HullBUG – Hull Grooming Crawler Robot with Fluorometric Fouling Recognition

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Abstract

This paper describes the Hull Bio-inspired Underwater Grooming (HullBUG) System developed by SeaRobotics with support from the US Navy and extensive testing performed by Florida Tech, of Melbourne, Florida, USA. The HullBUG is a crawler robot that supports largely automated underwater ship hull cleaning. Hull grooming (i.e. light cleaning with focus on bio-film removal) can now be accomplished without divers, frequently and relatively cheaply. The robot uses various attraction mechanisms, including hydrodynamically generated negative pressure, and magnetic attraction for attachment to the hull surface. A multichannel fluorometer which automatically detects chlorophyll in the bio-film is utilized in the guidance system. Efficacy studies on numerous grooming methods on different coating types with variable periodicities have been studied. Utilizing advanced control algorithms and sensing systems, a highly automated hull grooming system is now a reality.

1. Introduction

With over 90% of the world's commerce transported by various shipping means, the need to improve ship hull efficiency is critical. Pressure from both the environmental and financial communities is forcing the industry to re-evaluate operational practices to improve overall efficiency of the shipping process. With bunker fuel prices rising and increased interest in regulatory activities associated with reduced environmental impact, the improved hull efficiency associated with clean hull operations is essential. Reported improvement in hull efficiency and the resulting decrease in fuel used range from 5-20%. That depends on numerous factors such as transit speed, coating condition, geographic area of operation, and current corporate hull cleaning practices. It's safe to say a substantial increase in fuel efficiency will result from proactive grooming. Progressive shipping companies with instrumented ships and other companies utilizing operational data are studying fuel efficiencies vs. cleaning protocols to refine their process. These efforts will result in newly defined best practices for ship operation.

Environmental pressures are mounting to achieve the following objectives:

- Reduction in the transport of Aquatic Invasive Species (AIS)
- Reduction of Green House Gases (GHG)
- Broadening the application of biocide free coatings

The goal of SeaRobotics HullBUG technology is the deployment of autonomous hull grooming system to implement a "Proactive Hull Grooming Process." Proactive grooming is the process of frequent grooming, or light cleaning, of the ship hull. The process keeps the hull clean with no more than a bio-film level of fouling. Operating with clean hulls reduces the transport of Aquatic Invasive Species from port to port, as well as significantly reducing the generation of green house gases (GHG). With 3 kilograms of GHG generated for each kilogram of bunker fuel burned, a 5% decrease in fuel burned translates into large decreases in GHG emission. The global shipping fleet emits approximately 1 Giga-ton of GHG yearly. GHG emission from the global shipping fleet could decrease by 50 million tons yearly through the use of proactive grooming.

An additional environmental benefit of proactive grooming, is the enabling of new coating technology. Biocide free foul release coatings will become more applicable to low operational pace fleets, such as the US Navy. Harder coatings will be more applicable to high operational pace fleets such as cargo ships with heightened attention to hull cleanliness.
Advanced systems, such as the HullBUG, have been enabled through the continuous improvements in micro electro mechanical systems (MEMS) technology, the miniaturization of sensing systems, increases in computing capability, decreases in energy used by distributed processing systems, and improvements in battery energy density.

2. System description

The HullBUG system is comprised of the HullBUG vehicle and an operator interface system, an optional tether and tether winch system. When running in an autonomous mode the tether and winch are removed. The system then utilizes battery power and communicates via RF modem while at the surface.

![HullBUG kit with tether and winch](image1)

The HullBUG vehicle system is comprised of the vehicle and a work package.

![HullBUG vehicle with grooming and cavitating water jet cleaning work packages](image2)

Work packages have been developed for grooming, light cleaning, and heavy cleaning. Grooming and light cleaning work packages utilize soft brushes for grooming, and progressively stiffer brushes for light cleaning. The heavy cleaning work packages utilize cavitating water jet and high pressure water jet cleaning systems.

The systems can be used for proactive grooming, light cleaning, or for the removal of hard fouling. Numerous ancillary systems can be used to enhance the functionality of the HullBUG. Various position reference systems, acoustic communication systems, and numerous imaging systems, both acoustic and optical, can be used for improved system performance.

3. Computer architecture

The HullBUG utilizes a distributed computing architecture as illustrated below:
Fig. 3: Distributed computing environment. Most sensors and actuators incorporate integrated processing systems.

At the core of the distributed processing system is a multiprocessor stack. This stack performs the high level command, control, and communication functions. It utilizes a Linux based 500MHz ARM9 CPU processor supported by PCI and PC-104 connectors, multiple memory devices including RAM, Flash, Micro-SD and Full-SD card slots, and a user programmable FPGA. The primary CPU board also includes numerous I/O devices. These include multiple channels of analog I/O, RS-232 and RS 485 serial channels, USB 2.0 and SATA ports, gigabit Ethernet, as well as watchdog timer circuits. The main processor board is supported by a multi function board, which provides additional analog and serial I/O as well as specialty circuit functions. These circuits are under processor control to provide pulse width modulation functions, opto-isolated I/O, motor control command output, as well as commutation sensor input, and current feedback. This support board also provides power distribution with power control functions and health circuit interfaces.

The primary control and communication processes are coordinated by the main processor board. Internal communications between processors are described by an Interface Control Document (ICD). The ICD provides a messaging protocol which is implemented throughout the system and allows for the implementation of various high level autonomy or third party control processes. Communications to the distributed processing and sensing system is performed using a socket based communication protocol, allowing for the monitoring of each of these channels from remote sites when access is possible. The socket based communication approach allows for ease of development and aides in the diagnosis of system problems.

The control system components provide an extension to the distributed computing environment. The actuators used in the HullBUG are controlled by processor based intelligent motor controllers. The motor controllers receive commands from the main control computer and provide the motor husbandry functions. All the motors used in the system are brushless DC requiring the motor controllers to perform the commutation function using sensor feedback or running sensor-less control
algorithms. These electronically commutated motors include thrusters, propulsion/drives, negative pressure attraction devices, magnetic wheel actuation devices, and grooming tool drive motor systems. Each of these components has unique requirements for processing and analysis of feedback data. Sensed data includes motor current, winding temperature, hall sensors for commutation, and encoder feedback for quadrature control and odometry. Various motor control routines are also utilized. The thrusters are generally run using speed or current control algorithms, as are the negative pressure attractors, and the grooming tool motors. The propulsion motors are run using a speed control inner control loop mode, with a position, depth, and orientation control outer loop.

Numerous sensors are utilized in the HullBUG system at both the micro and macro level. At the lowest level are the motor phase sensors used for commutation, as well as temperature sensors used to limit motor currents when stalled or over powered. The next level of sensing occurs with general health and status sensing. Currents, voltages, and leak detectors fit into this category of device. Both analog, and discrete I/O interfaces are utilized with these sensors. The leak detectors use a processor based algorithm with a multi-aspect transducer to provide leak detection at all orientations.

4. Situation awareness and navigation sensors and processing

Sensors are also used for situation awareness at various levels. The lowest level of situation awareness sensing lies with the bumper sensors. Bumpers are integrated to detect obstacles which will impede the operations of the vehicle during either forward or reverse motion. A bumper sensor processing algorithm can estimate the location of the sensed obstacle and implement an evasion strategy. The micro acoustic ranging (MARS) sensors and the scanning micro acoustic ranging (SMARS) sensors are used for simple detection of protruding obstacles and hull presence. Voids in the hull, such as bow thrusters, sea chests, inlets/outlet ports, and the bow and stern can be detected by these sensors.

![Fig.4: Typical obstacles on the hull](image)

Although optical sensing is possible with good results over very short range, the turbidity of the water can restrict the sensing range to 5-10 cm. Optical sensors which do not produce point cloud data, require sophisticated image processing algorithms to decrease false positive results in the presence of typical hull damage. Common forms of damage found on commercial ships are dents, scrapes, and anchor chain scares. Acoustic sensing is best used in this high turbidity environment. Use of acoustic sensing poses other challenges. Short range sensing required for small vehicles such as the HullBUG require a multi-range processing algorithm. The range is split between near field and far field processing to accommodate transceiver ringing and near field reflected power levels. The surface detection is estimated based on an energy analysis of the "best return" in the temporal sampled data. Both the MARS and SMARS sensors have an integrated signal processing CPU used to coordinate the transmission of acoustic energy, as well as to range gate, sample, and analyse the sampled data. In addition, the SMARS uses a motor controller to control its scanning motion, and process the sector mapped range data.

Navigation of the HullBUG is implemented using both embedded sensing, as well as high level external sensors. Embedded sensors including multiple pressure sensors, attitude sensing using tri-axial accelerometers, various rate sensors such as MEMS rate gyros and fiber-optic gyros, and tri-axial magnetometers, are used to control the HullBUG and define its orientation compatible with its six-degree-of-freedom (6-DOF) motions. Each sensor provides both pre and post processed data. The sensor data processing allows for raw data, multi transducer filtered data, data provided in engineering units, as well as multi-sensor filtered data using Kalman Filters. Each sensor incorporates a digital signal processing CPU.
Navigation is improved using high level complex sensor systems. These systems can be video cameras when operating the HullBUG in low turbidity water using a tether, or as complicated as an acoustic imaging sensor in an autonomous operating mode. In clear water video based imaging is low cost and effective, however, in highly turbid or autonomous operations, video data may yield unusable imagery, or imagery requiring complex scene segmentation and scene interpretation algorithms. Sensors which yield point cloud range data can be used with simpler algorithms.

Fig.5: Results of Laser Scanning a test plate in reasonably clear water

Laser scanners, and acoustic imagers provide point cloud range data, and each have advantages and disadvantages from a cost and complexity perspective. In addition to the local, or near field sensors, just discussed, acoustic position system can be very effective. Although ultra short baseline (USBL) acoustic positioning systems have their challenges in the “ducted” high multipath, high noise harbor environment, they can assist in both along hull positioning in both tethered and autonomous operating modes, as well as a acoustic communications device during autonomous operations. USBL system utilizes the phased arrival of acoustic wave fronts impinging on three closely spaced transducers. Providing adequate sensory data, and utilizing an interface control document (ICD) for messaging enables the use of numerous high level autonomy engines. Third party approaches such as the Mission Oriented Operating Suite (MOOS) and the Robotic Operating System (ROS) can be implemented using a command translator. These systems allow access to various general, as well as purpose written sensor processing and autonomy algorithms. These software packages can be run as a separate control process or on a dedicated CPU board. The autonomy functions can operate as a “backseat driver” to direct decision making and respond to vehicle health issues or situation awareness sensor input.

Fig.6: Typical decision arbitration logic common to advanced autonomy engines

SeaRobotics has been working with several groups to refine concepts for feature based navigation on the underwater ship hull. Feature based navigation has great potential for reducing the cost of underwater hull navigation, however significant challenges exist. The challenges start with feature detection. The required sensors are expensive, reasonably high bandwidth, and require significant “image processing.” The task is complicated by the grooming/cleaning function. A hull recently out of dry dock, which is in the process of being groomed or cleaned can present a “feature devoid” environment. This is an environment without significant features for use in local navigation or global navigation and re-visitation. Future system will utilize variants of the feature based navigation technology to decrease the overall system cost, improved positional accuracy, and provide improved autonomy.

In addition to system operations and navigation, HullBUG can deploy various inspection sensors. Common sensors utilized in hull husbandry measure parameters in an effort to assess hull integrity.
These sensors measure hull plate thickness, underwater hull coating thickness, cathodic potential, crack detection, and biofilm detection and monitoring. Most of these sensors are generally available with the exception of crack detection which is in the research stage. SeaRobotics has worked with a research institution to assess an adaptation of medical ultrasound techniques for the detection of cracks on the back side of the hull plate. These cracks generally form near frame welds and other internal attachments, or in areas susceptible to internal water pooling. Pitting corrosion and stress cracking fall into this category of hull defect.

The SeaRobotics BioFilm Detector (BFD) is an electronic device for the detection of marine growth on the underwater surface of a ship. The underlying technology used by the device is a fluorometer for the detection of chlorophyll found in the green film layer initially growing on the surface. This biofilm precedes the growth of larger species such as barnacles and tube worms. Through the use of a multiple channel fluorometer, the HullBUG vehicle can follow the edge between a groomed and ungroomed section of the hull resulting in more efficient grooming of the surface. Alternatively, using the BFD during an inspection transect will validate the grooming coverage of the hull and specify any required rework.

Fig.7: Uncalibrated 8 channel data from Fouled, Groomed, and hand cleaned fluoropolymer based foul release IS 900, and biocide based control depletion polymer antifouling coating BRA640

Fig.8: Averaged channel data for the 8 channels for Fouled, Groomed, and hand cleaned test plates used to gather the data in the previous graph
The biofilm detector has two analog circuits, a transmitter and a receiver. The received signal is processed using a digital signal processor (DSP) and the results transmitted via serial port at 50Hz. The BFD utilizes structured, pulsed illumination in a narrow frequency band, to excite fluorescence from the chlorophyll. The resulting fluorescence is optically selected, filtered and analyzed by the integrated DSP.

The data from the BFD has been incorporated into a transect control algorithm allowing the HullBUG to traverse the hull with a monitored overlap with respect to the prior grooming transect.

The measured fouling level for the ship can be evaluated based on the degree of fouling and the location on the ship. Under-hull fouling typically forms at a reduced rate due to the relative decrease in illumination. The hull grooming periodicity can be adjusted based on the measured and mapped biofilm present prior to grooming, along with geographic location and current anticipated fouling pressure. Utilization of this method will minimize cost for the grooming process as well as minimizing the potential for coating ware.

5. Attraction Mechanisms

The HullBUG system utilizes several attachment methods depending on the conditions and operational requirements. Attachment mechanisms utilizing negative pressure devices, as well as magnetic attraction are implemented. Navy combatant ships have restrictions on the use of magnetic devices which can impart an unacceptable residual magnetic signature on the hull, detectable by influence mines. Two forms of negative pressure attractors are in use for this class of hull. The first utilizes the suction formed by a rotating volume of water similar to the suction formed by typical vertical axis rotary hull cleaning brushes. A negative pressure region is formed allowing attraction in both contact and non-contacting conditions. In an alternate negative pressure attractive method, a closed volume is formed using active and passive rotating seals. The attractive force is maximized using this method. Both negative pressure devices offer adequate efficiency to enable autonomous operations. A magnetic attraction system has also been designed and implemented by SeaRobotics. The magnetic wheel system is designed to provide large passive attractive forces. The system has been designed to allow for modulation of the attractive force, as well as self-cleaning of the wheels.

6. Field work

The HullBUG system has been tested in numerous venues including the SeaRobotics test tanks, Florida Tech/ONR large scale test facility, Naval combatants (DDG), container ships, barges, and a SWATH casino ship.

![Fig.9: Ongoing HullBUG testing on numerous platforms for grooming and cleaning](image)

In addition to the HullBUG development and field tests, extensive testing has been performed by Florida Tech to study the periodicity required for effective proactive grooming given the local fouling...
pressure and grooming methodology. The constituent biological organisms and species have been analyzed along with their settling behaviors and their settling rates. These studies have resulted in extensive data sets generated by fouling studies over the past 6 years.

![Fig.10: Typical grooming study performed at Florida Tech; 6 months of fouling as evidenced by the control panels on the left, and results of proactive grooming on the right for both foul release and copper based ablative anti-fouling coatings](image)

The testing illustrated above is part of the on-going study of proactive grooming concepts and methods being evaluated by ONR. Field testing has reinforced the effectiveness of the grooming system.

![Fig.11: Container ship grooming in South Florida. Left-Before Grooming, Right-After grooming](image)

Container ships with their high operational pace are very different from naval vessels which spend considerably more time at dock. Both systems share the common benefits of grooming and the efficiencies associated with operating a clean hull.

Varying hull shapes and sizes have also been found during field testing. Illustrated below are the challenges associated with navigation and obstacle avoidance on the two Littoral Combat Ship (LCS) hulls. Each hull must be segmented into sections for grooming and inspection. The sections each have challenges which will become more prevalent in shallow water combatants of the future, such as hard chines, complex stabilizers and contours near the jet drive inlets.
Commercial hull shapes have been found to be more consistent, in general. Each hull type has challenges for the navigation, obstacle avoidance, and positional awareness systems required for efficient HullBUG operations. Experience with each new hull type will allow incremental improvements, leading to improved operations and evolving HullBUG capabilities.

In addition to proactive grooming and light cleaning, the HullBUG has been outfitted with a heavy cleaning work package.

The cavitating jet cleaning work package is accompanied by a diesel powered 37 kw, high-pressure pump system. This type of system has been used extensively by diver deployed wands or "guns" for the removal of heavy calcareous growth and hard fouling from mooring chains and other subsea structures. This type of system is also currently being deployed as a work package on work class ROVs.

7. Conclusion

The HullBUG system has evolved into a capable platform for both grooming and cleaning. Through the evolution of compact, low power computing, as well as improved sensing capabilities the system can be commercially deployed as a tethered system, and is currently being tested for autonomous operations.

The financial benefit to shipping industry is significant. Overshadowing the financial benefits, however, are the tremendous environmental benefits from the reduction in Green House Gases (GHG), reduction in transport of Aquatic Invasive Species (AIS), and the enabling of a broadened use of biocide free underwater hull coatings.