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14. ABSTRACT
The Hull Bio-Mimetic Underwater Grooming (HullBUG) Vehicle System under development holds the potential to dramatically change current hull cleaning methods and their environmental impacts. Frequent use of the HullBUG, a small autonomous cleaning device, on the hulls of Navy ships in port by applying light cleaning pressure or grooming results in a cost effective solution to the underwater fouling problem.
As part of overall HullBUG development the Grooming Tool is an integral part of the system. This tool and variations of it have been used by Florida Institute of Technology (FIT) during several years of testing activities. FIT was assigned the task to come up with a set of parameters that FIT would want in the next generation tool. SeaRobotics was assigned the task of developing a grooming tool that would address those parameters. After review by Navy and FIT personnel the agreed to design was built and tested. This report documents that effort and several other sub-system activities that ran in parallel contributing to the overall progression of the HullBUG design.

15. SUBJECT TERMS
HullBUG, Grooming Tool, underwater hull cleaning, autonomous vehicle, underwater navigation

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HULLBUG TECHNOLOGY DEVELOPMENT FOR UNDERWATER HULL CLEANING, FINAL REPORT

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1 Contract Information

Contract Number	N00014-09-C-0852
Title of Research	HullBUG Technology Development for Underwater Hull Cleaning
Principal Investigator	Don Darling
Organization	SeaRobotics Corporation

2 Statement of Work

The Hull Bio-Mimetic Underwater Grooming (HullBUG) Vehicle System under development holds the potential to dramatically change current hull cleaning methods and their environmental impacts. Frequent use of the HullBUG, a small autonomous cleaning device, on the hulls of Navy ships in port by applying light cleaning pressure or grooming, results in a cost effective solution to the underwater fouling problem. The frequency of grooming is selected based on the hull coating and the local fouling pressure on the docked ships or ships at anchor. Frequent grooming prohibits the development of mature fouling colonies and limits fouling to a manageable bio-film layer.

To further development of the HullBUG Vehicle System the following technical objectives were defined and listed in the contract statement of work.

2.1 Technical Objectives

- Grooming tool development
  - Refinement of existing tool designs with feedback from FIT
  - Design and fabrication of horizontal brush tool
  - Down select to a tool to implement on the vehicle
  - Support role in the operation of the gantry system
- Flow Sensor
  - Purchase COTS sensor
  - Evaluate in the tank with a simulated inlet/outlet
  - Investigate lower cost and smaller in size flow sensor alternatives
  - Integrate flow sensor into navigation plan
  - Test on a ship with an actual inlet and outlet
- Biofilm detector
  - Integration with navigation software
  - Tank testing of foul line following navigation
  - On ship testing of sensor
- Range finder
  - Continued development of the MARS
  - Integration of the MARS onto the vehicle
  - Full integration of range finder into hazard negotiation software
  - Evaluation of laser based range finders
- Navigation
  - Integration of Marine Sonic Acoustic Positioning System
  - Expand software to incorporate global navigation
  - Decision making navigation synthesis software design
- Vehicle Development

  - Implementation of more communications ports
  - Larger pressure vessel
  - Isolation circuitry
  - Reliability improvement through field testing
- Operations
  - Joint operations with Oceaneering
  - Tank testing at Vero Beach Facility
  - Tank testing at Hobe Sound Facility
  - On ship testing of navigation software
  - Multiple vehicle operations design
  - Scenario of operations plan
  - Demonstration at project reviews
  - Demonstration at project reviews
- Attend project review meetings twice yearly

3 Sub-system Status

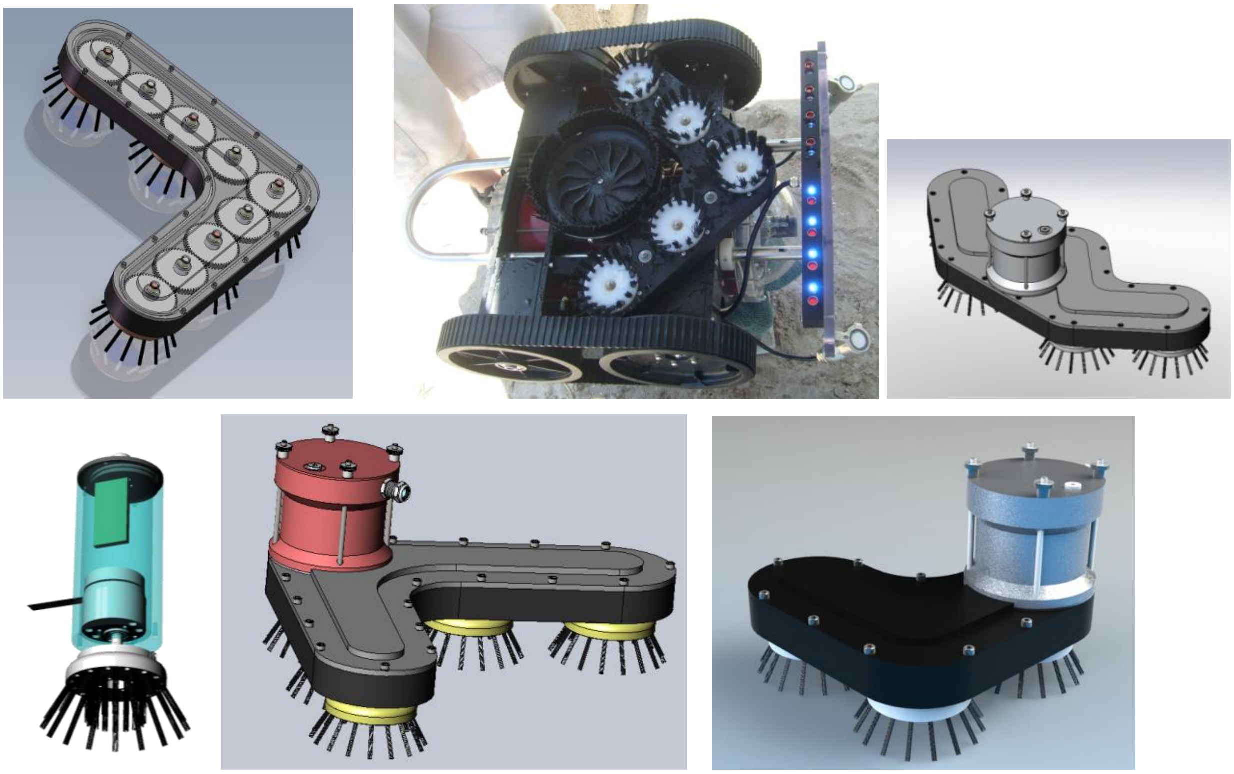
3.1 Grooming Tool Development

As part of overall HullBUG development the Grooming Tool requires particular attention. This tool and variations of it have been used by FIT during several years of testing activities. In 2013 Grooming Tool development was again a focus. FIT was assigned the task to come up with a set of parameters that FIT would want in the next generation tool. Upon receipt of FIT provided parameters SRC would take these parameters and propose a mechanical configuration that met them along with the electrical requirements to power the new Grooming Tool. A conceptually designed SolidWorks model would be generated to better understand the packaging and mounting of the tool on the FIT vehicle. Motors and controllers would be sized for the expected loads and incorporated into the solid model. After review by Navy and FIT personnel the model would be refined and updated. Once approved, detailed drawings of the Grooming Tool and associated compliant mounting device would be generated. These drawings would be vended out to approved vendors for quoting. Quotes would be obtained for different levels of production in order to better understand the savings associated with buying more. Once a good pricing model was developed and quantity purchased determined, parts would be vended out and manufactured. These parts would then be assembled at SRC. A test program would then follow to fully qualify the design.

In the later part of 2013, approval was given to manufacture one Grooming Tool, one Compliance Mechanism and one Grooming Tool Test Fixture. Production of these items were started in the last quarter of 2013 with the goal to start a test and acceptance program in early 2014.

3.1.1 Grooming Tool Iterations

The grooming tool has developed through several iterations over several contracts. The initial grooming tool was developed in a chevron configuration utilizing gear train power transfer. The design and grooming tool motor controller was studied using parametric analysis considering Maxon and SeaRobotics controllers with various combinations of RPM, seals, loading, in and out of the water. These studies led to improved designs of the controller, seals, and brushes. Five headed brush grooming tools were subsequently built for the FIT test tank trolley assembly as well as for the prototype HullBUG system. Additionally several variants of the grooming tool were designed and built to support testing by others.



Grooming Tool Concepts

Development efforts to date have emphasized the need to provide a stronger acting and more compliant Grooming Tool compared to existing and previously designed tools. To that end it was determined that a new Grooming Tool would be designed, technically reviewed, constructed and tested.

Gantry Grooming Tool

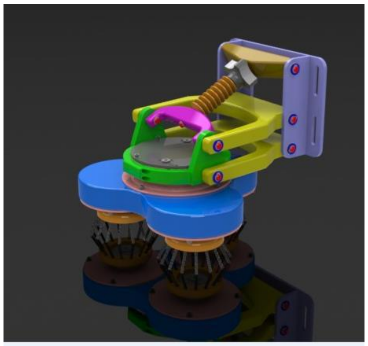
3.1.2 FIT Supplied Parameters

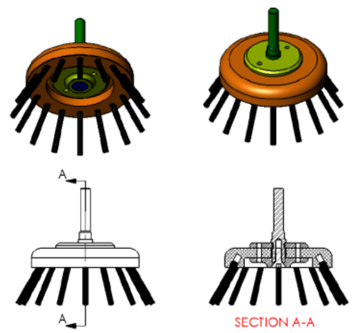
Based on grooming tool studies, FIT has developed a set of specifications that will be the basis of future grooming tool research. More power, more speed and optimal brush to brush center locations were the dominant themes. The following specs were provided by FIT as guidance for future Grooming Tool design.

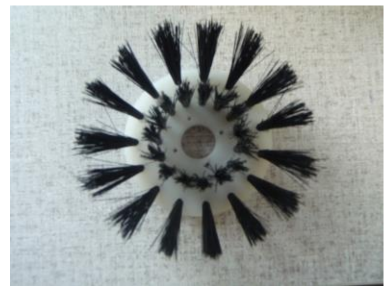
- 1000 RPM
- 240 mNm per brush
- 12 cm center to center distance

3.1.3 SRC Conceptual Design

After a fairly extensive review of various motors/gearboxes and mounting combinations a 3 headed tool appeared to be the most logical concept to pursue. Three brushes are mounted to individual planet gears that are connected to a central sun gear that is directly connected to the motor. That motor gear box combination is mounted in a vertically compliant mechanism that provides approximately 3.5 inches of vertical travel. Three of these three headed tools are mounted in close proximity such that 9 brushes are operating and the 12 cm center to center distance is maintained. A conceptual layout of how these tools might be positioned on the vehicle was presented during a teleconference on 4/12/13. Grooming tool brush holder mount was discussed as a potential trouble spot.

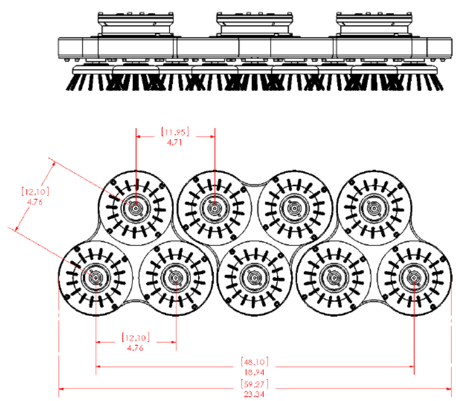




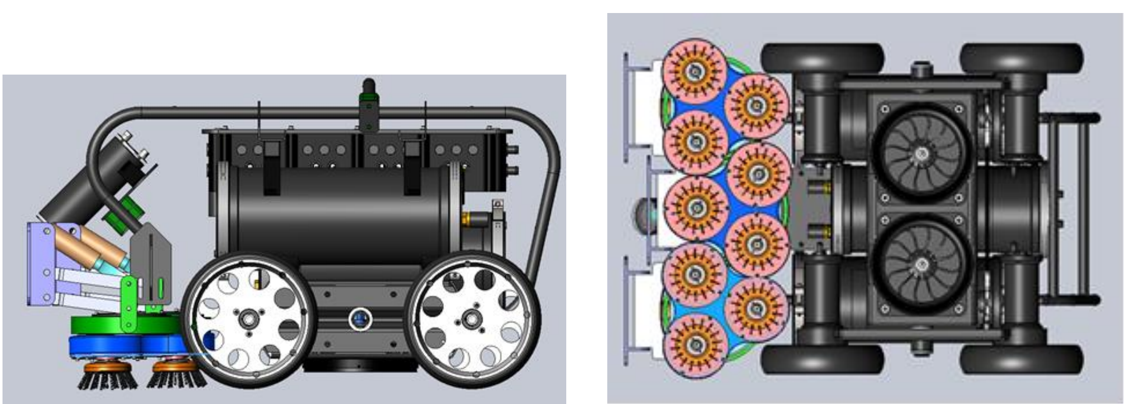


3 Headed Tool and Vertical Compliance Mechanism

Brush Holder Mounting Scheme



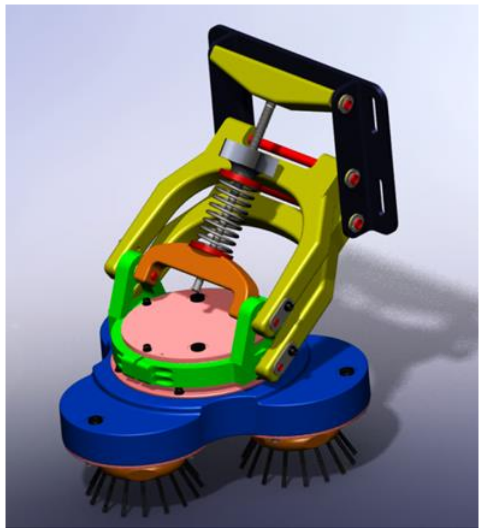
12 cm Center to Center Distance Mounting Configuration



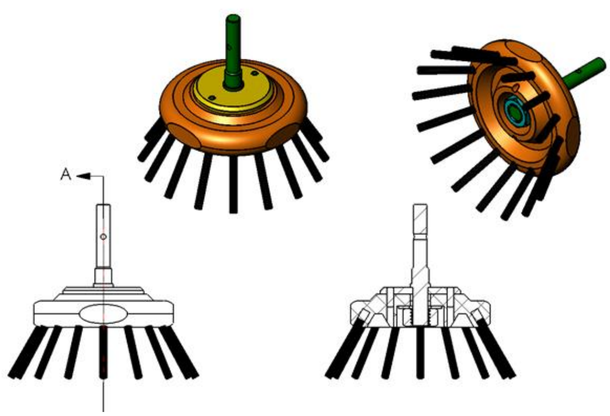
Conceptual Location of 3 Grooming Tool Assemblies

3.1.4 *Navy and FIT Design Review*

A telecom was held on 7/17/13 to discuss the more mature design. The Grooming Tool Brush Holder Mount had been redesigned to more closely mimic commercial products and to limit downtime from the possibility of galled stainless steel fasteners.



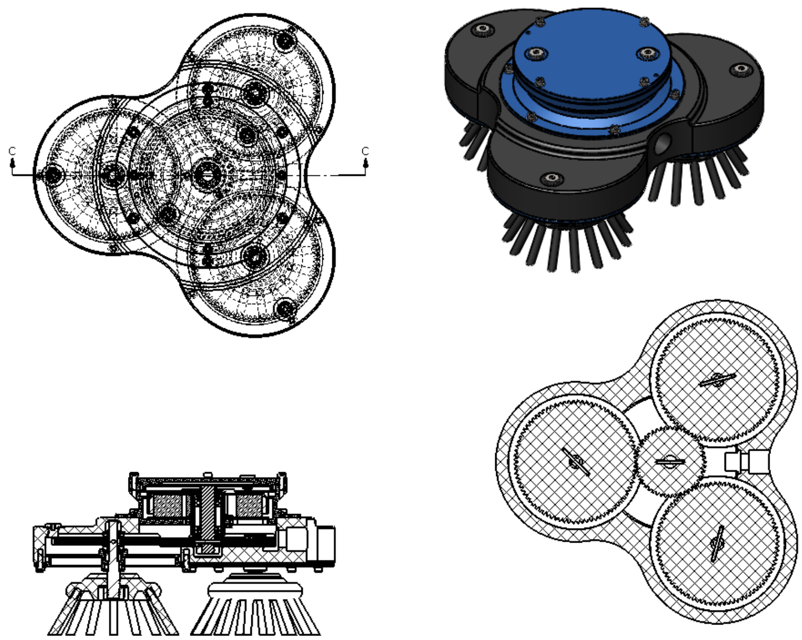
Updated 3 Head Grooming Tool Concept and Compliant Mount



Updated Brush Holder Mounting Concept

3.1.5 *SRC Detailed Design*

All of the parts for the 3 headed tool were detailed, dimensioned and tolerances added to enable quoting by commercial machine shops. A top assembly drawing was created that identified all machined parts as well as all purchased hardware



Top Assembly

3.1.6 *Production Strategy*

Detailed drawings were submitted to vendors for quote in varying quantities. As expected prices per unit would drop when total purchased quantities increased. SeaRobotics, ONR and FIT discussed the idea of buying more units to take advantage of the price break with the accompanying risk of lost money if testing obsoleted some parts. The idea of building one and testing it before building others was also discussed and determined to be the least expensive way forward with the most impactful information set developed for the money spent.

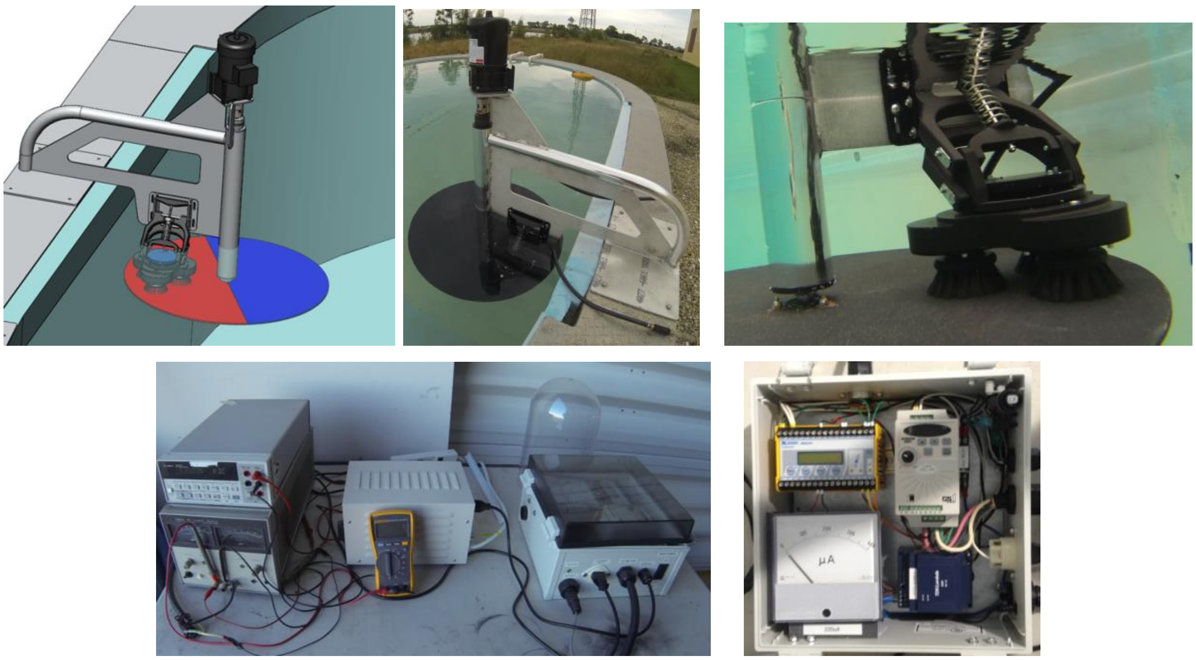
During this period an effort was also made to estimate the cost of a reasonably simple test device that consists of a motor, bearing support and underwater rotating disk.

3.1.7 *Production and Testing Strategy*

After a general review of several different production and testing strategies it was determined that a single 3 headed Grooming Tool and Compliance Mechanism be constructed for extended testing at SRC. A dedicated rotating disk type mechanism would be designed and constructed to support testing. Functionally, the disk rotating underwater would allow the Grooming Tool to run continuously over a constantly moving surface. The rotating disk could be painted with more than one different coating allowing the grooming tool to run over different coatings in one revolution of the disk. In this way the grooming tool and compliance mechanism would be endurance tested. Simultaneously, some information would be gathered as to the wear resistance of the paint. Making the testing even more realistic, bumps and divots could be added simulating the varying surfaces found on a ship hull. This constantly rotating device could run virtually unattended for long periods and work to qualify the Grooming Tool, Compliance Mechanism, the brushes and the paint the system it is designed to groom.

3.1.8 Production

On 8/8/13 production was authorized to fabricate 1 newly designed Grooming Tool and 1 single axis Compliance Mechanism. As part of this effort the go ahead was also given to design and fabricate a test fixture. The bulk of this work was completed by the end of the year with testing slated to start early 2014.



Underwater Test GT Test Fixture

3.1.9 Testing Results

The following pictures illustrate the degree of wear experienced by the brushes over an extended period.

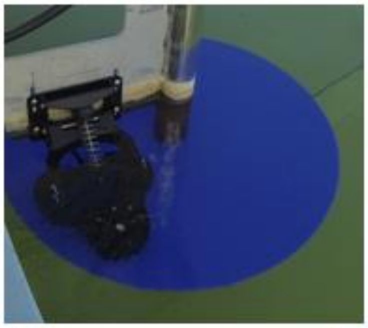
2/25/14
0 cycles

3/17/14
8,400 cycles

3/12/14
4,200 cycles

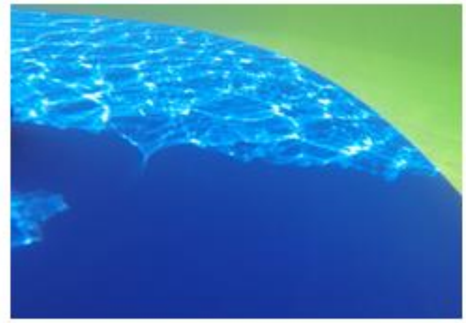
4/18/14:
172,260 cycles

The following pictures illustrate the degree of wear on the paint system after several hundred cycles of brush passage.



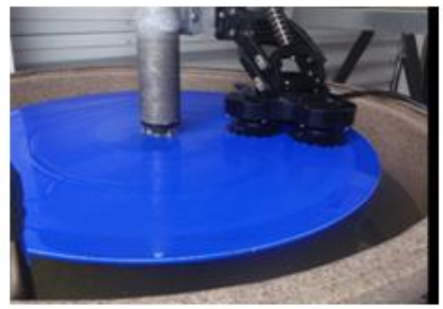
2/25/14
0 cycles

3/17/14
8,400 cycles



3/12/14
4,200 cycles

4/18/14
172,260 cycles



The following tests were performed with the apparatus:

- Test 1 West Marine bottom paint disk cycles -- 60,522
- Test 2 International, Intersleek 900 disk cycles – 172,260
- Total disk cycles run on 3 head GT – 232,782
- Travel distance per revolution = Mean disk dia x π = 400 mm x 3.14 = 1.25 m
- Travel distance to date = 232,782 x 1.25 = 291 km
- Cleaning width of one cleaning assembly, three 3 headed tools = 580 mm
- Area cleaned with 9 headed tool and equivalent travel distance = 291 km x .58 m = 168,780 m^2
- Wetted area of Arleigh Burke class destroyer DDG-51 -- 3001 m^2
- Equivalent destroyers cleaned 168,780/3001 = 56

A summary of the testing follows:

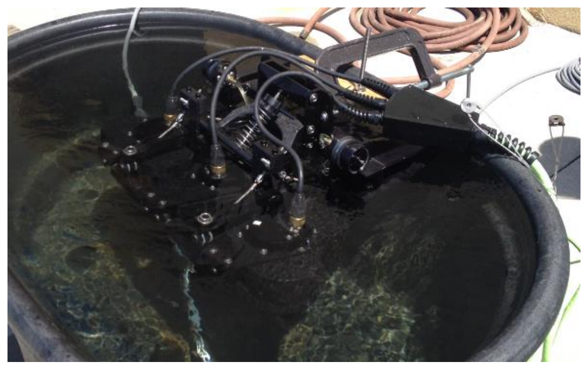
- 30” steel disk
- International, Intersleek 900
- Disk 11 RPM
- Equivalent travel speed 30 cm/s
- Bristle .010 dia polypropylene bristle
- Brush 350 RPM

- Total Hours Run—261 to date
- Total disk cycles run—172,260 to date
- Equivalent median travel miles—177 to date

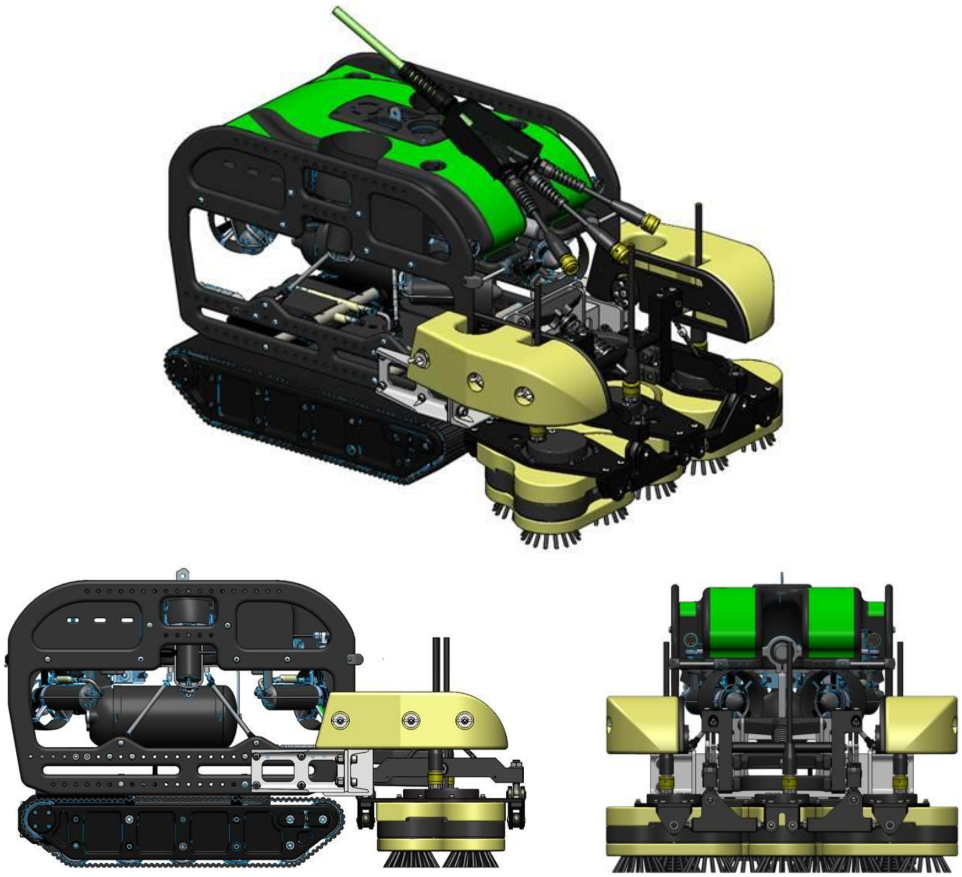
Equivalent paint life cycles at 2 grooming passes per week—1656 years

3.1.10 Nine Head Tool

After completion of the 3 headed tool design, fabrication and testing effort the Navy engaged FIT and authorized SRC to build a 9 headed tool that would mount on a FIT supplied vehicle. The 9 headed tool consisted of three, 3 headed tools arranged, side by side, in a fashion that met FIT's requirement of head to head center distance.



FIT Grooming Tool and In-water Testing



FIT Grooming Tool Mounted on FIT Vehicle

3.2 Flow Sensor

At the beginning of HullBUG research a preliminary study was performed that identified various water flows, inflows and outflows, from the hull as an issue depending on how large a hole and how high the velocity. Relative to HullBug, driving over a sizeable hole, appeared to be problematic in any case, flow or no flow. The Negative Pressure Attraction Device (NPAD) is used to hold the vehicle onto the hull. When the HullBUG runs over a large depression or hole the load on the motor increases and attraction force drops precipitously. Identifying the hole, seeing it in some way, and navigating around it became the project's focus. Further development of the flow sensor and related navigating techniques was put on hold until a reliable method was determined to identify these hazards prior to running over them. The MARS sensor development was continued in the hope that some variation of it would solve this difficult problem.

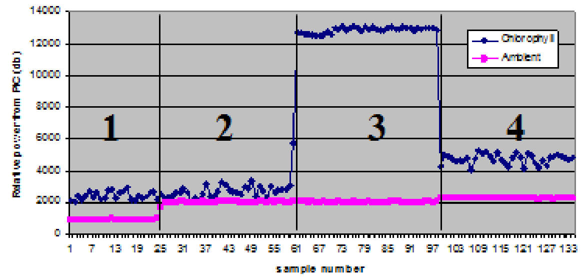
3.3 Biofilm Detector

The SRC biofilm detector was compared against several COTS single channel units including:

- Seapoint, volume, single channel, 2.5"dia x 6.6"long, 10Hz data rate
- Turner Designs, volume, single channel, 1.25"dia x 5.7"long
- Wet Labs WETStar, pumped system

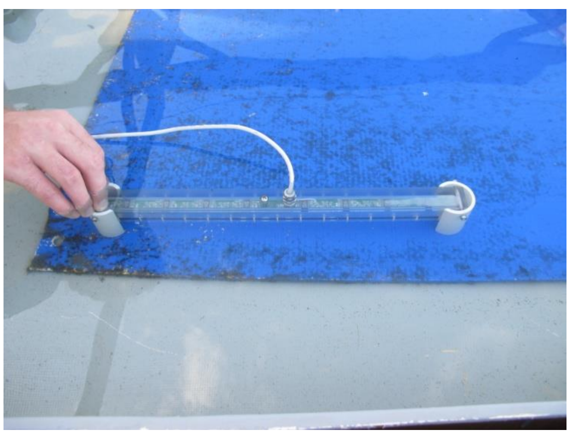
- Wet Labs ECO, single channel, 2.5"dia x 5" long, 8Hz data rate

The 8 channel SRC unit was the only multichannel unit at the time of evaluation, and allowed the ability to design the system into a bumper of other required appendage.

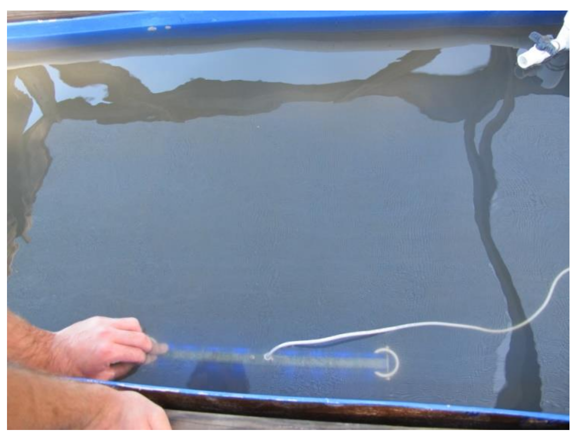


Work was begun on an extended biofilm detector test plan to be incorporated with the routine panel testing performed by FIT personnel.

- Tests were conducted at the FIT test site
- Panels used were taken from the lagoon
- Results clearly show that the biofilm can be measured with the BFD on Silicone
- Results on epoxy paint are not conclusive
- Further testing on Copper based paint is needed
- Further testing on biofilm layers formed in low light conditions such as found on the bottom of a ship is needed.



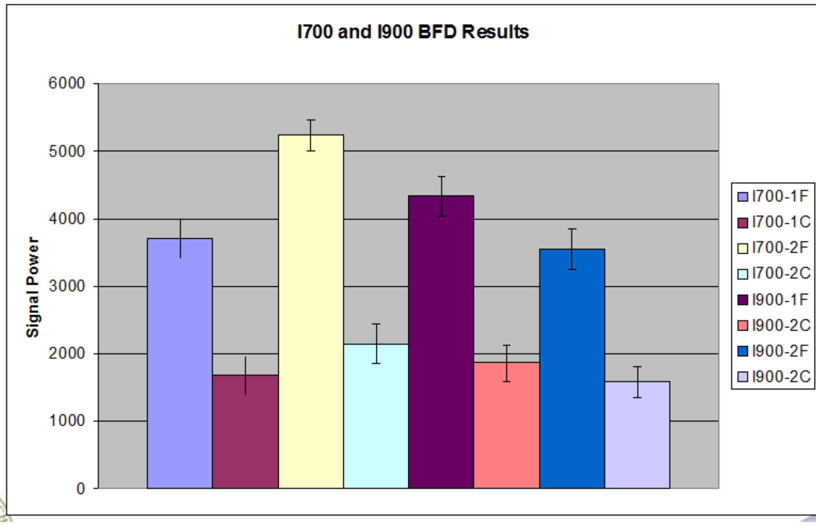
Clear Water Testing



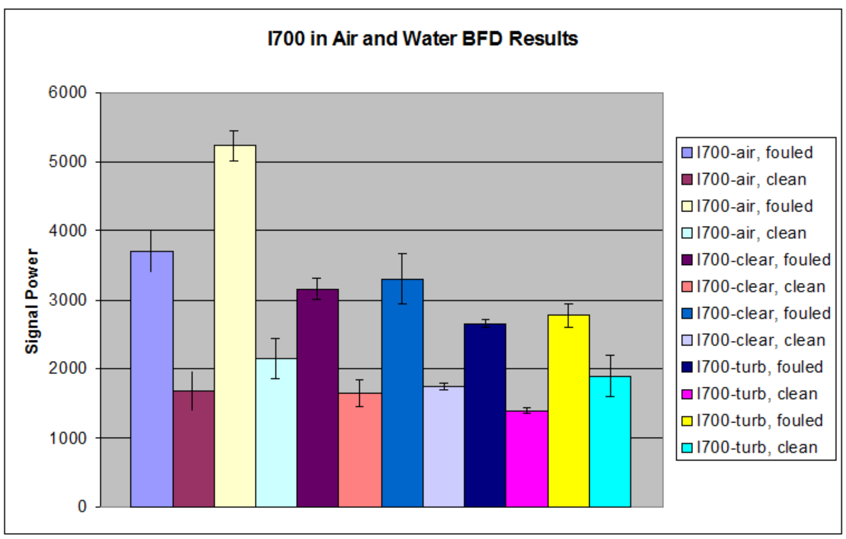
Turbid Water Testing

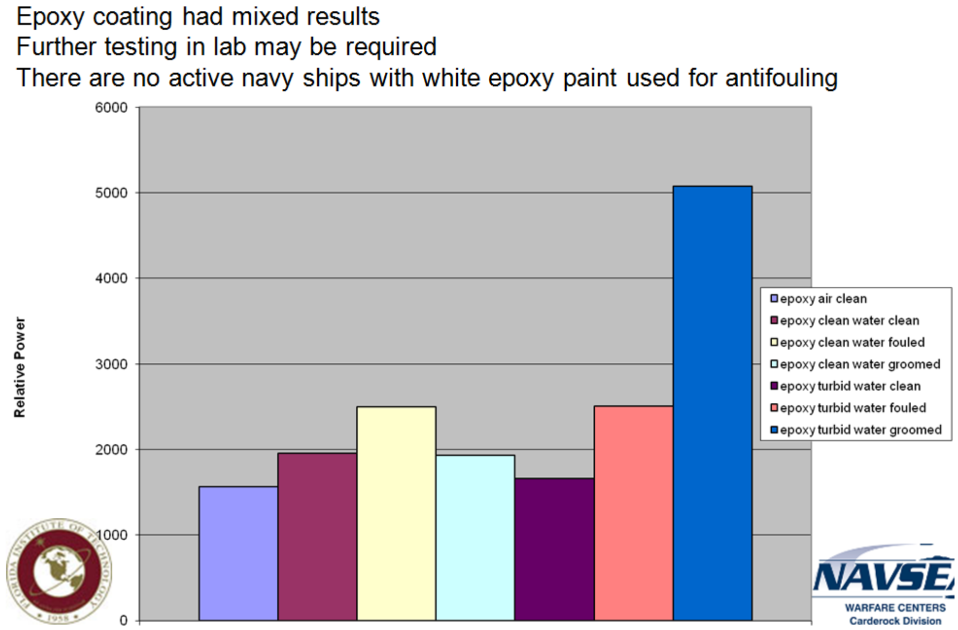
3.3.1 Biofilm Detector Data

Results from I700 & I900 silicone based antifouling coatings in air
(F is fouled and C is cleaned)



Results from I700 silicone based antifouling coatings in air, clean water and turbid water





3.4 *Range Finder*

An analysis of common obstacles completed on the prior contract was used to improve the obstacle avoidance capabilities of the HullBUG system. Simple simulation of the obstacle avoidance behavior was performed and limited in water testing was performed.

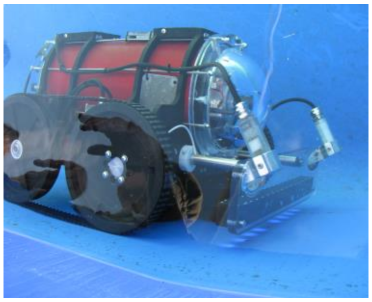
Various obstacle avoidance sensors were reviewed with some tested in a controlled setting. Including:

TRITECH PA500	IMAGENEX 863 Altimeter
TRITECH Micron Altimeter	KONGSBERG MS1007
TRITECH Micron Scanning Sensor	SeaRobotics MARS

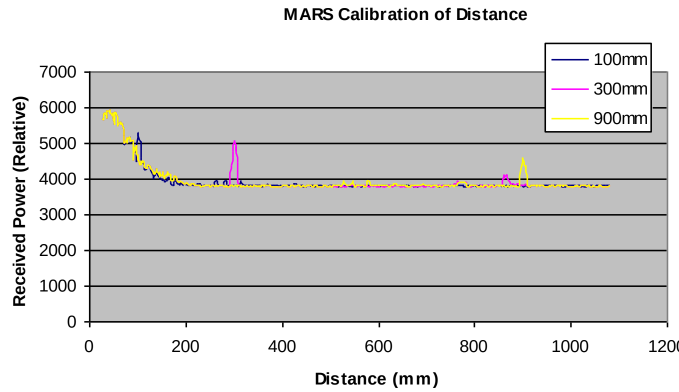
The Micro Acoustic Range System (MARS) was selected for further development and testing due to its small size, shape, power and minimum range considerations. The system worked well with limited precision for gross obstacle detection.

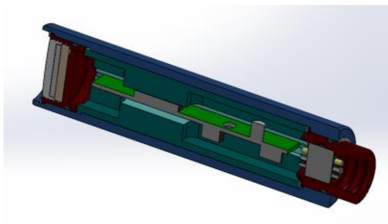
Scanning sonars were also evaluated with the Imagenex 881 and the BlueView MB2250 compared against a scanning version of the MARS sensor. The high cost of the COTS sensors as well as the size and lake of acceptable minimum range performance led to the initial development of the scanning MARS sensor. Intial testing proved promising and further development of this device is warranted. Results of some of this testing is shown below.

Various single beam echo sounders, scanning echosounders, and multi beam rangers were evaluated as well as laser scanning solutions. Unfortunately, none of the COTS systems performed well in the range/resolution/speed of response/cost trade-offs.



HullBug with MARS sensors

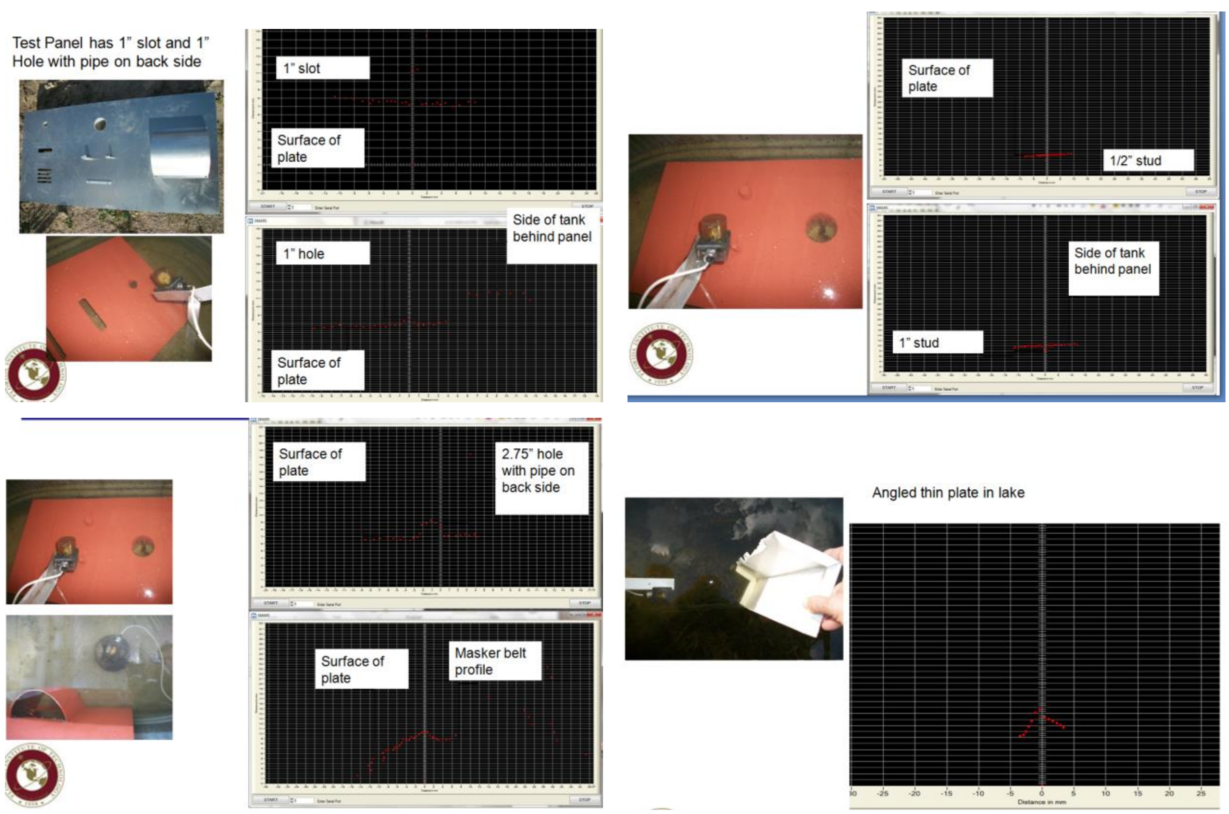




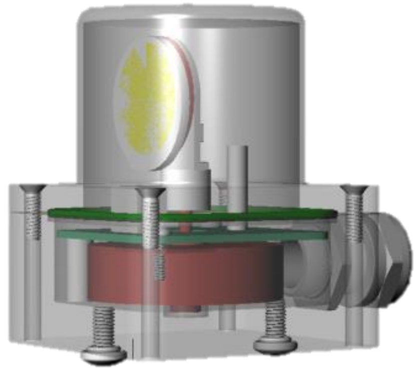
Improved MARS Sensor

MARS Sensor Assy

3.4.1 Scanning MARS Data



Scanning MARS Data



Scanning MARS Sensor

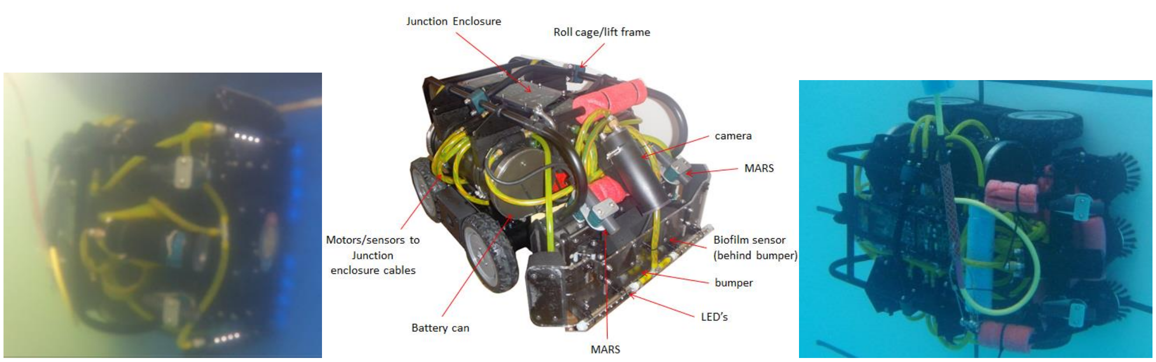
3.5 Navigation

During the contract a strategy was developed for surfaces with a slope greater than 15 degrees and for those greater than 15 degrees. The vehicle control algorithm was modified to automatically switch modes using hysteresis when this slope transition occurs. The algorithm relies more heavily on accelerometers at greater slopes and on an integrated rate gyro at shallow slopes.

Obstacles avoidance challenges increased with testing. Dry dock blocking areas on the lower hull with heavy encrustation as well as challenging surface coating inconsistencies were found.

Difficulties using the integrated gyro were evaluated and an improved performance gyro was integrated. This approach led to the integration of the Fiber Optic Gyro (FOG) on the vehicle built for FIT.

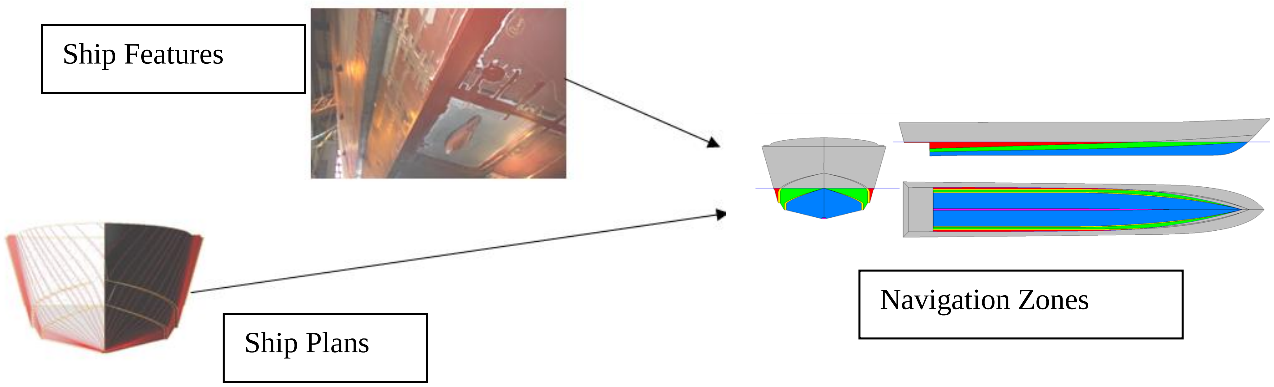
HullBUG



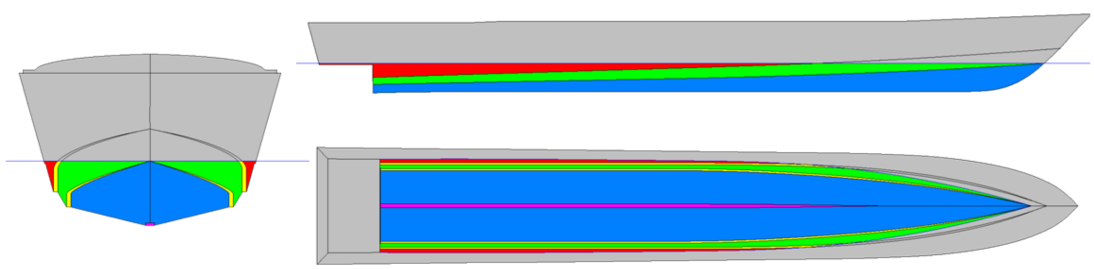
FIT Vehicle

3.5.1 Ship Specific Navigation Issues

Successful and efficient navigation is highly dependent on the type of ship being navigated on and any mission planning that is done prior to the operation. In conjunction with an SBIR funded contract SRC evaluated two different vessels and identified features to avoid and specific zones that would require a navigation strategy specific to that area. Information about the ship is best obtained from dry dock survey and original ship plans.



- Zone 1 (Red) vertical sides above top step to waterline
- Zone 2 (Green) nearly vertical side between lower step, upper step and waterline
- Zone 3 (Blue) Bottom of ship not including keel plate
- Zone 4 (Magenta) Keel plate
- Zone 5 (Yellow) Narrow steps on side of hull, 2 on each side



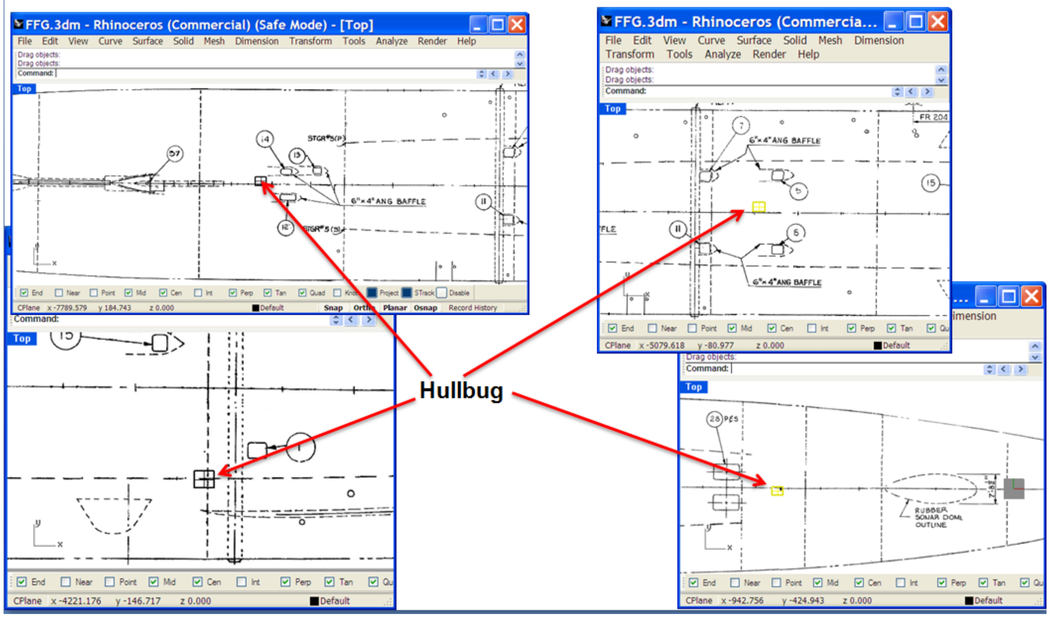
From the zones identified above a strategy for navigating would be developed. For example in Zone 1:

- (Red) vertical sides above top step to waterline (port and starboard)
- Navigate using depth control mode in parallel paths
- Gravity vector control mode for vertical transits to next parallel path
- Bounded by waterline (top), step in hull (bottom), stern
- MARS sensor detects boundaries
- No hull features of concern

3.5.2 Feature Navigation Issues

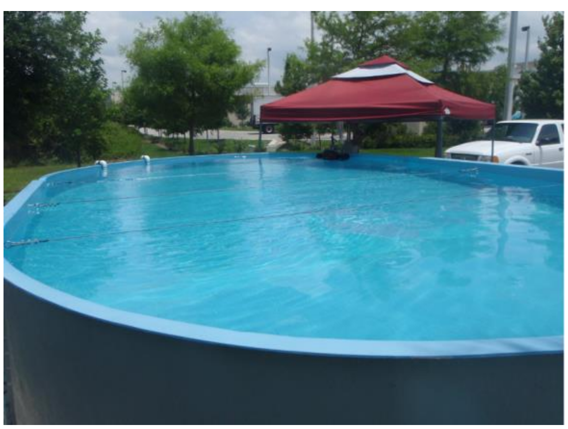
Navigating around the many features found on a military ship will provide challenge in addition to the ship hull itself. Allowable clearance is needed to navigate around obstacles.

- Vehicle must be less than ½ gap width for trouble free grooming



3.6 Vehicle Development

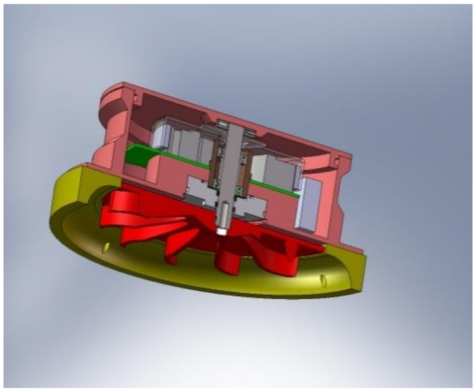
During the contract the vehicle subsystems and the vehicle platform were run in the SRC test tank for endurance and MTBF evaluation. The circular tank was utilized to run these tests on the oval “race track” to allow hours of uninterrupted testing. HullBug could be run in an autonomous mode with now connection to the surface. It could also be run with a Wi-Fi float antenna allowing uninterrupted travel with continuously available control link to the vehicle.

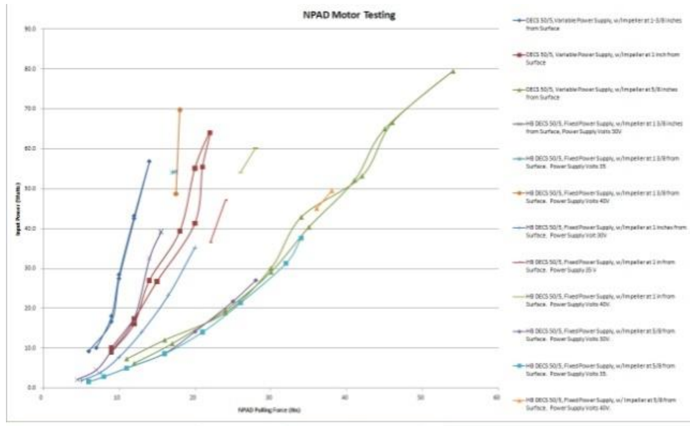


Leak detectors, humidity sensing, general health sensing, GFD and various sensors were added to the system. The MARS sensor was integrated for wall and cliff type obstacle detection. The biofilm detector was integrated and a demonstration of line following performed at the FIT test facility. Various bumper arrangements from flex detection bumpers to mechanically sensed bumpers were evaluated.

Numerous tests were performed during the preliminary design, bench testing and integration phases leading up to integrated system testing.

3.6.1 *NPAD Design*





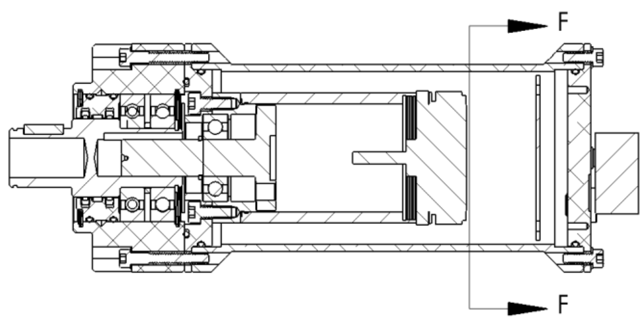
NPAD Cross Section NPAD Performance

The negative pressure attraction device was evaluated for reliability and heat transfer issues with a redesign to improve the MFBF and increase the attraction as rated by lbf/watt vs. gap distance. Increased motor power was realized with a lower speed/higher torque motor, and improved seals were designed into the housing.

3.6.2 *Drive System*

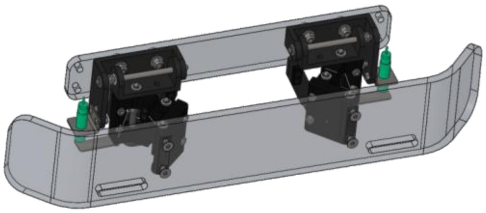
The drive housing for the tracks/wheels was redesigned with an circular aluminum cross section to improve seal performance and decrease leakage due to the prior material selection.

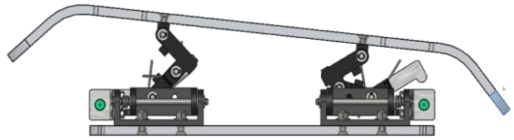
Belt and wheel variations were preformed to evaluate coefficient of friction enhancement predictions suggested by FIT parametric materials analysis.



3.6.3 *Bumper Design*

As part of a related SBIR program a multi axis bumper was designed to detect obstacles encountered at diffent angles. The bumper could detect obstacles from the front, from the left and right sides. This bumper was later included in a grooming test bed vehicle specifically built for Florida Institute of Technology.





3.6.4 *FIT Vehicle Development*

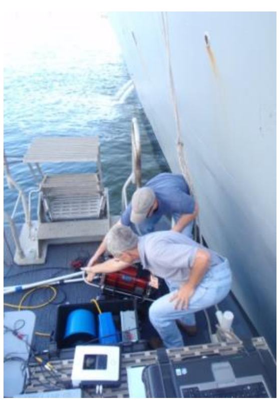
During the contract the FIT Harbor Test Facility was conceptualized along with the vehicle that was planned for use at that facility.

FIT Test Vehicle

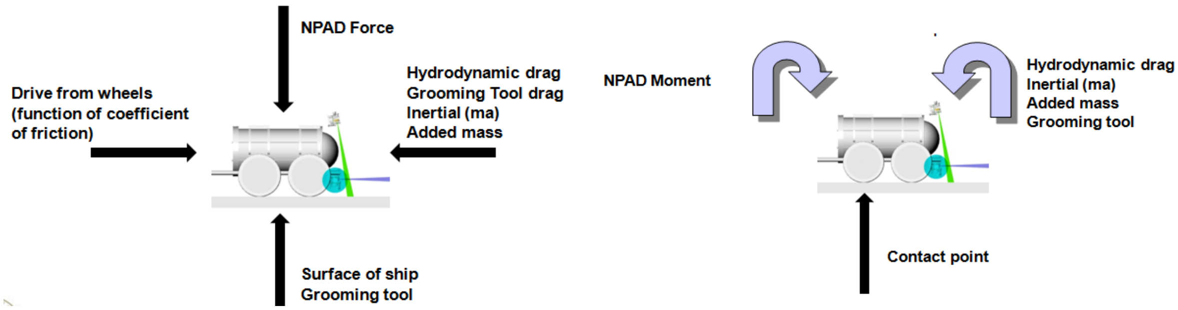
3.7 Operations

Successful operation of the HullBUG system on the sailing vessel Adele was performed in Key West. The demonstration was invaluable in assessing performance of the system on light fouling present on a properly maintained AF coating.

Various “Ships of Opportunity” were identified for potential in water testing of the HullBUG system. These ships included several museum ships, container ships, and naval vessels such as FFGs and DDGs in the Jacksonville area.



Operations on the FFGs funded by an SBIR award and using the HullBUG prototype encountered numerous issues and added to a list of lessons learned. Issues ranged from the manipulation/avoidance of the oil boom, to greater than anticipated fouling, NPAD and grooming tool height synchronization, as well as operation from the support dive boat and its proximity to the oil boom. Important insight were realized through the brief testing sessions afforded in conjunction with the SBIR contract regarding attachment force, sensitivity to CB-CB locations of the submerged body.



Results of testing suggested improvements could be made using a 4 wheel drive approach vs. the track system which was tested on the FFG hull.

3.7.1 *Logistics*

Handling of the vehicle, launch and recovery are significant issues that need to be addressed. In the autonomous mode the vehicle operates independently from the operators. When tethered it can operate autonomously or under direct operator control. The tether provides a high bandwidth real time data link to the vehicle which allows the operator to view video images of vehicle progress and to monitor navigation points and system health during the mission execution. If many situations the tether becomes a logistical problem wrapping itself around dock fenders, oil booms or obstructions on ship. An alternative to that mode of operation is to operate with a relatively short floating buoy that allows a high bandwidth RF link to be established with the HullBUG. This mode of operation reduces tether drag and the possibility of entanglement. High speed communication is still available and the relative location of the vehicle is maintained by keeping track of the buoy. To give the vehicle maximum flexibility to operate it can operate tether free, in a fully autonomous mode. In any of the operating modes the logistics of getting the vehicle in and out of the water, and possibly continuous handling of the tether must be considered.

3.7.2 *Operating Support*

The following steps outline typical operation of the HullBUG system:

1. Assign two sailors the following tasks, vehicle operator, RHIB operator/tether manager
2. Secure a RHIB for transporting vehicle to waterline location
3. Vehicle and OIS should be unpacked, tether connected, and powered up either on the pier or on the deck of the ship
4. Operator to run through checklist
5. Vehicle runs through automated power-up system checkout and issues a report
6. Operator chooses mission using OIS menu
7. Vehicle is placed into RHIB and driven over to launch position at waterline

8. Vehicle is placed onto side of ship
9. RHIB is recovered
10. Vehicle conducts in water automated system checkout and issues report and green light to go
11. Operator starts mission
12. Operator monitors sensor(s) of interest
13. Tether manager deploys/recovers tether as required
14. Operator pauses mission as needed, investigates items of interest
15. At end of mission vehicle drives or is driven to waterline for recovery
16. RHIB recovers vehicle
17. Mission data files are downloaded from vehicle
18. Mission report is created using post mission report routine within OIS
19. Vehicle is washed down and battery charged
20. Vehicle systems are put away

3.7.3 Lost Vehicle Location and Recovery

When operating autonomously the possibility exists that the HullBug vehicle can become detached from the ship hull. Since it is essentially a neutral vehicle it may drift with the current and be lost. Techniques are available to anchor the drifting vehicle, to locate and then recover it. The following sections detail some equipment that can be used in this effort.

- Acoustic locating beacon activated by loss of power
- Droppable anchor (option) activated by loss of power or by command. Vehicle could float to the surface and anchor could embed itself into the harbor bottom preventing the vehicle from floating away.
- Strobe light which would always be on during a mission.
- Radio emergency beacon activated by loss of power or by command
- Acoustic directional receiver (option) to find lost vehicle

Example Vehicle Location and Recovery Equipment