically powered. The twin hulls are connected by a superstructure that can also accommodate various combinations of sensors and equipment used to perform a multitude of experiments. The unique feature of the ship is the modularity of the equipment that can be installed on its deck. Depending on the research project, either a complex structure such as a Launch and Recovery System (LARS) for underwater robots can be installed, Fig.3, or a completely empty deck is possible. The vessel specification can be seen in Table I.

Table I: Vessel specifications of the modular research platform SeaML:SeaLion

Length	2.2 m
Width	1.5 m
Draft	0.6 m
Max Speed	8 kn
Voltage level batteries	48 V
Short BaseLine (SBL)	Waterlinked R100
Lidar	Velodyne vlp 16
ROV	Bluerobotics BlueROV2

SeaLion is controlled by a central computer, a small form factor PC (Intel NUC). This PC communicates with several small single-board computers via Ethernet. Consequently, all domain controllers are connected to the same Local Area Network (LAN). Moreover, a 5GHz connection allows a stable and fast connection between the ship and the shore station. On the software side, the ship is based on the open-source middleware package Robot Operating System (ROS). SeaML:SeaLion has already been validated through several sea trials in the Port of Hamburg and a public demonstration throughout the Intelligent Transportation Systems (ITS) Congress in 2021. This demonstration shows the robotic service approach developed in the RoboVaaS (Robotic Vessels as a Service) project see *Schneider et al. (2020)*. The project aims to make maritime operations in ports more efficient and safer by integrating and connecting smaller ASVs (Autonomous Surface Vehicles) and ROVs (Remotely Operated Vehicles) to offer new services to the shipping industry.

4. Underwater localization

This section briefly reviews the sensors used for underwater localization, the sensor fusion mechanism and ROS packages used, as well as the test setup developed to execute and validate the state estimation algorithm. Finally, the results of the ROV localization tests are presented.

4.1 Multi-sensor fusion of the ROV

Since accurate state estimation for a mobile robot requires the fusion of data from multiple sensors, four different sensors were combined to obtain an overall pose estimation with an error less than using each sensor in isolation.

For the sensor fusion of the ROV, an inertial measurement unit (IMU), a short baseline (SBL), a doppler velocity log (DVL) and a depth sensor were used. The IMU provides a three-axis linear acceleration and angular velocities about the XYZ axis. These measurements are noisy, drift over time, and are affected by water temperature, besides the electronics and actuators of the ROV itself. The SBL feeds direct XYZ position observations of the ROV relative to the ASV reference frame. It mainly consists of a transmitter mounted on the ROV and four receivers mounted on the ASV. Once the acoustic signal is received, the distances between the ROV and the ASV receivers are calculated based on the time delay and the speed of sound in water. Using the triangulation method, the position is calculated in the reference frame of the ASV, and then it can be projected into the ASV global frame. Although SBL provides direct absolute position data updates, its measurements are noisy, produced at a low rate, and subjected to random discrete jumps, *Chterev (2018)*. The DVL operates by sending 4-beam acoustic waves out of a transducer and then receiving the bounced waves back. It then measures the phase shift across those four beams and computes the speed relative to the seabed *Hegrenæs et al. (2016)*. DVL measurements, apart from the relatively low acoustic rate, are prone to high noise and significant data outliers. The depth sensor feeds depth observation relative to the water surface based on the sensed pressure. As the depth sensor provides direct depth readings with high accuracy, it is beneficial to trust its ready than the SBL's Z position. Therefore, this work focuses mainly on the XY position and velocity.

The Madgwick filter is used to fuse angular velocities and accelerations readings from the IMU raw data into an orientation, *Madgwick (2014)*. The Robot localization package is employed to fuse all available measurements of the mentioned sensors above. This package is an implementation of a generalized extended Kalman for ROS. It supports the fusion of multiple sensors with a high level of customizability, making it well-suited for the problem of nonlinear state estimation for various robot platforms moving in 3D space. It uses an omnidirectional motion model to project the state forward in time and corrects that projected estimate using sensor data *Moore and Stouch (2016)*.

4.2 Test setup

In the following, the test setup to validate the underwater localization of the ROV relative to ASV ($p^{g}_{s/g}$ in Fig.1) is described. The test setup consists of two systems, one providing the base station for short baseline acoustic positioning (SBL) and the other providing the ground truth values for underwater localization, Fig.4.

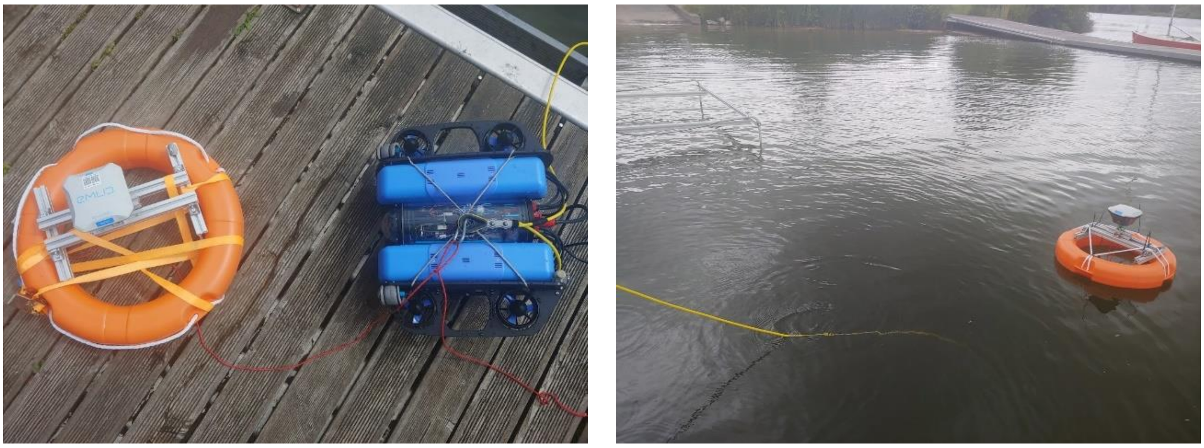

Fig.4: Ground truth test setup for underwater localization

The test rig was statically docked on a jetty during these trials to validate the underwater localization. The SBL (Waterlinked R100) systems transmitters were mounted on the test rig at 70cm from the water surface. To ensure transferability, the individual receivers were positioned identically to the positions on the SeaML:SeaLion. A single-band RTK GNSS receiver (Emlid Reach RS+) was used to measure the geodetic position accurately. Real-Time Kinematic has been the standard for precise localized positioning in the surveying, engineering construction and machine control industries, *Bisnath (2020)*. The SAPOS®-HEPS service was used for the correction data for accurate real-time positioning. According to the provider, https://www.sapos.geonord.de/heps.php, this enables the accuracy of less than 3 cm.

In addition to the base station, it is crucial to have a ground truth for localization during validation. For this purpose, the approach chosen was to project the position of the ROV underwater onto the water surface. Fig.4 shows the setup used. First, the GNSS RTK station was mounted on a floating platform and connected with a rope to the topside of the ROV. Next, the ROV was submerged in water at a depth that put enough tensile strength on the rope to keep it straight. Finally, the ROV was set to depth hold mode and sailed around while capturing data.

4.3 Test results underwater localization

The results from the experiments to validate the underwater localization are presented in the following. The test series was conducted on a lake in Hamburg, Fig.5 at sea state 1. The distance between the two jetties is 15 m and the water depth ranges between 2.5 and 7m in the test area. Fig.5 shows the three different measured and calculated positions of the ROV. The green line is the ground truth position of the GNSS RTK Station, the red path is the result of the Extended Kalman filter (EKF) and the blue line is the result of the SBL.

Fig.5: Visualization of the measurement results of the localization tests on the lake

The GPS coordinates were post-processed, and the Root Mean Square Error (RMSE) was calculated by averaging the distance between each position emitted by the Reach GPS RTK overwater GPS and the closest position emitted by the SBL or EKF within 0.01s time interval. The results of 3 different test runs are shown in Table II.

Table II: Evaluation of the test runs

Run	**Positions compared** [samples]	**Odometry** [m]	**RMSE SBL/RTK** [m]	**RMSE EKF/RTK** [m]
1	290	51	0.779	0.36
2	612	102	0.289	0.198
3	1045	220	0.606	0.454
4	613	164.5	0.424	0.289

As can be seen from TableII, the maximum deviation of the EKF in the four test rounds is 0.45 m. A small section of the test run is evaluated in depth below to get a better insight of the results of the EKF.

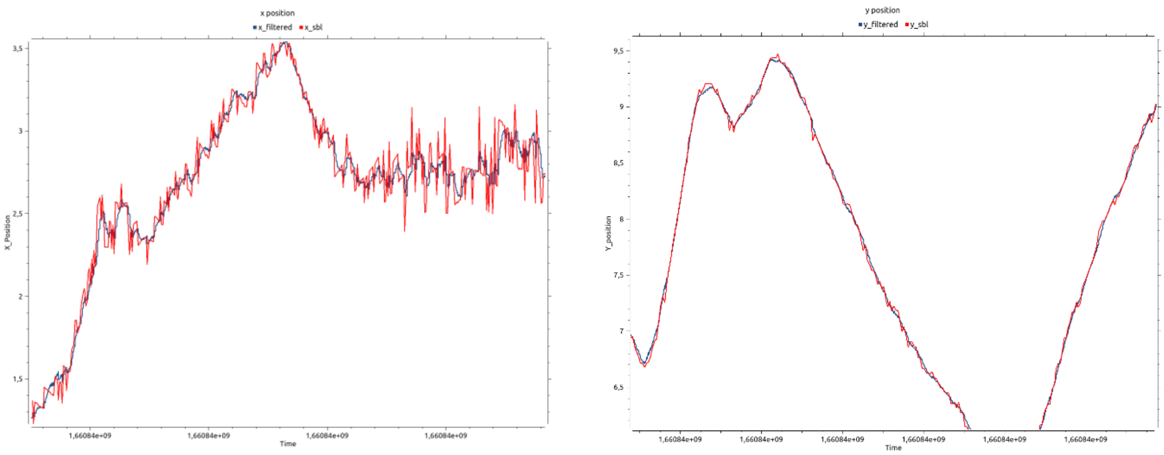

Fig.6: XY position filtered compared to the raw SBL data

The sensor fusion algorithm could filter out the noisy SBL readings and successfully estimate a more accurate XY position of the ROV, Fig.6. The EKF was also capable of predicting the future XY position with respect to the ASV frame at a high rate of 50 Hz before receiving the updated SBL low-rate readings at only 2 Hz. This is also very useful in situations where the SBL loses connection for a long time (sometimes up to 1min), during this time, the localization algorithm relies mainly on the DVL's continuous velocity readings and IMU heading by dead reckoning starting from the last fused position. Besides the normal noisy DVL signal, its data outliers were successfully detected and eliminated, resulting in highly stable DVL measurements as shown in Fig.7.

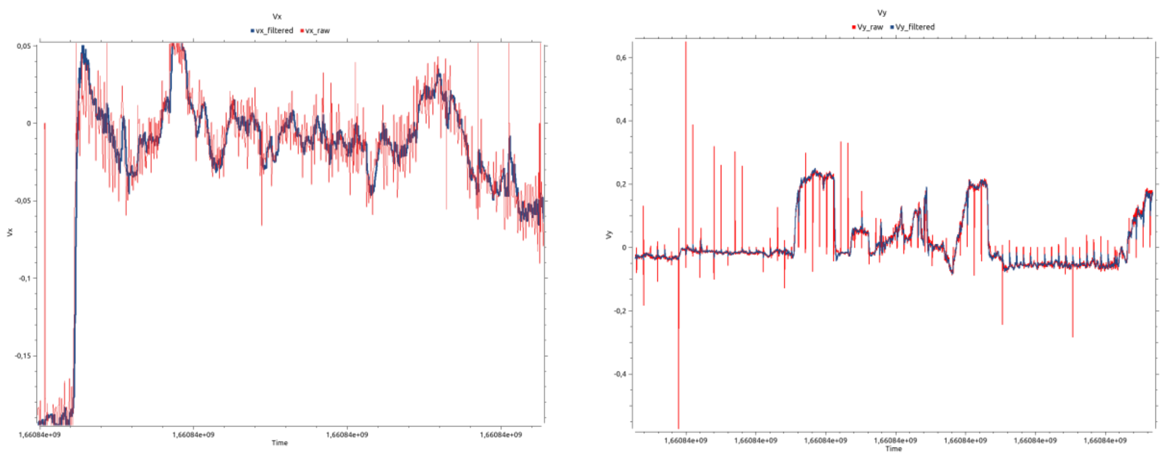

Fig.7: XY velocity filtered compared to the raw DVL data

5. Outlook

The publication introduced an approach for the autonomous inspection of ships. The individual steps of the inspection, an approach to solve the localization problem and also the validation tests of the ROV's subsystem of underwater localization were outlined. Further investigations are aimed at testing the entire system in port and also determining the offshore suitability of the approach. Soon, it is planned to test the capability of the whole system offshore to provide services for ships on anchorage. Another potential field is the inspection of Offshore Wind-parks and other infrastructure. Since the vessel is so small and entirely electorally driven, it can access areas where access for bigger fuel-driven vehicles is prohibited.

Besides the underwater part, the ASV has been put through its paces in various tests since its introduction. These included port surveys, autopilot investigations, and robot-as-a-service studies. Further development of the USV aims at two aspects: developing autonomous services in the maritime sector and developing an intelligent situational awareness controller. These developments of new controls and algorithms are not only carried out in the real port environment but also in a simulation.

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Frequent and Habitual: How Autonomous Robots Can Make Routine Grooming and Inspection Accessible

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Abstract

Consensus holds that keeping a ship's hull clean is highly beneficial, yet cleaning is typically conducted once the macrofouling becomes too bad to ignore, rather than at a more optimal, efficient frequency. This paper will explore how advances in small autonomous robots can enable a proactive approach to cleaning and inspection, with no disruption to ship operations. Improvements to navigation and control technology can enable small, driverless solutions that can be easily deployed whenever the vessel is idle, in-port or at anchor, without disrupting other ship operations. It will present a functional overview of inertial and feature based navigation in a hull relative coordinate plane, as well as how a micro-fouling removal system interacts with modern coating systems, and fits within the current regulatory framework. Additionally, representative fuel consumption calculations will be presented to demonstrate the value proposition in adopting a proactive approach to hull maintenance.

1. Introduction

Biofouling is a problem. All stages of biofouling are a problem for the shipping industry, but the traditional approaches towards biofouling control have been directed towards macrofouling, or the later stages of growth. Waiting until macrofouling is present to conduct a cleaning is waiting too long. Fuel consumption penalties have increased, the growth may present an environmental threat if not captured during cleaning, and aggressive cleaning methods necessary to remove macrofouling risk damaging the coating system. More frequent cleaning of ship hulls would certainly benefit the operators and the planet, if they could be completed in an efficient and economic manner. Advances in robotic technology can now enable small robots to operate autonomously to perform frequent and habitual cleaning evolutions, preventing the biofouling from reaching the macrofouling stage, resulting in improved fuel consumption and greenhouse gas emissions, a reduced environmental threat and a reduced risk to the coating system.

2. Benefits of Proactive Cleaning

The International Maritime Organization (IMO) has set a goal of a 40% reduction in greenhouse gas emissions for the international shipping industry by 2030, with that goal increasing over the coming decades. These are laudable and necessary goals, but also extremely challenging to achieve. The shipping industry is working hard to develop new technologies to meet these goals, including alternative fuels, emissions cleaning and capture solutions, and improved hydrodynamic features for hulls, propellers and rudders. Great progress is being made on these approaches, but many of them are only applicable to newly built ships, or are extremely difficult (and expensive) to implement on existing vessels. Fortunately, there is one approach that can be taken for all vessels, existing and new - proactive in-water cleaning.

The most straightforward way to reduce emissions is to reduce fuel consumption. Fuel consumption can be reduced through efficient operations, including ensuring the hull is as hydrodynamically efficient as possible. Once built and painted, the hull needs to be kept as clean as possible. Any growth on the hull will have a negative impact on performance. A recent report published by the IMO's Glofouling Partnership has indicated that a very thin layer of slime (~0.5 mm thick) covering 50% of the hull can increase emissions as much as 20-25%, *NN (2021).*

Fig.1 shows the impact that early-stage biofouling can have on Greenhouse Gas (GHG) emissions (and by direct correlation, fuel consumption). While there is variation in the performance of vessels with light slime or a deteriorated coating, its clear that there is a measurable impact. At the heavy slime level, the variation is significantly less, and the impact greater than a 20% increase in emissions (and fuel penalty). At current fuel prices (800 USD/t), for a ship that burns 100 t/day, a 20% penalty translates to 16,000 USD additional in fuel being burned per day. Given that it takes a variable about of time for a vessel's fouling condition to reach the point of a 20% penalty, factoring water conditions, operational profile and coating system, its not a simple equation to calculate the exact daily cost of the fouling.

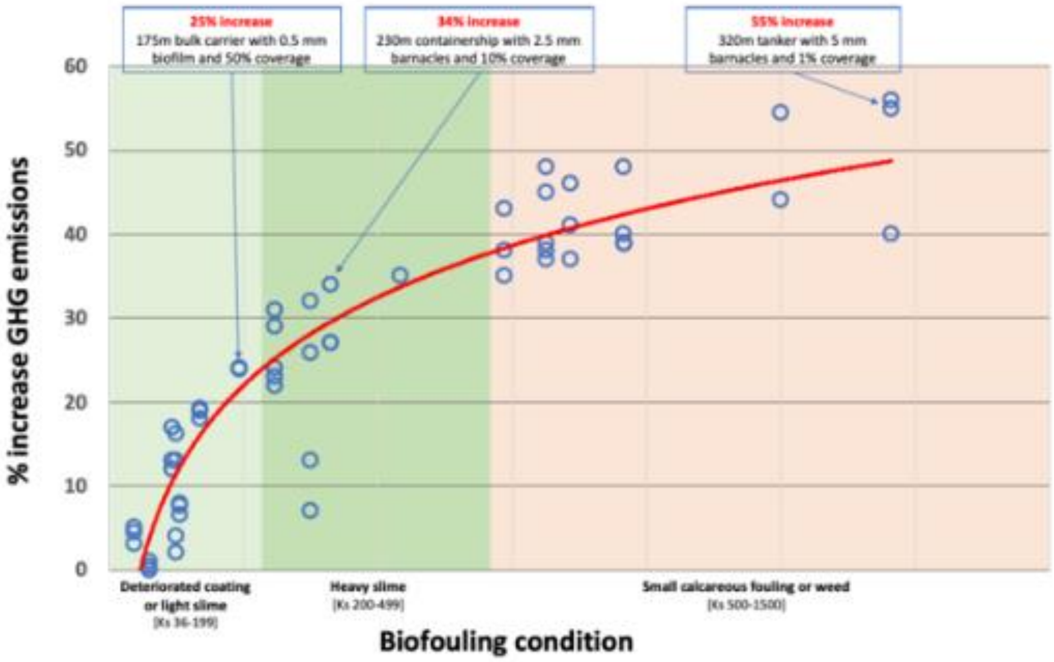

Fig.1: Impact of ship hull biofouling on GHG

However, that level of growth can occur rapidly in warm waters, and is not easily detected. Very little of a ship's submerged hull is visible, and so without a diver or ROV inspection, the actual condition of the hull is unknown, and the understanding of the fouling condition and its impacts are possibly underestimated.

Proactively cleaning the hull at a much greater frequency, using gentler tools designed to remove the slime-like microfouling, can greatly improve vessel efficiency at little risk to the coating system. A proactive approach resets the vessel to a clean condition every month or so, netting a savings in fuel every day, when compared to allowing the fouling and fuel penalty to grow until the annual cleaning occurs. This fuel savings directly translates to reduced emissions and a cost savings for fuel. Further, this increased efficiency translates to other fuel sources, which may prove to be more expensive than current heavy oil and diesel fuels.

Beyond the financial and emissions benefits of dealing with microfouling, a further benefit is regarding the control of potentially invasive aquatic species. Microfouling has less chance of introducing invasive species than does macrofouling, *TC (2021)*. Further, regulations are being implemented for the control of invasive species that will effectively mandate more frequent cleaning. IMO regulations have already addressed how to control the spread of invasive species through proper management of ballast water, but hull fouling has been identified as an extremely high-risk factor requiring additional management practices. Australia is already implementing regulations to address the threat. The Australian Department of Agriculture, Water and the Environment has published the Australian biofouling management requirements, *NN (2022)*, stipulating that incoming ships address biofouling; through proof of having a biofouling management plan, having cleaned the vessel of all biofouling within the past 30 days, or use of an Australian-approved alternative biofouling control method. While Australia is out in front with published guidance, the IMO's GloFouling Partnerships Project is working on a global scale raising awareness and driving regulations to help protect the world maritime environment, and it would be naive to think that Australia will stand alone.

At the risk of oversimplifying things, any ship making a transoceanic voyage to Australia is going to have to prove that they have been recently cleaned, or otherwise demonstrate that they are not creating a biosecurity risk to Australian waters. A proactive cleaning approach will support compliance with these and similar regulations. A shipping leaving a port with a clean hull and making a continuous oceanic transit to its destination will have, at most, early stage microfouling, and what microfouling that is present will be pelagic in nature rather than littoral from the previous port, and thus present minimal risk to the new environment.

Microfouling can be removed via gentle means that reduce the risk to the coating system. This serves a two-fold purpose, both ensuring the coating system remains on the vessel to perform its intended protective, anti-corrosive role, as well as keeping paint chips and particles from entering the water column. Long-term testing of panels coated with common ablative coatings has shown no signs of scratching over approximately 25 cleaning evolutions, and accelerated testing has shown that only approximately 15 microns of coating will be removed over 1000 passes. Considering that a cleaning evolution would likely only result in 4-5 passes at most over a given area, both the short term and long-term risks to the coating system are low. Similarly, the potential impacts to the environment from the cleaning are low, as any single cleaning evolution will not remove any appreciable coating from the vessel.

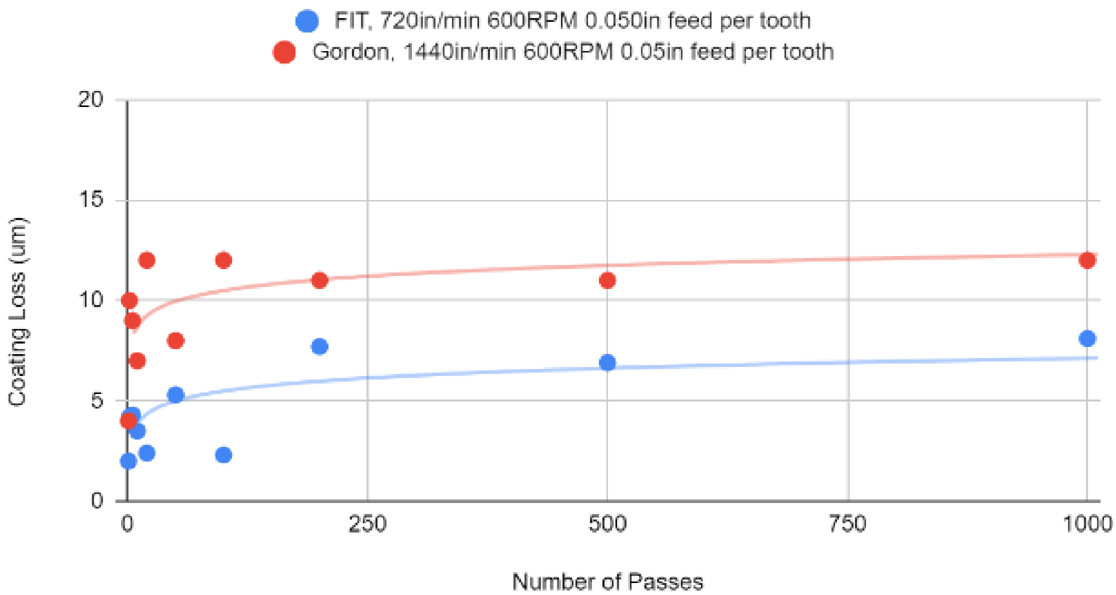

Fig.2: Coating loss over repeated grooming passes

3. Barriers to Proactive Cleaning

The benefits of proactive cleaning seem fairly straightforward, however the concept has yet to gain a commercial foothold. This is because until recently the only way to undertake a proactive cleaning regimen would be to use the reactive solution on a frequent, routine basis to tackle microfouling instead of waiting for macrofouling. This is suboptimal on a couple of levels. First, the tools for reactive cleaning are designed for removing macrofouling, not microfouling. As such, these tools may not effectively remove the microfouling, and their more frequent use may be detrimental to the health of the coating system. Perhaps more crucially, a reactive cleaning system can take multiple days to clean an entire ship, removing the ship from its normal operating routine. Doing this once a year may be fine, but once a month will have significant impacts to both the vessel operator and port facility. The vessel will be out of operation for a greater period of time, and could potentially lose an entire revenue generating voyage from its annual schedule and the port facility will be locked up with a vessel undergoing maintenance vice offload/onload. Third, it is not economically attractive. The cost for the reactive solution will likely be similar whether its removing slime or barnacles.

4. Autonomy to the Rescue

Armach Robotics has developed a dedicated proactive cleaning solution that overcomes the barriers identified above. The cleaning methodology is optimized to clean early stage microfouling, a vessel can be completely cleaned in a single day, and through the use of autonomy and reduced onsite infrastructure and manpower, the annual cost is significantly lower than a reactive solution similarly employed would be.

Armach's solution uses a fleet of small, autonomous robots (known as Hull Service Robots (HSR)), Fig.3, equipped with soft brushes to proactively clean vessels during a normal inport period, with minimal disruption to other inport activities. The HSR is a hybrid flying and hull crawling robot, approximately 1 m long and weighs less than 35 kg that can clean ~650 m^2 (7,000 sq feet) per hour. The brushes used on the cleaning head have been extensively tested to ensure they work optimally with the coating system being cleaned, effectively removing the microfouling while not damaging or accelerating the wear rate of the coating. The HSR is equipped with a forward-looking sonar and forward and rear looking cameras to document the condition of the hull, pre and post cleaning.

Armach's ultimate differentiator is the use of autonomy and precision on-hull navigation to overcome all three barriers.

Fig.3: Hull service robot

Fig.4: Clean hull

If the HSR knows exactly where it is on the hull at all times, it can be programmed to cover the entire hull efficiently and prove that it provided 100% coverage of the hull. Efficiently providing 100% coverage of the hull is critical to a successful proactive cleaning approach. If spots are missed, the microfouling can grow into macrofouling, defeating the purpose of proactive cleaning. That's pretty obvious. But the HSR needs to provide that complete coverage in as little time as possible, minimizing contact time with any specific spot on the hull. An 8-12 hour in-port period simply does not allow time for the HSR to run back and forth over the same spot on the hull. Equally importantly, as gentle as the brushes are to the coating system, repeated contact with the same spot, particularly if clean of fouling, is suboptimal to the coating system.

Because the HSR is autonomous, no one is needed to actively pilot it. Where a reactive system may require as many as 4-6 people to oversee operation of a single system, multiple Armach HSRs can be monitored by a single person. Because of the small size of the HSR, no significant infrastructure is required for its launch, operation and recovery. Multiple HSRs can be operated from a single operations unit, typically a commercial van or small trailer, located on the pier near the bow and/or stern of the vessel. Running multiple HSRs on a vessel allows for it to be completely cleaned within 8 hours or so, while still allowing routine pier operations to continue, avoiding any impact to the vessel's operational schedule. These factors all combine to create a more economical solution as compared to proactive use of a traditional cleaning system.

Most positioning systems and methodologies in use across robotics are concerned with where the robot is in relation to the earth, and have varying degrees of tolerance for their accuracy. For a hull cleaning application, earth relative positioning doesn't really address the issue - what matters is where the robot is on the ship. Even tied at a pier, a ship can move slightly, and that movement could exceed the required accuracy to ensure complete coverage of the hull. The HSR is designed with a proprietary system to identify and maintain position relative to the hull (hullographic position). Armach Robotics sister company, Greensea Systems, has been developing this hull relative positioning technology for the past 4+ years in partnership with the US Navy's Office of Naval Research. Built on Greensea's industry leading OPENSEA open-architecture software platform for marine robotics, the hullographic positioning system utilizes a fiber optic gyroscope based Inertial Navigation System (INS), Doppler Velocity Logger (DVL), precision odometry and forward-looking multi-beam sonar to establish and maintain positional accuracy within 15 cm regardless of distance traveled. After launch, the HSR is flown into position near the hull, rolled 90° and attached to the hull, held into position by a low-pressure adhesion system (no magnets needed!). The HSR then builds a map of the hull with the sonar as it crawls along the vessel. The INS, DLV and track odometry work together, monitoring precise alignment and distance traveled to update the vehicle's position relative to the hull. Even the best INS-based systems will inherently develop an error over time, so a novel feature-based sonar navigation capability enables the system to reference its position against previously identified features on the hull to update the vehicle's position periodically, correcting for any accumulated error. The sonar also provides for obstacle detection and avoidance. With this positioning capability, cleaning patterns can be programmed within the control software, and the HSR can be turned loose to perform its work. Video, sonar and all positional information is logged during the evolution, providing a complete report on the pre and post cleaning condition of the hull.

The value of this pre and post cleaning report cannot be overstated. Foremost, it provides proof to the owner and operator that the complete hull was addressed, and that the service paid for was the service provided. Further, it provides a meaningful output that can be incorporated into existing and future performance monitoring systems, allowing for real world data regarding hull fouling to be included, enabling increased performance optimization. Owners and operators will have routine reports available that can be provided to regulatory agencies to meet invasive species/biosecurity control requirements, including providing proof of actual hull condition and entry into an active biofouling control program. Additionally, the reports can be provided to the maintenance teams to aid in drydock planning cycles.

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Joint Efforts among a Ship Builder, an AFC Maker, Maritime Research Institutes and an IWC Company for GHG Emission and Biofouling Reduction

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Abstract

In this paper, solutions, by collaboration with Korean Ministry of Oceans and Fisheries with its $24 million funding, its research institutes in engineering, bio-chemistry, policy, an IWC company, the Korean Registry, a shipbuilder, an antifouling coating maker, are introduced. Where the solutions are now and will be in a few years.

1. Introduction

Changing landscape of In Water Cleaning (IWC) is being accelerated due to IMO's convention on ships greenhouse gas emission reduction and global effort to prevent spread of oceanic invasive species via ships. As one of the best operational methods to reduce greenhouse gas emission from ships, IWC demand will increase drastically and despite The GloFouling Partnership Project becoming convention seems many years away, the guideline is expected to be approved by Marine Environment Protection Committee (MEPC) in 2023. More and more countries are adopting their own IWC approval regulations, including IWC equipment's biofouling capture rate and degree of water treatment. There are 497 companies certified with Lloyd's In-Water-Survey (Aug. 2022), majority proving IWC, and only a handful of companies are capable of biofouling capture and water treatment. Demand is increasing but the supply is being disrupted.

As IWC demand grows and more countries are adopting anti-invasive species via ship, there have been more development in underwater inspection, cleaning, fouling prediction etc. It is no longer about only being environmental with extra cost. It is natural to ask, how efficient an IWC is?, can the IWC's performance statistically be proven?, how fast it cleans?, of course all being environmental. Plus, there are artificial intelligence inspection, full autonomous ROV control and so on, that regulators like and help the industries.

As IWC demands grows there will be more need for:

- Biofouling pre-risk assessment, hull performance monitoring, IWC performance evaluation
- IWC in flexible situations, short stay, anywhere, capacity
- Environmental at competitive pricing

What our group has now for the needs are:

- Fouling risk alarming system, hull performance monitoring, IWC evaluations tools
- LOA 350 full hull cleaning in 8 hours, and IWC in all anchorage up to 3 kn current
- 99% treatment of bio, non-bio and metal particle above 10 μm

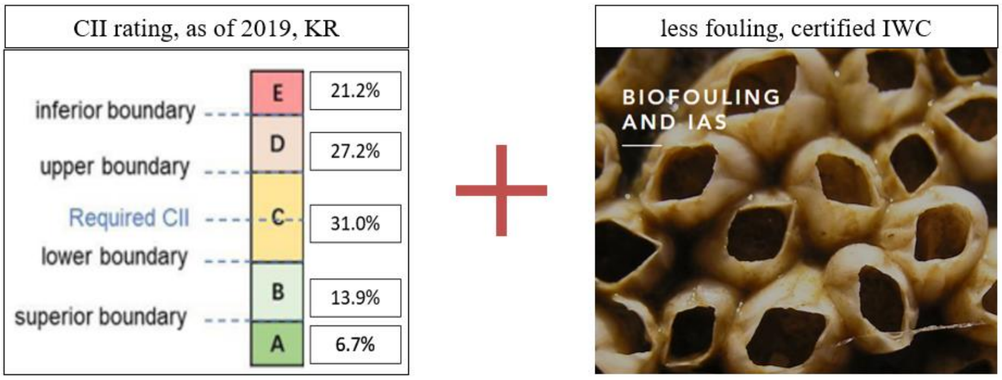
In a few years, our group will have followings:

- Full autonomous ROV cleaning, autonomous AI inspection
- Statistical results of IWC quality
- LOA 350m full hull cleaning in 4 hours,
- 99% water treatment of melted metal
- …

2. New Needs from shipping

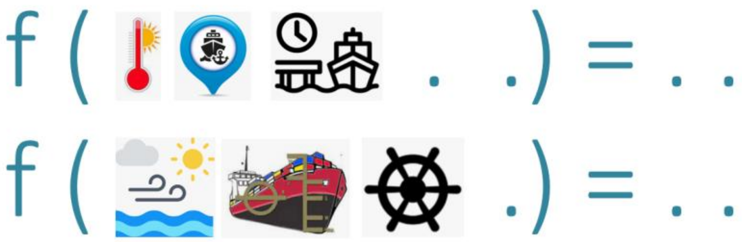
2.1. IWC demand

As of 2019, 48.4% of all ships are Carbon Intensity Indicator (CII) D and E (Korean Registry), the revised GloFouling guideline will pass MEPC in 2023, not mandatory but many more countries are adopting regulations for IWC. IWC being best operational method to reduce fuel and greenhouse gas, the demand will drastically rise. Despite the increase in demand for IWC, more and more countries are limiting ways of IWC, that if conventional divers do not adopt new technology, there will be IWC supply disruption.



2.2. New Needs

To reduce greenhouse gas emission, pre-biofouling risk assessment become important. By experience we know rate of biofouling growth has a certain correlation with temperature, locations etc. Also hull performance monitoring became more important but there are too many variables to accurate performance measurement. Lastly, all IWC quality is different, IWC with a solid statistical quality is needed. Because resources are scattered, it might be a difficult task with own resources.

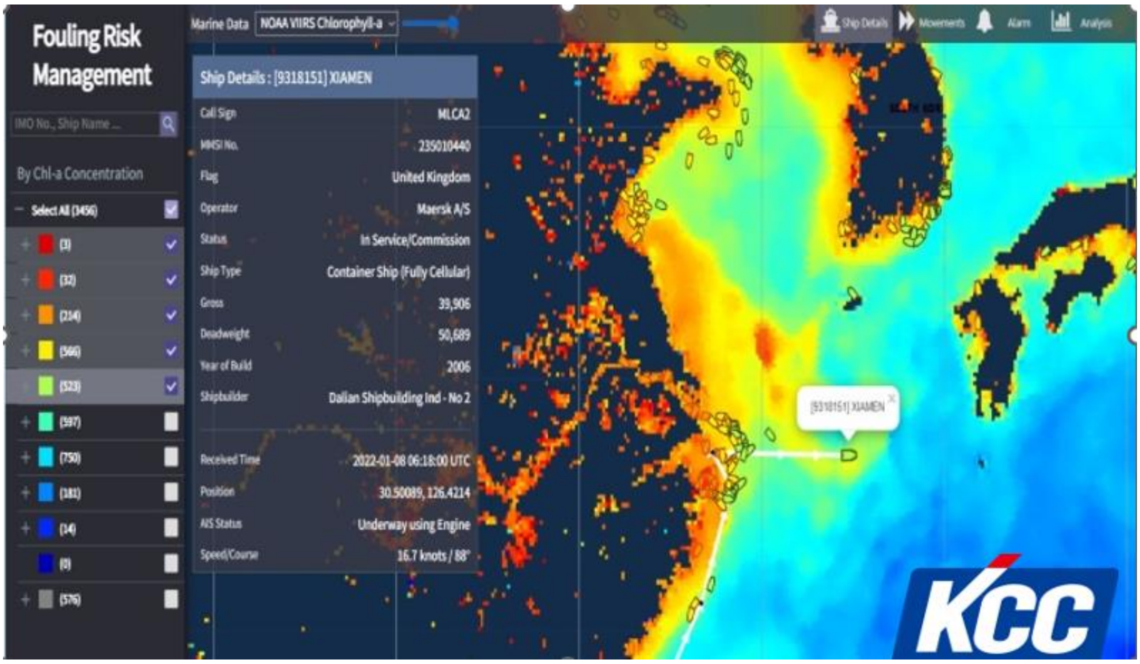


More IWC means in more different situations, or difficult situations. In average container ships stay 14 hours in Korean Ports, but with the bunkering schedule of 6 hours, the actual hull cleaning time may be 8 hours only. For most tankers, anchorage seems best or only options and there is fast current. Bulk carriers, loading/unloading areas are anchorage like. In short, shipping will need cleaning which is fast and at the same time more cleaning location options. For example, IWC in Singapore anchorage while bunkering, Atlantic anchorage of Panama regardless of current speed.

3. Current Performance

3.1. A.I. Fouling risk alarming system

Rather shipping companies have own smart shipping monitoring or not, pre-biofouling alarming system is necessary, because for a shipping performance evaluation, it needs certain time to compare hull efficiency. The quality of hull inspection using a small ROV is becoming close to or equal to divers, so does the cost of general hull inspection is dropping to free or hundreds of dollars.

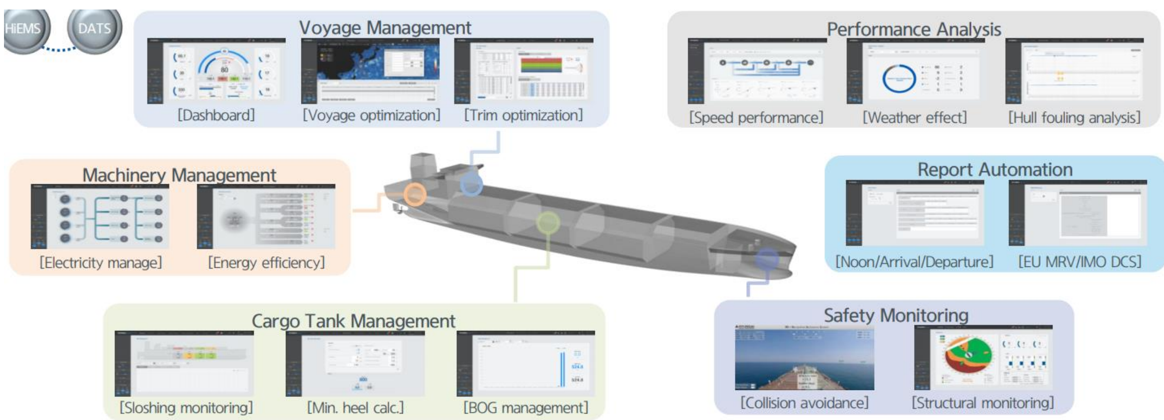


Source: KCC Marine Coatings

3.2. Smart shipping

Ships are getting smarter, with remote voyage management, performance analysis, machinery management, cargo tank management, report automation etc. According to Hyundai Global Service, 250 ships were delivered and 500 ships contracted.

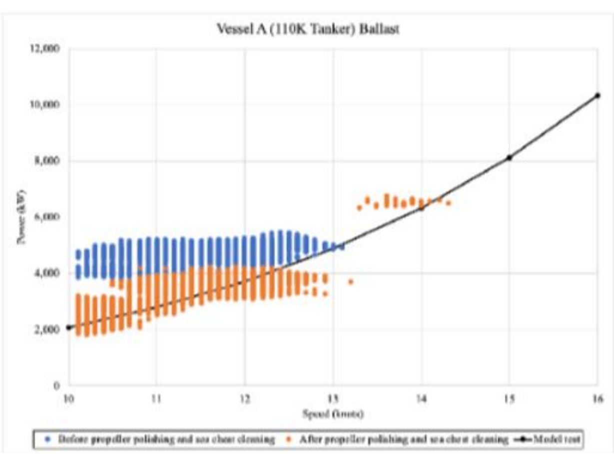

Source: Hyundai Global Service

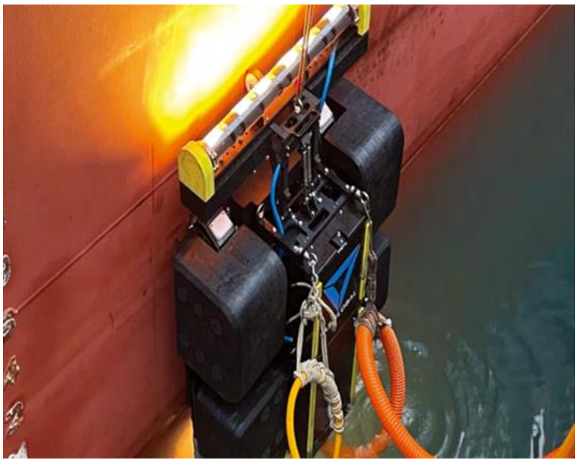


Source: Hyundai Global Service

3.3. IWC performance evaluations

Every IWC results vary. Currently, ISO 19030 based hull and propeller performance results after IWC are being accumulated to generate cleaning performance' certifiable with arithmetic mean, hoping as close result as after drydocking performance improvement.





Source: left: Beom Jin Park (KRISO), right: Tas Global

3.4. IWC Cleaning speed

Full hull cleaning of LOA 336 m ship in 8 hours is provided in Busan New Port on 2nd of July 2022. For full hull cleaning for LOA 366 m containership in 10 hours on 18th of July 2022,

Vessel Name	MAERSK ALFIRK (LOA 337M)
Cleaning scope	Vertical, Bottom hull & Niche area
Constraint	workable hours only 9 hrs. short stay(15hrs), Bunkering/crane interference (6hrs), heavy fouling
Working hours	8 hours (July 2nd 2022)
Input Asset	5 inhouse divers, 4 Robots, 10 robot operator

Vessel Name	Hapag-Lloyd, LEVERKUSEN EXPRESS (LOA 366M)
Cleaning scope	Vertical, Bottom hull
Constraint	following day, one vertical hull cleaning(LOA 255M) & one full hull cleaning (LOA 330M), light fouling
Working hours	10 hours (July 18th 2022)
Input Asset	4 inhouse divers, 4 Robots, 10 robot operator

3.4. IWC Cleaning speed & against current

In anchorage west coast of Korea, the current speed can reach 3.6 knots. Only ROV IWC is possible in the area. On 1st of June 2022, LOA 336 m, 152k GT ship's vertical hull cleaning was finished in 8 hours, LOA 333 m, 161k GT ship's vertical was cleaning in 4.5 hours when the current was at spring tide and reaching 2.6 knots.

Vessel Name	C. CREATOR (LOA 336, 156,452 GT)	VL PRIME (LOA 333M, 161,770 GT)
Cleaning scope	Vertical hull cleaning	Vertical hull cleaning
Constraint	cleaning two ships in a roll in spring tide and when current speed reaches 2.5 knots, light fouling	
Working hours	8 hours (1st June 2022)	4.5 hours (2st June 2022)
Input Asset	4 Robots, 10 robot operator	

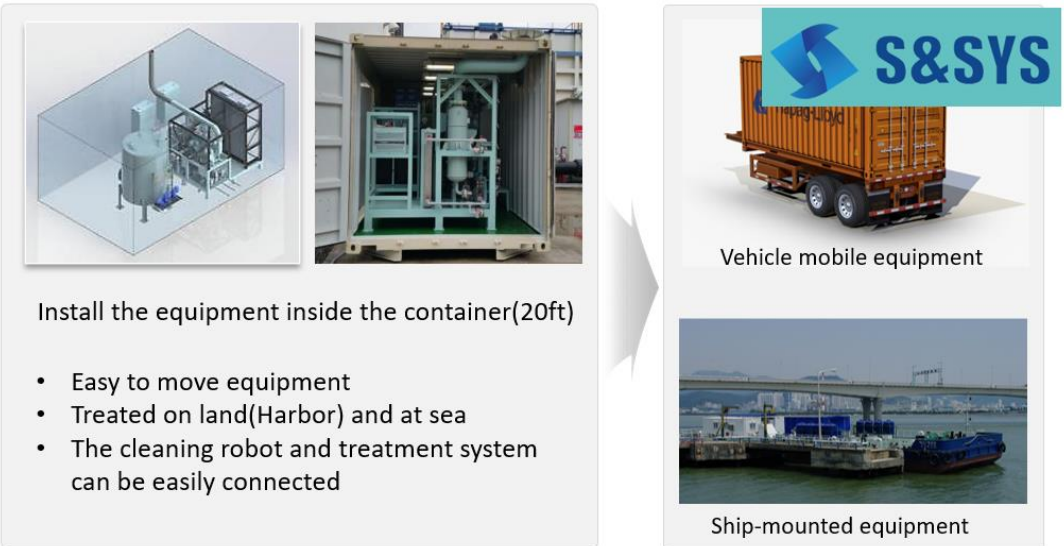
3.5. Capture and water treatment

Being environmental is necessary, it is no longer the key point of IWC, because capturing alone and water treatment alone is an easy task. Rarity is IWC robot’s locomotion efficiency with the capturing and water treatment.

4. In a few years

4.1. Water treatment

Ballast water treatment system makers will start selling water treatment system for IWC, in 2~3 years. The system will be all fit to any requirements plus melted metal too.



Source : S&Sys

4.2. ROV Advancement

In a few years, full hull cleaning of LOA 350m will take only 4 hours with 4robots, 8 hours with 2 robots. The speed of hull cleaning is getting faster 20~30% every year for technology improvement. In 3 years, full autonomous IWC, autonomous AI inspection, accurate in water positioning system, real time fully integrated IWC and water treatment system will be available.

Taking Biofouling Not Seriously Today Will Have Serious Effects Later

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Abstract

Shipping is heading for a biofouling Catch 22: Oversimplification of the challenge on one side lead the industry to make solutions to the problem that does not work. The stakeholder with the biofouling risk (read: the port), will then have all incentives to support a «clean before you arrive» attitude, because they do not want solutions that do not work in their port, because that results in pollution. Local regulations demanding vessels to be clean before they arrive puts a high pressure on vessels to be clean. We, as an industry, need to do something about this. Otherwise we will stumble ahead and in 2027 sit there with a much bigger environmental problem than today and wish we could go back to 2022 and make it all right to start with.

1. Introduction

Biofouling has been a challenge for the shipping industry since its inception and managing biofouling has been an important aspect of efficient operations. In modern times the primary tool for biofouling management has been application of antifouling coatings infused with various toxic substances to prevent or limit the biofouling. At the time TBT was prevalent in the industry as a low cost and efficient means to manufacture efficient antifouling coatings. Following increased knowledge on the negative environmental effects, the IMO banned the use of TBT in antifouling coatings in 2008. Other substances commonly used in current antifouling coatings are under regulatory scrutiny and a further regulatory tightening is expected in order to preserve our oceans.

As there are no antifouling coatings with 100% efficiency, ship owners have always been using in-water hull cleaning (IWHC) as a supplement the biofouling management toolbox. The IWHC cleaning industry has always been, and for most parts still is, an unlicensed and unregulated activity in relation to environmental effects with no oversight or control of emissions to sea, Fig.1.

Fig.1: Traditional dust cloud from IWHC without capture

2. Challenges

Traditionally the IWHC has been performed without capture, as illustrated in Fig.1 – an open loop method, where all debris is released directly to ambient waters. This practice has three sources of pollution from the IWHC removal process:

1. Organic matter (from biofouling),
2. Toxins (from coating),
3. Microplastics (from coating and, if used, plastic brushes).

The vision of some policymakers to ban open-loop IWHC and diligent follow up of the enforcing entities in the early 2000s created an environment for innovation by creating, in effect, a market for sustainable closed-loop IWHC solutions. This has had the positive effect of spurring many IWHC operators to invest in and commercialize such solutions, as well as enabling several ship owners to adopt more sustainable biofouling management policies.

For the shipping industry as a whole the transition to sustainable practices through adoption of sound closed-loop IWHC practices currently face two main challenges:

1. Race to the bottom
   A lack of quality data and peer reviewed research creates a knowledge gap and subsequently many ports still have not adopted any regulations on IWHC operators. Equally many ship owners are not able to differentiate the environmental merits of the various vendors and therefore have limited tools available in the selection of vendors. This also creates an opportunity for IWHC operators to offer sub-par services to ship owners under the claim of being high standard.

2. Solution to pollution is dilution
   Several operators of traditional open-loop IWHC solutions have since ban in open-loop IWHC been proposing cleaning concepts such as grooming, high-frequency cleaning, proactive cleaning etc. as a workaround to the pollution regulation. The underlying idea all these concepts share is that by an open-loop IWHC for a vessel with a higher cleaning frequently will have less emissions to sea for each clean, when comparing to an open-loop IWHC for a vessel on a "standard" cleaning frequency. An appealing proposal at first glance, this logic fails to factor in total emissions to sea per vessel. Furthermore, the proposals of such technologies are not substantiated or documented by data or research documenting effects from real operating conditions.

At present these challenges are the main obstacles for further innovation and adoption of environmentally sound closed-loop IWHC technologies and, ultimately, a furthering of the safeguarding of our oceans.

3. The way forward

To overcome this challenge, the most pressing issue is to close the current knowledge gap and to share this between the stakeholders. The starting point for this is for IWHC providers to collaborate with researchers, regulators, and ship owners to generate robust data on environmental effects and to publish peer reviewed research.

ECOsubsea has been and will always be collaborating with reputable partners to advance the protection and safeguarding of our oceans. Therefore, ECOsubsea is calling out to all stakeholders who would be interested in contributing to the advancement of closed-loop IWHC in a joint effort to close the existing knowledge gap and ultimately to advance the environmental credentials of the shipping industry.

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To Clean or Not to Clean

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Abstract

Improving fuel performance through avoiding or removing biofouling is a low hanging fruit for most vessels. This paper describes an approach for prediction of biofouling growth based on simple and readily available parameters regarding operational patterns. The algorithm developed utilises the ship's exposure time and the sea surface water temperature in the areas of trading as basis for predicting the biofouling growth of three different fouling stages: slime, soft fouling and hard fouling. Based on the vessel's trading data the model indicates when a ship is a candidate for hull cleaning. It can also be used to forecast cleaning demands when the vessel's future trading pattern is known. The model projections were tested using data provided by a ship operator on the fuel performance and cleaning history of several vessels.

1. Introduction

As described by *IMO (2011)*, marine biofouling is the accumulation of aquatic organisms such as micro-organisms, plants, and animals on immersed surfaces in the aquatic environment. Marine biofouling growth on a surface happens in stages and depends on a variety of parameters, *Arndt et al. (2021), Nurioglu et al. (2015), Uzun et al. (2019*). According to the Woods Hole Oceanographic Institute (*1952*), the growth of marine biofouling as a function of several parameters for a given surface and with unlimited experimental data can be described as follows:

$$\text{Biofouling} = f(SST, psu, pH, \nu, I, S, t, m_t, \sigma, \theta_c, R_t, \eta_c)$$

with SST as the sea surface temperature, psu the parameter for salinity, pH as acidity, υ describes the speed of the water flow, I is the light intensity, S is for the concentration of nutrients, t for the time of exposure to water, m_t is the microtexture, σ gives the surface potential, θ_c as the contact angle of surface (degree), R_t is the surface roughness and η_c is the antifouling coating performance parameter, i.e. the effectiveness of the antifouling coating, including the performance of the chemical content and the leaching rate.

However, not all parameters will have similar impact on the biofouling growth and some parameters such as sea surface temperature, salinity and exposure time play a more decisive role than others, *Arndt et al. (2021), Uzun et al. (2019*).

Fossil fuel may not be cheap any time soon and the fuels on the decarbonisation agenda may be priced at a level projected to be corresponding to +1.500 USD/ton. So, the measures to reduce fuel consumption on ships will play increasingly important roles to reduce costs and increase energy efficiency ratings. A range of studies have concluded that the accumulation of fouling has a highly negative impact on vessel performance, depending on the severity of the fouling and it will increase the fuel cost of the ship by 10-35%, *Demirel et al. (2017), Monty et al. (2016), Munk et al. (2009), Schulz and Swain (2000), Schulz (2007)*.

Antifouling coatings and reactive biofouling management already play an important role in reducing the negative effects of biofouling on ship performance. More focus on proactive measures may allow vessel owners or operators to avoid performance affecting accumulation of biofouling organisms on the hull, *Georgiades et al. (2018)*. *Oliveira (2020)* showed that continuous and frequent cleaning of the early stages of biofouling has little negative effect on the coatings tested. Compared to reactive cleaning, which may involve measures against advanced fouling stages, e.g. hard fouling, proactive cleaning is preferable because early biofouling stages, e.g. slime and soft fouling, can be removed with little force. The individual vessel performance tools used onboard today may include reactive statements regarding the effects of biofouling growth based on an increase in fuel consumption, but fuel performance data are not readily available to third parties, and it is the objective of the work reported here to develop an indicative tool based only on readily available data for vessels. In the tool, a set of parameters monitor a vessel's biofouling level based on historical geoposition data to assist users in the decision-making process when to clean or not to clean.

2. The model

The aim of this model is to predict hull biofouling independently of fuel consumption data, and it is based on readily available data and shipping sailing patterns.

2.1. Dominant parameters

Uzun (2019) showed that it is possible to simplify biofouling growth modelling by neglecting less contributing parameters. In his time-dependent biofouling model the biofouling growth is based on the most dominant factors; the time of exposure (t) and the coating performance parameter (ηc). The performance of antifouling coatings varies depending on the geographical region. Here, the most important parameter is the sea surface temperature (SST).

Based on these findings we developed an algorithm that can estimate biofouling growth for three different biofouling stages: slime, soft fouling, and hard fouling. Since hard fouling on the hull will give a greater fuel penalty and involves more time-consuming and abrasive cleaning techniques, we have chosen to aim the model at a proactive biofouling management approach, which will recommend cleaning the hull before hard fouling becomes established on the hull. With that thought in mind we focus on the first two stages of biofouling in the model to make the recommendations.

We used *Uzun's* (*2019*) Eq.(1) which results from field tests with Self-Polishing Copolymer coating over three years to calculate fouling rating. Rankings antifouling coatings according to efficacy are not included in the presented model. The equation is a Gaussian function describing a symmetric bell-shape curve and only the half-curve bell was used to describe the saturation phase at the maximum point. To accommodate the limited growth capacity, the fit is fixed at the maximum point.

$$FR(t) = \mathrm{a} * \mathrm{e}\left[-\left(\frac{t-t_0}{\tau}\right)^2\right] \qquad (1)$$

with FR as rated biofouling growth, a: maximum rating (slime = 20, soft = 50, hard fouling = 100), t: sum of exposure time, t_0: time that rating reaches to the maximum point and τ: half-width of the bell curve. t_0 and τ are used as antifouling coating performance parameter (ηc) because they describe the growth curve with delay time and maximum point.

Table I: Antifouling coating performance parameter t_0 and τ for slime and soft fouling adopted from *Uzun et al. (2019)* page 191 Table 2

Type of fouling	Location	T_E [°C]/ T_M[°C]	t_0 (Time that rating reaches to the maximum point)	τ (half-width of bell curve)
Slime	Equatorial	30	87	37.08
	Mediterranean	20	271.9	99.31
Soft fouling	Equatorial	30	271.4	73.11
	Mediterranean	20	385.5	124.4

Uzun's experiments took place at two different sea surface temperatures, 20°C (Mediterranean) and 30°C (Equatorial). For the biofouling states, slime and soft, and the two temperatures, the constant values of the curves, t_0 and τ, (representing the antifouling coating performance parameter) are listed in Table I. In order to calculate fouling ratings at different sea surface temperatures the antifouling coating performance parameters (t_0 and τ) were linearly interpolated or extrapolated according to *Uzun (2019)*. Values are no shown.

The specific growth rate μ(t) can be calculated from the partial derivation of equation 1 with respect to t. The rated biofouling growth for each exposure time is calculated by multiplying the specific growth rate with the exposure duration.

$$FR(t_i) = \mu(t) * t_i \quad (2)$$

With $FR(t_i)$: rated biofouling growth for individual exposure period, μ(t): specific growth rate and t_i: individual period duration.

When a hull has received a fresh antifouling coating, biofouling growth is inhibited for a certain period of time, a lag phase. During the lag phase the individual growth rate μ(t) is low. Since the information about the last IWC or dry-docking of the vessel is not readily accessible using a specific growth rate based on Uzun et al (2019) was not possible and we use the maximum growth rate to predict biofouling, Comparing results using specific μ(t) and the maximum (μ_{max}) showed that after the lag phase where μ(t) is small both curves follow the same trend and consequently the use of μ_{max} provides a conservative approximation for our model.

The estimated total biofouling growth for the investigated period, FR_{tot}, is the sum of individual biofouling ratings. The model can be adjusted to provide more refined estimates when additional information like IWC events or coating properties are available.

2.2. Sea surface temperature

The monthly sea surface temperature with a resolution of 0.25°C was harvested from NASA. The model will look up the associated temperature of the location at the start of the individual exposure times. In case there is no sea surface temperature data for the requested period, the data from the same month of the last year will be used. The files with the temperature data are updated at appropriate intervals.

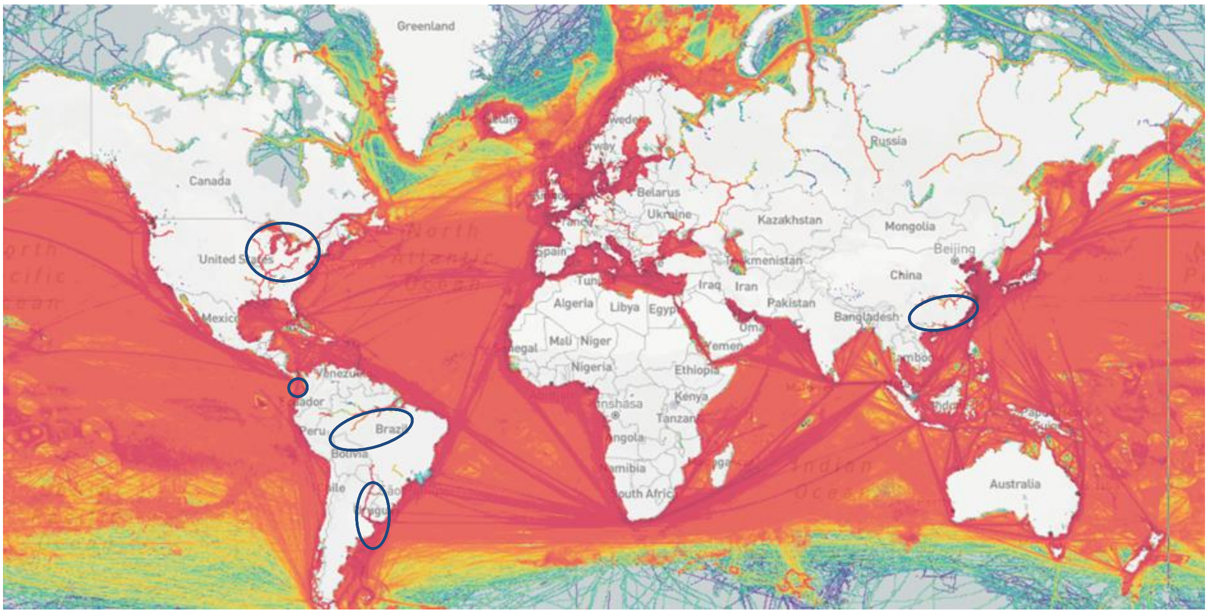


Fig.1: Freshwater systems relevant for international shipping, *MarineTraffic (2022)*

2.3. Fresh water areas

The biofouling growth is inhibited or fouling communities can be reduced when vessels stay or sail in freshwater areas. Studies have shown the exposure to freshwater can kill off marine biofouling organisms by osmotic shock, *Brock et al. (1999), Davidson et al. (2014), Moreira et al. (2014)*. The model will assess if the vessel has sailed in a freshwater region that is relevant for shipping and will account for that. The regions included in our model are marked with blue circles in Fig.1.

2.4. Frequency of exposure

The duration of the exposure time can have a greater impact on the growth of the biofouling, especially in combination with stays in regions with high sea surface temperatures. Therefore, we also analyse the frequency and duration of exposure periods and apply the information if a vessel meets one of our criteria. Fig.2 shows a frequency chart over two years shows the number of individual exposure events in question in the respective duration bins.

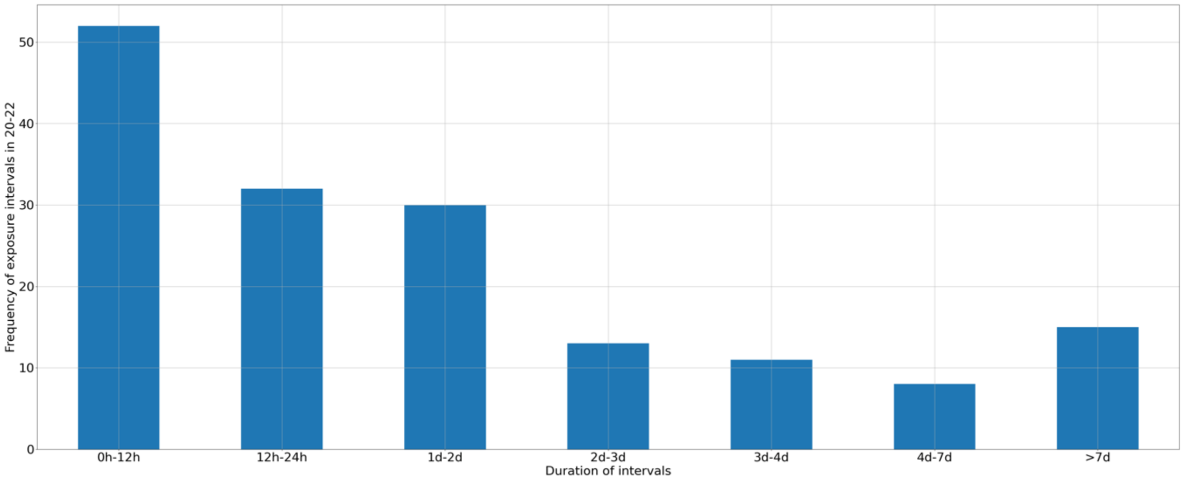


Fig.1: Frequency diagram of the cumulated exposure times, subdivided according to the respective duration of the intervals for a period of 2 years

3. Testing the model

To test our model, we used real ship performance data kindly supplied by from Navigator Gas. The datasets of four vessels included performance data logged every 15 minutes for the last two to five years. We also obtained a list of in-water cleaning and polishing events carried out on two ships, as well as dry dockings and when the hull received a new coating.

The vessel performance data was analysed in regard to the fuel consumption over time and fouling rating. For the fuel analysis we have only used main engine data where the ship is underway. Fuel consumption depends on a variety of factors, such as speed, load, wind, currents, hull roughness, etc., (*Bialystocki (2016)*. We decided to focus exclusively on the fuel/speed ratio as a simple monitoring of the fuel consumption. The timing of the cleaning events is usually not exclusively due to increased fuel consumption, but also e.g. long layovers, change of charter or calls in countries with specific regulations regarding biofouling can be additional reasons to have the hull cleaned.

We analysed fuel data for the ships and plotted trendlines. Fig.2 (a) presents an example of one of the fuel consumption diagrams we compiled. This shows the fuel consumption for one of the ships examined for a period of about 2.5 years. The individual fuel/speed data points and a five-day moving average trend line have been plotted. In some cases, a correlation was found between fuel consumption and the timing of cleaning, while in others it was somewhat less conclusive, which might be explainable by several reasons e.g. changing of sailing patterns, laden or unladen, weather etc.

The total rated biofouling growth was modelled for slime and soft fouling. Fig.2 (b) shows an example of the rated biofouling growth for the same vessel as the fuel consumption plot over the same time span. We choose to illustrate the rated biofouling continuously since this represents the situation when no cleaning event data is available. We compared the rated biofouling results with the results of the fuel consumption analysis. In ~50% of cases we observed the expected upward trend in fuel consumption after we predict a significant increase in biofouling (bearing in mind that fuel consumption is heavily influenced by load and conditions related to weather and currents not included in the simple model).

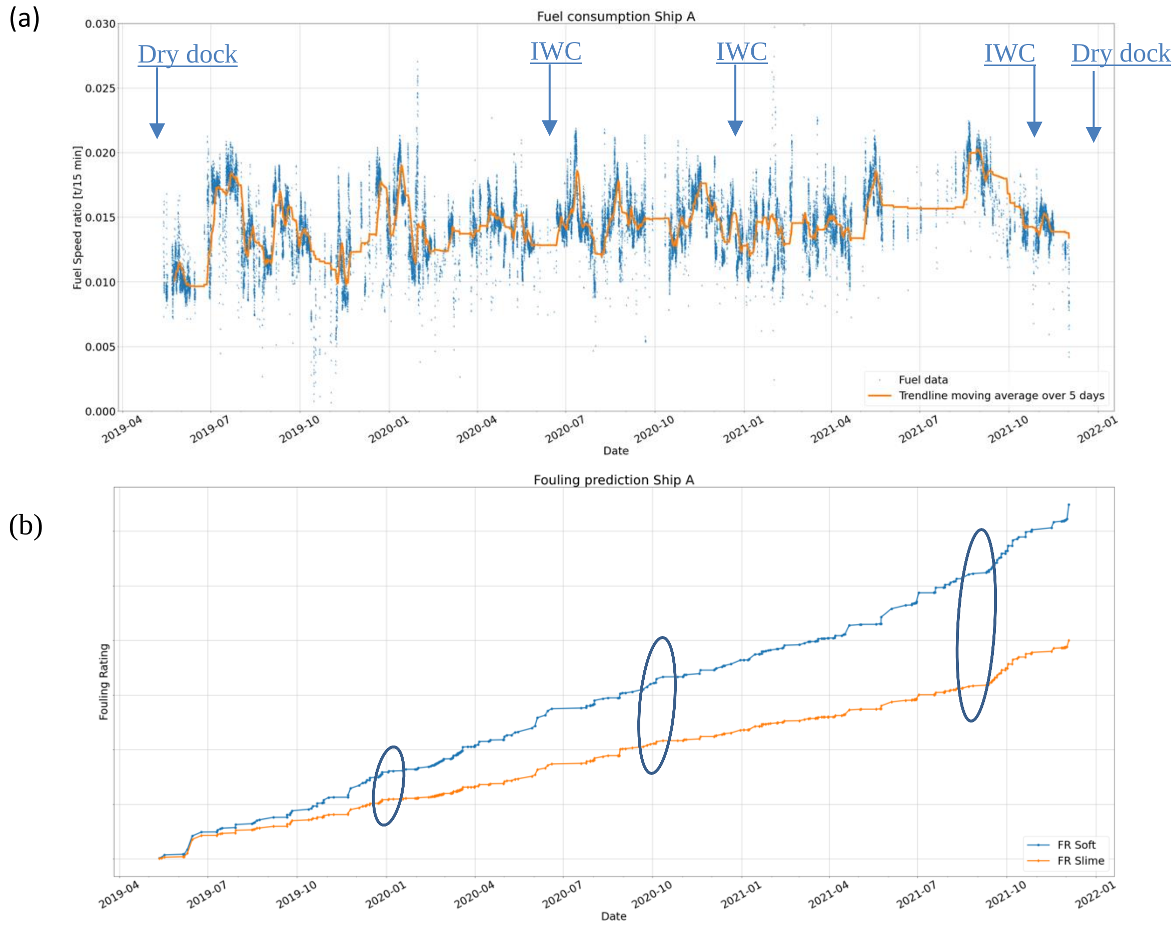


Fig.2: (a) Vessel fuel consumption data in 2020 five-day moving average trendline is shown in orange. (b) FR_{tot} for the same period based on the same real-world vessel data. Soft fouling is shown as blue line and slime as orange line.

In the presented example we marked the areas with circles where the modelling suggests considering a hull cleaning. The first circle correlates well with the seen increase fuel consumption in Fig.2 (a). We know that in January 2020 the ship underwent a propeller cleaning and first half a year later the hull was cleaned. For the second and third circles, we see that the detected significant increase in fouling is closely related to the time at which the vessel was subjected to an underwater hull cleaning.

4. Web-based application

4.1. Workflow of the model

The model analyses AIS data going back one year and can already make a recommendation on this basis alone. However, a number of events have a decisive impact on the onset and continuity of the growth of biofouling. This includes dry docking, in-water cleaning events and voyages in freshwater in this model. Therefore, if this information is available, it can be entered and is then reflected in the result.

While cleaning events are directly inserted as date input, when available, the freshwater voyages are identified through the vessel's geoposition.

The simplified flow chart in Fig.3 gives an overview how the model is designed. The query is started by entering the IMO number of the vessel. The corresponding AIS data is retrieved and processed in the model. With the algorithm we look if the vessel in question has been sailing in the defined freshwater areas und take the outcome into account. In addition, the sailing patterns are processed to determine the exposure times. Together with the associated sea surface temperature, μ_{max} and the possible input of cleaning events and dry dock the biofouling growth on the hull is estimated and summed up for the investigated period. The result is then used to check whether the criteria for a cleaning recommendation are met or whether the hull is still in good condition in terms of biofouling. In addition, the vessel may be flagged if it is considered critical in terms of duration of exposure, frequency or sea surface temperature. This indicative information can be used, for example, as a pointer to initiate a more targeted investigation in connection with increased fuel consumption.

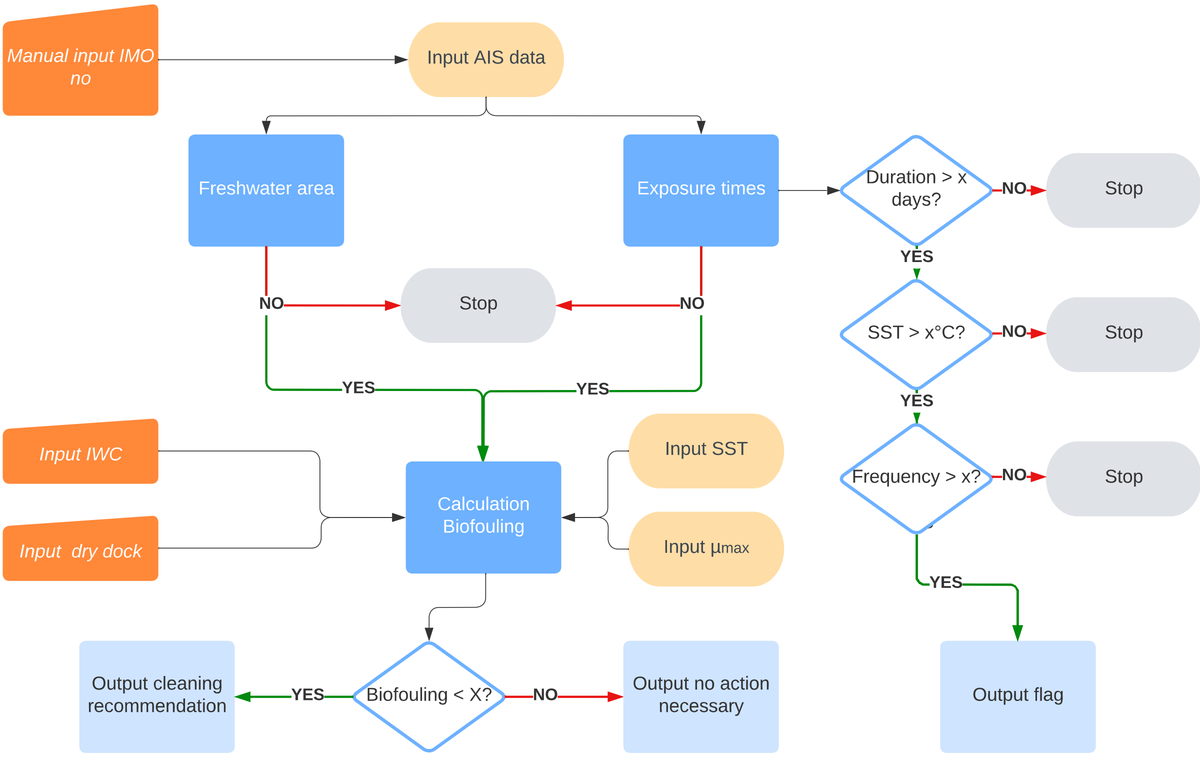
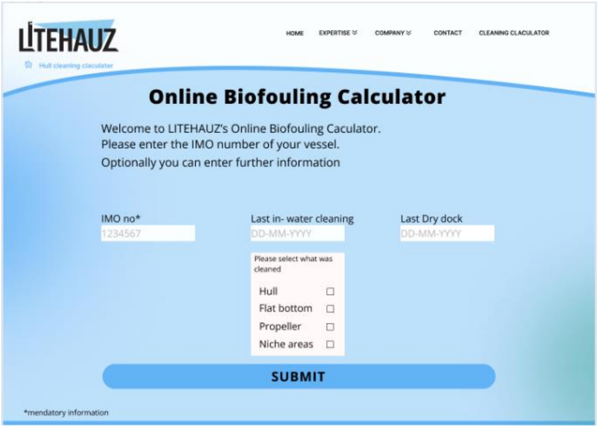


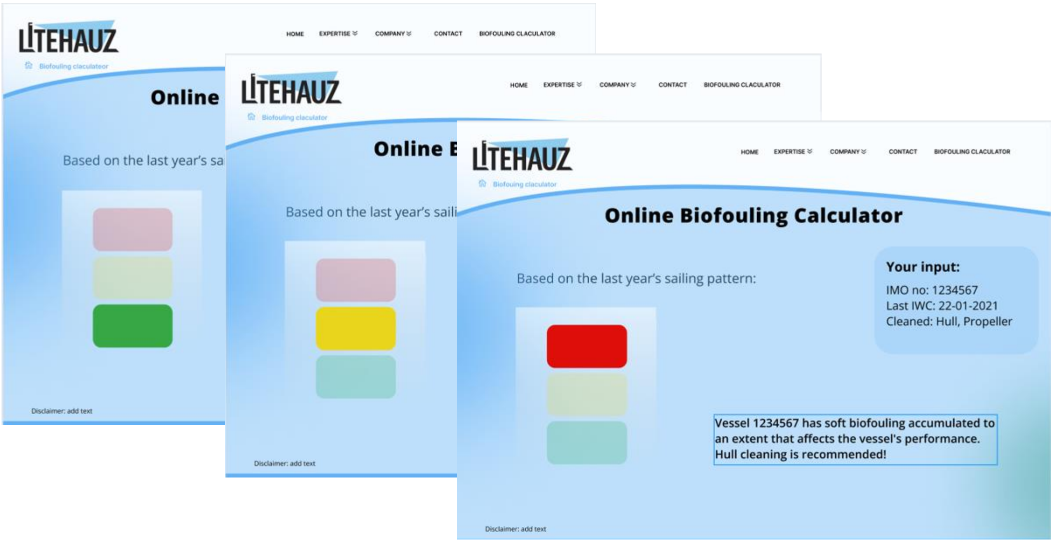
Fig.3: Flow chart of fouling prediction model

The model is used in a web-based application as an online fouling calculator. It is hosted on the LITEHAUZ homepage, in a restricted area where users must log in to view the content. As displayed in Fig.4 (a) there is an input page where the IMO number of the ship has to be entered. With this information alone it is possible to start the request. However, the user will have the options to insert information of the last in-water cleaning or dry-docking in addition to what was cleaned. This information will be processed by the software to refine the output of the request.

The results of the requested vessel will be presented as displayed in Fig.4 (b). The output of the result is designed in a simple and easy to understand style. We have provided a kind of traffic light system that shows a green, yellow, or red light depending on the result. A short explanation or recommendation will appear for each colour. In addition, a separate marking will appear if a ship falls into one of the categories described, e.g. in the case of a long exposure period. This information can be used to help decide on an appropriate maintenance schedule.



Input page (a)



Output page (b)

Fig.4: Web-based fouling calculator

The software predicts biofouling growth on individual vessels and has a number of possible applications. It can be used by shipping companies or hull cleaning companies to plan in-water hull cleanings. In particular, if vessels have a consistent shipping pattern, it could be used as a forecast tool. The model can provide more refined results when more detailed information about the hull coatings and the last cleaning of the hull is available.

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The View on Biofouling Management from a Cleaning Company

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Abstract

This paper addresses how to deal with some of the many factors involved in creating and maintaining a Biofouling Management Plan (BMP), in particular those that are related to underwater hull inspection and cleaning. The paper will touch briefly upon topics like what a BMP is, the work and strategy involved, and more in depth on hull inspections as a shortcut to improving your vessel performance and what to consider before conducting the hull cleaning. The paper will also address the impact of the rising needs for regulatory compliance, implications and penalties from non-compliance and the importance of accurate and clear reporting.

1. Introduction

1.1. What is a Biofouling Management Plan

Biofouling Management is the task of minimizing the biologic marine growth (biofouling) on a vessel's hull.

The task's importance has its origin in IMO's Guidelines for the control and management of vessels' biofouling to minimize the transfer of invasive aquatic species (Biofouling Guidelines), *International Maritime Organization, Resolution MEPC.207(62) (2011)* as well as more and more countries and ports implementing their own sets of regulations specifying requirements for entering their waters and ports. The purpose of guidelines and regulations is to protect the global and local port and ocean environments against biologic pollution and invasive aquatic species.

For Owners/operators/technical managers etc. Biofouling Management is an administrative prevention and maintenance task in collaboration with the further technical management team, external service suppliers, the Captain, and colleagues from the HQSE department. Relevant environment and port authorities also play an important role in this matter.

Further to this, it is important to add that Biofouling Management is also about keeping the hull as clean and frictionless as possible. This will considerably contribute to improving the vessel's performance and with reduced fuel consumption and carbon emissions added to it.

A Biofouling Management Plan is an important tool to have for each vessel and the plan with its corresponding record book comprise the framework for successful audits and compliance to the relevant authorities' regulations for documentation, reporting and proof.

A Biofouling Management Plan can consist of, but not be limited to:

- Vessel data
- Anti-fouling system
- Anti-fouling certificates
- Vessel operating profile
- Area description
- Anti-fouling operations and maintenance
- In-water cleaning and maintenance
- Safety
- Disposal of biologic waste
- Recording requirements
- Training

1.2. Why is biofouling Management Important?

Biofouling Management is important for a number of reasons, and these can differ depending on your role and job scope in the business. There can also be many reasons and intentions for implementing Biofouling Management, these include:

- Complying to global and local authorities' regulations on water pollution
- Strengthen your company's competitive edge in the environmental change
- Improve vessels' performance relating to fuel costs and emissions

IMO and local authorities have started forming and implementing regulations for protecting the global and local waters against water pollution and the spread of invasive aquatic species.

1.3. Stricter regulations and requirements for protection against biological pollution

Authorities are introducing stricter regulations and requirements for protection against biological pollution and the spread of unwanted invasive species in the global port and marine environments.

In this context, it is typically expected that you are the one who has an overview and insight into the vessel's documentation for compliance with environmental requirements and regulations from the relevant authorities - embodied in the vessel's so-called Biofouling Management plan.

1.4. Reduction in fuel costs

Biofouling Management has always been important in terms of vessel performance and fuel economy. Several studies indicate that biofouling on the vessel's hull increases water resistance to such an extent that fuel costs increase by up to 40%.

For this economic reason alone, it is important that the maritime industry's technical maintenance teams take an interest in Biofouling Management.

1.5. Green transition and reduction of CO2 emissions

The maritime industry is in full swing with the green transition in order to live up to the market's expectations for achieving the industry's target for reducing CO2 emissions. Some of the new regulations that are coming into force by January 2023 is CII-ratings and EEXI-certifications. Both are important measures that will help the global fleet move towards a cleaner future

The biofouling management plan will be a big part of being compliant with these regulations and it will have to be looked at more seriously in the industry.

2. Strategies

The choice of strategy should address and be decided on the following parameters: costs, the shelf life of the solution and the flexibility of the vessel's operating profile.

In broad terms, you can have 3 different anti-fouling strategies:

- A preventive strategy
- A responsive strategy
- A combination of a preventive and responsive strategy

2.1. Preventive strategy

The preventive strategy focuses more on the hull coating and sensor systems that exist in the market. The choice of a preventive strategy carries heavy acquisitions in advanced anti-fouling systems like paint/coating, surface treatment and hardware products physically installed on the hull.

For those choosing this strategy alone, a minimal need for ad hoc hull cleanings is often anticipated in the belief of the anti-fouling system(s) prevents biofouling more or less completely.

The advantages of this strategy as a standalone include less administration of the Biofouling Management Plan and lower maintenance costs for hull cleaning in the periods between planned dry dockings.

The potential downsides include high acquisition costs and less flexibility in relation to the vessel's operational profile in order to keep the anti-fouling solution's guarantee.

2.2. Responsive strategy

The responsive strategy does include acquisitions of preventive anti-fouling systems, but it is at the same time anticipated that hull and niche area cleanings will play a big role in the overall maintenance of the hull.

The advantages include lower acquisition costs on anti-fouling systems and more flexibility regarding changes to the vessel's operational profile.

The potential downsides include higher running costs for maintenance of the vessel hull and more administration of the Biofouling Management Plan's record book, but compared to the higher original costs, this could prove to be a better and more financially viable solution in the long run.

2.3. Combination Strategy

A third option is to choose a Biofouling Management strategy that prevents biofouling with the combination of a solid anti-fouling system (paint, coating, surface treatment and devices) and regular hull inspection with a plan for subsequent cleaning if necessary.

It is a strategic choice with approximately equal distribution of costs for prevention and control in order to avoid biological pollution.

With the choice, you and your colleagues acknowledge the risk of biofouling on the vessel's hull despite preventive measures.

At the same time, it is a strategic choice where regular inspection of the hull is assigned a high value in relation to planning the right cleaning activities, so that the vessel performs optimally and complies to industry and authority requirements.

The advantage of this choice is flexibility in relation to changes to the vessel's operational profile as well as ongoing documentation of the condition of the hull in relation to the life of the anti-fouling solution and the need for cleaning.

The disadvantages may be more administration and updating of the Biofouling Management plan's Record book.

3. Changes to the Biofouling Management Plan

The operating profile of your vessel(s) may change in relation to fleet capacity and market conditions.

The changes in the operational profile can also influence the risk profile for biofouling.

For example, the changes may result in the vessel having to operate in new, warmer waters with a lower sailing speed and more periods when the vessel is stationary.

These changes can expose the vessel to more biological growth than the vessel's preventive anti-fouling system is designed for.

As part of the vessel’s maintenance team, you should revisit the Biofouling Management plan and update the vessel's operating profile if the vessel is about to change long-term speed or sailing and freight route.

When you update the vessel's operating profile for short-term changes in the vessel's operating profile, you must be aware that you also specify and describe the relation between the vessel in motion and periods when the vessel is stationary (at anchor or in Port terminal) in the plan's Record Book.

At the same time, you must update information on the planned duration between dry docks.

4. Getting Started with Biofouling Management

More and more technical maintenance teams are tasked with introducing plans for anti-fouling systems and for maintenance and cleaning of the vessel's hull and niche areas.

As mentioned in the introduction to Biofouling Management, the Biofouling Management plan is a central tool.

The plan must be drawn up for each vessel, which you are responsible for.

4.1. Preparation of Biofouling Management plan

The following must initially be described in the plan:

- Master data and operating profile for the Vessel
- Information on applied anti-fouling system and certificates
- Information about the systems, hull and niche areas exposed to biofouling risk
    - External Hull surfaces
    - Hull appendages and fittings
    - Steering and propulsion
    - Seawater intakes and internal seawater cooling systems
- Plan and management actions for anti-fouling operations & maintenance

In addition, organizational procedures and employee training must be described and incorporated in relation to:

- In-water cleaning & maintenance between dry-dockings
- Safety policies according to recommendations provided by your anti-fouling suppliers
- Sustainable disposal of biological waste

4.2. Continuous updating of the Biofouling Management Record Book

Finally, you should prepare a system for activity journaling (Record Book) in relation to ongoing detailed recording of:

- Data from in-water inspections of systems, hull and niche areas

- Completed maintenance and cleaning actions on systems, hull and niche areas

The vessel's activity log must also be prepared for continuous updating on:

- Periods of time when the vessel was laid up/inactive for an extended period of time
- Periods of time when the vessel was operating outside its normal operating profile

Then you are well on your way to professional Biofouling Management

5. Roles

To be able to maintain a biofouling management plan, then there are 4 important stakeholders that all needs to work together to be able to operate the vessel in the optimal environmental way.

5.1. Owners/Operators

Their role is to have a detailed BMP for each of their vessels and make sure that technical managers follow it.

It is important to have a good understanding on how does the vessel design, anti fouling coating, trade routes and maintenance strategy all work together to be able to achieve the optimal performance and environmental protection.

5.2. Ports & Local government

Their role is to set out the local rules for how maintenance can be done and what are the vessel owner or service provider allowed to do in their area.

It is important to have a clear picture of what is needed to protect the environment and what can service providers do to help them and the vessels owners/operators.

5.3. Service Providers

Their role is to provide a service that is as safe as possible and as environmentally friendly as possible. It is also their role to clearly communicate to the other stakeholders on what is technically and financially possible to do to protect the environment.

5.4. Anti-Fouling system providers

Their role is to provide the best possible prevention system for their customers. It is also to understand the impact their systems have on the environment and what to do with the system if it is not operated in the right conditions.

To be able to have proper biofouling management plans in place, it is important that all 4 stakeholders have good communication between them. it there is no understanding and corporation, then it is not possible to do what is best for the environment and the global trade.

6. A Closer Look At In-water Cleaning & Maintenance

6.1. Inspections – A visual shortcut to better vessel performance and informed maintenance decisions

Securing great vessel performance is a crucial task to most owners and operators. The objectives to the task are mainly to:

- Optimize costly fuel consumption
- Minimize costly and climate-threatening carbon emissions
- Achieve more precise route planning to optimize time spend sailing.

6.2. The biofouling impact is hard to detect before it's too late

Many factors impact your vessel performance, and everything from engine performance to software measurements and performance can play a big role. But at the end of the day, if you do not look at all your factors with a clean slate, you won't be able to assess things diligently.

Therefore, regular hull inspections are a visual shortcut to proactive decision-making in order to safeguard great vessel performance.

Making informed decision is critical to any business decision, and it is no different to having a good biofouling management plan. Making good decisions to increase your vessel performance is of paramount importance.

Underwater hull inspections are very likely the most easy and efficient method of providing trustworthy visual data about biofouling and the condition of the hull.

Typically, the visual data is presented as subsea images or videos of the hull. The data show the coverage and types of biofouling throughout the hull.

6.3. When and why to conduct a hull inspection

There are not exact measurements to help technical teams decide when to perform a hull inspection. It can depend on a combination of the operating profile of the vessel:

- Type and condition of the anti-fouling system such as anti-fouling coating
- Age and type of the vessel
- Historic travel routes of the vessel

In general, it is important to inspect your vessel if you suspect biofouling of any sort, as this will most likely affect your vessel performance data significantly. Based on C-Leanship's experience with hull cleanings and customer information, it is recommended that you clean your hull if you have more than 30% biofouling. Though, a rule of thumb is to inspect the hull of the vessel at least every 6 months, especially if the vessel has traveled in warm waters or have had idle times on its voyage.

6.4. What to learn from a hull inspection

The visual biofouling data from the hull inspection reveals information about the exact coverage throughout the hull. It also reveals important information about the biofouling on the hull – especially in terms of:

- Type(s) of biofouling growth
- Expected hardness
- Precise locations

Having this information at hand is important to the prioritization and enablement of the right service operations. The visual inspection report from your service supplier must be added as documentation to your Record Book in the Biofouling Management plan of the vessel.

6.5. In-water cleaning

When a biofouling issue have been found on a vessel, it is important to take the decision to do something about it. One of the options is to use a hull cleaning company.

Some of the main things to look out for when selecting the company to help with the hull cleaning is:

- Type of system (ROV or brush cart or drydocking)
- Type of cleaning method (waterjet, brushers, ultrasound, etc.)
- Safety
- Environmental impact (collection of biofouling, Filtration of effluent, handling of material after filtration, etc.)
- Impact on Anti-Fouling coating
- Disruption to vessel operation
- Local permits or approval.

7. Conclusion

There is still a lot of work to be done to put focus on biofouling management. Countries like New Zealand and Australia are reminding the global fleet of the importance of this, but more is needed to be done.

Key to minimizing the risk of invasive species and their environmental impact lies with Biofouling management. Therefore, increased communication between all parties is need and there needs to be agreement to work together to move in the right directions.

The market is slowly moving in the right direction and is also being pushed by new regulations. This will end up in a win-win situation for the vessel industry and the environment.

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The Clean Hull Initiative One Year Later: Towards an ISO Standard on Proactive Hull Cleaning

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Abstract

During PortPIC 2021, Bellona "soft launched" the Clean Hull Initiative (CHI) and proposed to develop an industry standard for proactive hull cleaning. The aim of the standard is to harmonize stakeholder requirements and needs, establish best practices and levelling the playing field between in-water cleaning service providers, spurring industry innovation. The CHI was globally launched at Nor-Shipping in April 2022, with an open invitation for interested stakeholders to join the effort. The preliminary working group for developing a standard, led by Bellona, is well on the way to develop a proposal for a standard, to be submitted to ISO later this year. This paper gives an update on the work done by the CHI with focus on the ISO standard scoping, summarizes the different considerations and discussions that has taken place between the stakeholders during the scoping of the proposal, and the way forwards with the standard.

1. Background

The build-up of marine life on ships' hulls, known as biofouling, is an age-old problem for ship operators and the shipping industry. Fouling slows the affected ship and can increase its fuel consumption by as much as 40%, boosting already high CO_2 emissions. The added fuel costs alone amount to over 33 billion USD yearly at today's high fuel prices, *IMO (2020)*. (Estimate based on fouling accounting for 9% of emissions from shipping, and a fuel cost of 1200 USD/ton.) And biofouling doesn't just slow down ships. The accumulation of marine life on hulls may spread invasive aquatic species in environments they're transported to, affecting biodiversity, ecosystem health and the livelihoods of coastal communities across the globe. Foreign aquatic species causes hundreds of millions of dollars in socioeconomic costs for coastal states. Scientists estimate that about 60-70% of aquatic invasive species are spread via biofouling on ships, *Hewitt et. al. (1999), Hewitt and Campbell (2010)*. It's something that regulators, ship operators, port authorities and conservation bodies are increasingly concerned about.

Removing fouling at an early stage, known as proactive hull cleaning, is a measure to remove microfouling and prevent the formation of macrofouling, and can be performed in an environmentally sound manner without capture when in combination with a suitable coating. Proactive hull cleaning is an emerging technology, which is currently listed as a recommended practice for light microfouling in the latest revision of the IMO biofouling guidelines (BFG), *IMO (2022)*. The IMO BFG is currently under revision, with an intent to finalize in 2023.

There is currently no international regulation or standard for hull cleaning of biofouling. With the increasing awareness on biosecurity worldwide, port authorities are introducing their own preventative measures, including legislation which arriving ships must comply with. The patchwork of regulations and policies globally create a complex regulatory landscape for ship owners seeking to manage biofouling proactively.

2. The Clean Hull Initiative

In order to reduce the regulatory barriers and increase the uptake of emerging proactive hull cleaning technology as a preventative tool, the CHI was launched by the Bellona Foundation at the Nor-Shipping fair in April this year, with an open invitation for interested stakeholders to join in. The collaborative project, started by founding partners Bellona and Jotun in 2021, brings together a growing number of stakeholders in both the private and public sectors and aims to develop an industry-wide recognised and accepted standard for proactive hull cleaning.

Fig.1: Panel discussion on safe proactive hull cleaning practices during the CHI launch event at Nor-Shipping in April. Roger Strevens (Wallenius Wilhelmsen, on stage right) moderated the panel, comprising Dr. Mario Tamburri (ACT/MERC and the University of Maryland, on screen right), Luc Van Espen (Port of Antwerp, on screen left), Stein Kjølberg (Jotun, on stage left) and Claus Winter Graugaard (Mærsk McKinney Møller Center for Zero Carbon Shipping, on stage middle).

The objective of the CHI is to accelerate the development and global implementation of an industry-wide standard on proactive hull cleaning, through working to increase awareness on the issue among key stakeholders and to lead the process towards ISO to develop a new standard for proactive hull cleaning. The standard will be an important means to establish proactive cleaning as part of the biofouling management toolbox and will also contribute to levelling the playing field between cleaning providers and drive innovation. Furthermore, it will lay the groundwork to ensure higher quality cleaning services to ship operators and drive the market for commercial proactive hull cleaning solutions.

At the time of the Nor-Shipping launch event, the CHI had 18 stakeholder members involved. As of August 2022, the initiative now has 30 contributing stakeholder members, with an additional ten members contributing to the working group to develop the proposal for an ISO standard. Members and contributors represent global ship owners, operators, regulators, port authorities, environmental and water quality regulators, cleaning technology developers and service providers, test facilities and the scientific/research community.

Current CHI stakeholder members are shown in Fig.2, and comprise Jotun, Armach Robotics, AzkoNobel, BSH (Bundesamt für Seeschifffahrt und Hydrographie/German Federal Maritime and Hydrographic Agency), CleanSubSea, DNV, Dorian LPG, Endures, Florida Institute of Technology, Center for Corrosion and Biofouling Control, Hapag Lloyd, Hempel, HullWiper, I-Tech, Limnomar, Litehauz, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Notilo Plus, Port of Antwerp-

Bruges, Royal Haskoning DHV, Scrufy, Shipshave, Solstad Offshore, Stolt Tankers, TAS Global, University of Maryland, Center for Environmental Science, Vessel Check and Wallenius Wilhelmsen.

Fig.2: Current stakeholder members of the CHI

3. Towards an ISO Standard on Proactive Hull Cleaning

In order to establish an ISO standard, a New Work Item Proposal (NWIP) must first be submitted to the relevant technical committee (TC) at ISO for review and approval via ballot. The NWIP should define the scope, justify why society need the standard, what sustainable development goals are met, identify who the stakeholders are, etc.

The working group has identified that the relevant TC to submit the proposed standard to will be TC8 ‘Ships and marine technology’, SC2 ‘Marine environment protection’.

The process to develop the NWIP was proposed as a three-round revision process, sandwiched between two workshops, as illustrated in Fig.3.

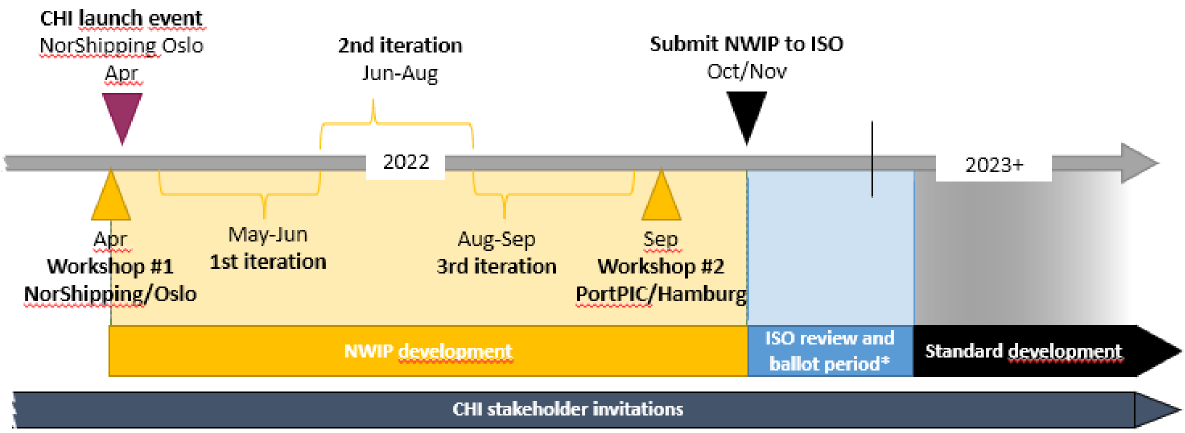

Fig.3: Timeline for NWIP development

The process kicked off with an initial workshop in April in Oslo this year (following Nor-Shipping), hosted by Bellona and Jotun. The goals of the workshop was to bring together stakeholders, add energy and direction to the work with developing an ISO standard on proactive hull cleaning, gain a common understanding how an ISO standard is developed, review prior and ongoing work on in-water cleaning (IWC) performance standards and guidelines, with focus on proactive hull cleaning, discuss the scope and content of a standard and agreeing on the next steps in developing the ISO standard and way forward until the next workshop in September. The workshop gathered in total 35 participants, representing in total 24 different stakeholders, nine countries and four continents. The meeting was set up in a hybrid meeting format, with 17 participants present physically in Oslo and 18 more attending on the linked Teams call.

Following the workshop, the coordinators summarized the discussions and distributed to the correspondence group for comments and input for the initial revision round. The group was presented with a proposed scope, a suggested text for purpose and justification for the standard, asked for input on relevant existing documents at the international, regional, and national levels as well as a draft outline of the standard. The participants were asked to provide input in a questionnaire. The questionnaire in the first round had two parts – the first part comprised 13 general questions on topics to include or not in the standard, and the second part asked members nine questions on whether they agreed to specific statements related to the scope, outline, and timeline.

In total, 21 members provided input through the questionnaire circulated in the first revision round. Submissions were received from all key stakeholder groups, represented as shown in Fig.4.

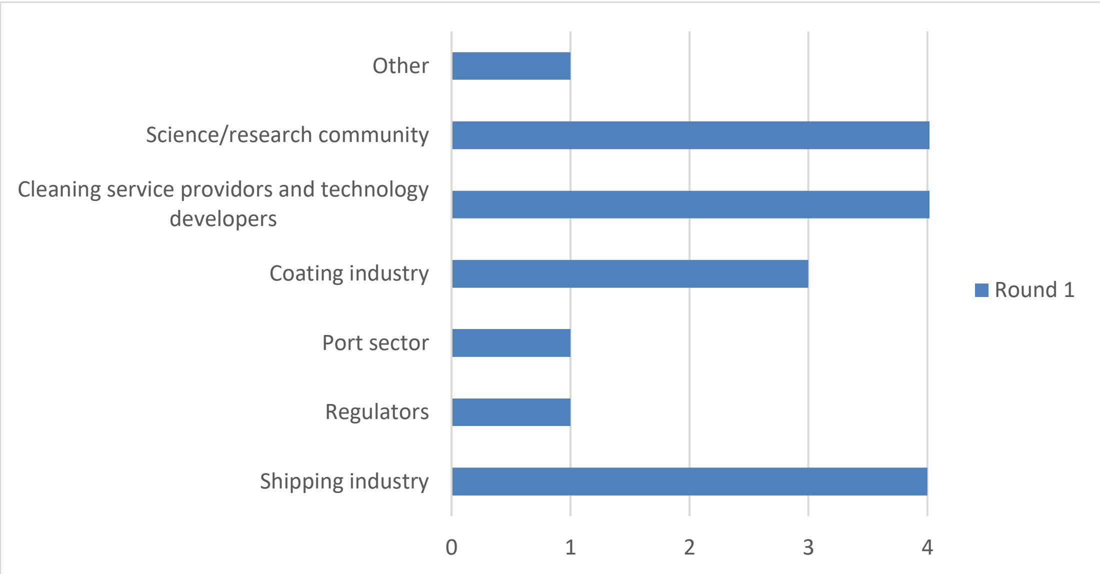

Fig.4: Distribution of members in the different stakeholder groups providing feedback in the first review round.

The proposed scope of the standard was to "[…] *specify standard methods for performing and documenting safe and environmentally sound proactive hull cleaning*." The standard will focus on the operation of proactive cleaning, as there are parallel efforts focusing on relevant topics such as inspection and classification of biofouling and validation of IWC systems.

In the first round, the group was mostly aligned for eight out of the 13 general questions, while the group was more divided in the feedback on the remaining five questions. The topics discussed and conclusions in revision round 1 can be summarized as follows:

- There was consensus in the group to try to align with revised IMO BFG as much as possible. Although several stakeholders are hesitant to agree to align before the final outcome of the IMO BFG revision process.
- There was consensus in the group that the standard shall provide guidance to coating manufacturers, to ensure compatibility between the hull coating and the cleaning technology. It is important to ensure that the coating is suited for proactive cleaning.
- The standard will provide standardized methods for equipment manufacturers and service providers.
- The group was divided on whether standard should address physical safety standards for divers or vehicles. Several members referred to other existing standards and codes, and that the

standard should refer to these. As the requirements may vary between standards and local regulations, one member suggested that the standard should set some minimum requirements to ensure safe operations and a level playing field for the various stakeholders. The coordinator proposed to further map global standards and requirements, and that the group later decide on whether the standard should refer to certain standard(s) or practices, and/or to include a minimum level of requirements in the standard.

In the second revision round, the group was asked 10 questions, where the first eight questions were specific questions following up on points that did not reach consensus in the first revision round, and the second part asked members whether they agreed to the revised scope and outline according to comments received in the first round. Round 2 also had several questions on topics to align the standard with the revised IMO BFG.

As the revision process is still ongoing, and the summary of the results of the revision round is not yet circulated, this paper will not go into details on conclusions in revision round 2. Based on the two previous revision rounds, the responses will be summarised and distributed to the working group. The workshop on 14 September will aim to finalize the draft scope and outline of the standard and agree on the next steps in developing the ISO standard proposal and way forward until submitting the NWIP later this year.

4. Further work

The NWIP will be submitted to ISO in Q4 2022. The NWIP will be subject to committee comments and ballot before approval and go-ahead for the further process of developing a standard. A timeline of 36 months for the development of the standard has been proposed.

The process in ISO is consensus based, taking into account comments from all stakeholders. Bellona and the CHI invites all interested parties to engage in the process towards establishing a safe and environmentally sound standard on proactive hull cleaning.

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4th PortPIC Conference

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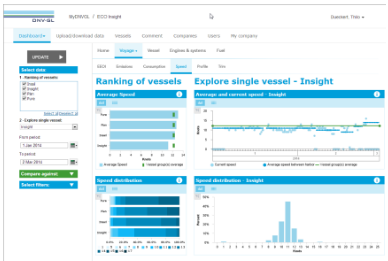


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21.07.2023	Final papers due

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