Development and evaluation of the *Stingray*, an amphibious maritime interdiction operations unmanned ground vehicle

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ABSTRACT

The U.S. Navy and Marine Corps conduct thousands of Maritime Interdiction Operations (MIOs) every year around the globe. Navy Visit, Board, Search, and Seizure (VBSS) teams regularly board suspect ships and perform search operations, often in hostile environments. There is a need for a small tactical robot that can be deployed ahead of the team to provide enhanced situational awareness in these boarding, breaching, and clearing operations. In 2011, the Space and Naval Warfare Systems Center Pacific conducted user evaluations on a number of small throwable robots and sensors, verified the requirements, and developed the key performance parameters (KPPs) for an MIO robot. Macro USA Corporation was then tasked to design and develop two prototype systems, each consisting of one control/display unit and two small amphibious *Stingray* robots. Technical challenges included the combination paddle wheel/shock-absorbing wheel, the tradeoff between impact resistance, size, and buoyancy, and achieving adequate traction on wet surfaces. This paper describes the technical design of these robots and the results of subsequent user evaluations by VBSS teams.

Keywords: MIO, VBSS, maritime interdiction, throwable robot, micro UGV, boarding, search, seizure

1. INTRODUCTION

Every year the U.S. Navy and Marine Corps conduct thousands of Maritime Interdiction Operations worldwide to enforce embargoes, intercept contrabands, prevent drug and human smuggling, and fight piracy. These operations are usually conducted by Visit, Board, Search, and Seizure (VBSS) teams using rigid-hull inflatable boats (RHIBs) or helicopters, often operating miles from the base ship. Through interviews, demonstrations, and tests conducted with VBSS teams and trainers, SPAWAR Systems Center Pacific (SSC Pacific) developed the key performance parameters for a portable, throwable robot that can best support their missions.[1] This robot can be used for advanced reconnaissance as the team is about to board a target vessel, to assist in compartment clearing, and for inspection of flooded compartments and bilges. Subsequent user tests and demonstrations have revealed that its applicability is much wider than originally thought. The same characteristics critical to VBSS operations also make the system a useful tool for land-based tactical operations, especially for missions involving streams and culverts.

2. REQUIREMENTS

Design guidelines for a VBSS tactical robot, determined through user tests using comparable robotic assets,[1] include:

- Size and weight: The robot should fit in a Modular Lightweight Load-carrying Equipment (MOLLE) pouch and weigh approximately 1.5 Kg.
- Ground mobility: The robot should be able to negotiate over normal deck obstacles such as ropes, cables, and anchor chains (3.75 to 5 cm tall), while not getting stuck on ship deck grating.
- Stability and traction: The robot should have enough traction to remain in place on oil and dirt contaminated ship deck, and be stable in all but the worst sea state.
- Ruggedness: The robot should survive a drop of 5 m or more onto a steel deck.

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14. ABSTRACT

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15. SUBJECT TERMS

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- Waterproof: At a minimum, the operator control/display unit (OCU) should be splash proof (IP64), while the robot should be waterproof to 1 m depth (IP67).
- Mobility in water: The robot should be able to cross flooded spaces, to allow inspection of flooded compartments.
- Sensors: The robot's video should work in both daylight and near total darkness. There should be at least one-way audio from the robot to the operator, preferably two-way.
- Picatinny rail: The robot should have a Picatinny rail to allow attachment of other sensors.
- Physical extensions: The robot should be able to accommodate a telescopic extension pole and allow attachment of a rope, so that it can be used in places that make deployment or retrieval difficult.
- Strobe distracter: The robot should carry a remotely activated strobe distracter to draw the attention of hostile forces or temporarily blind their dark-adapted vision. With a different strobe frequency and duration, this strobe can also be used as a locating aid.
- Multi-robot systems: Each system should include one OCU and two robots. The second robot can act as a spare, or be selectable from the OCU when both are deployed. The robot not currently selected should be able to perform motion detection to provide rear-guard functions for the VBSS team.

3. TECHNICAL CHALLENGES

The design guidelines were converted to explicit performance thresholds and objectives that required considerable research and development to achieve compliance. Through the Robotics Technology Consortium, Macro USA was tasked with the development of two prototype systems, each consisting of an operator control unit (OCU) and two *Stingray* robots. The areas that were the most challenging in the design of these robots will be discussed here, to include:

1. Weight threshold
2. Maximum volumetric envelope
3. Flotation in seawater
4. Mobility in water
5. Traction on wet, oily surfaces
6. Impact resistance

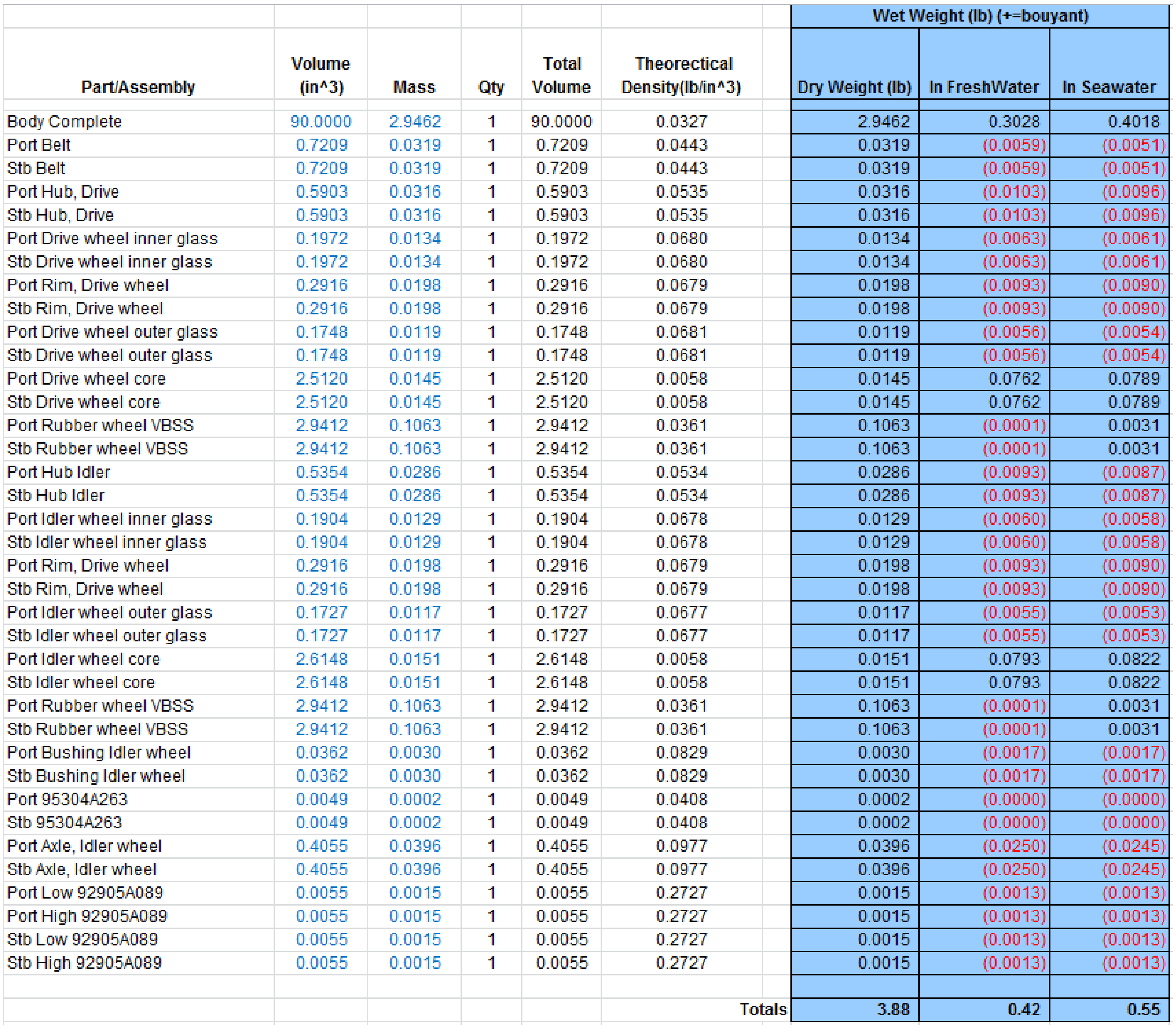
3.1 Weight threshold

The maximum weight ceiling of 1.8 Kg, when coupled to the other performance requirements, was a major challenge, especially due to the potentially conflicting requirements of low weight and density to achieve flotation versus high resilience and impact resistance to achieve the objective drop height of 10 m on a steel deck. As a result of these requirements, it was immediately clear that a simple modification of the existing Macro USA *Beetle* UGV chassis would not have been sufficient, and a full custom mechanical design was required. The choice of the materials, as well as the mechanical design itself, was of crucial importance and had to be carefully modeled and monitored in CAD software using finite element analysis (FEA) techniques to ensure that the weight limitations and ruggedness requirements were both met.

The resulting design was a woven carbon-fiber monolithic chassis coupled to aircraft-grade aluminum sides and hardware, woven carbon-fiber wheels and internal brackets, and closed-cell foam for flotation purposes. Titanium was initially considered for the metal components but not chosen due to the unnecessary extra costs and difficulty of machining associated with this material. FEA of the aluminum components of the *Beetle* showed that further strength was unnecessary.

An initial mass analysis/estimate performed using *SolidWorks*™ resulted in a total weight of 3.88 lbs (1.7 Kg), which was sufficiently low to allow for an acceptable factor of safety for potentially heavier-than-expected components in the actual prototype compared to the CAD model. Table 1 shows the initial mass analysis/estimates for *Stingray* components.

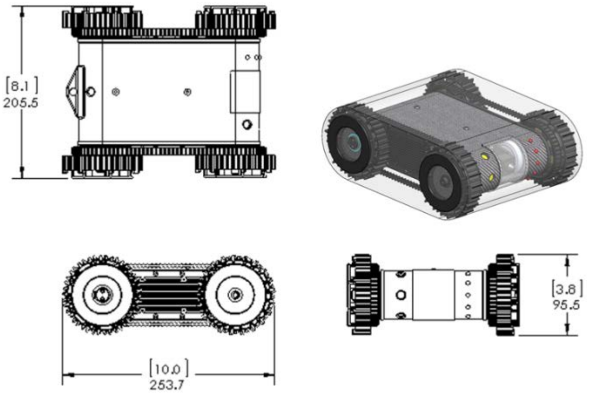
Table 1. Initial mass analysis/estimates for the Stingray UGV.



							Wet Weight (lb) (+=bouyant)		
Part/Assembly	Volume (in^3)	Mass	Qty	Total Volume	Theorectical Density(lb/in^3)		Dry Weight (lb)	In FreshWater	In Seawater
Body Complete	90.0000	2.9462	1	90.0000	0.0327		2.9462	0.3028	0.4018
Port Belt	0.7209	0.0319	1	0.7209	0.0443		0.0319	(0.0059)	(0.0051)
Stb Belt	0.7209	0.0319	1	0.7209	0.0443		0.0319	(0.0059)	(0.0051)
Port Hub, Drive	0.5903	0.0316	1	0.5903	0.0535		0.0316	(0.0103)	(0.0096)
Stb Hub, Drive	0.5903	0.0316	1	0.5903	0.0535		0.0316	(0.0103)	(0.0096)
Port Drive wheel inner glass	0.1972	0.0134	1	0.1972	0.0680		0.0134	(0.0063)	(0.0061)
Stb Drive wheel inner glass	0.1972	0.0134	1	0.1972	0.0680		0.0134	(0.0063)	(0.0061)
Port Rim, Drive wheel	0.2916	0.0198	1	0.2916	0.0679		0.0198	(0.0093)	(0.0090)
Stb Rim, Drive wheel	0.2916	0.0198	1	0.2916	0.0679		0.0198	(0.0093)	(0.0090)
Port Drive wheel outer glass	0.1748	0.0119	1	0.1748	0.0681		0.0119	(0.0056)	(0.0054)
Stb Drive wheel outer glass	0.1748	0.0119	1	0.1748	0.0681		0.0119	(0.0056)	(0.0054)
Port Drive wheel core	2.5120	0.0145	1	2.5120	0.0058		0.0145	0.0762	0.0789
Stb Drive wheel core	2.5120	0.0145	1	2.5120	0.0058		0.0145	0.0762	0.0789
Port Rubber wheel VBSS	2.9412	0.1063	1	2.9412	0.0361		0.1063	(0.0001)	0.0031
Stb Rubber wheel VBSS	2.9412	0.1063	1	2.9412	0.0361		0.1063	(0.0001)	0.0031
Port Hub Idler	0.5354	0.0286	1	0.5354	0.0534		0.0286	(0.0093)	(0.0087)
Stb Hub Idler	0.5354	0.0286	1	0.5354	0.0534		0.0286	(0.0093)	(0.0087)
Port Idler wheel inner glass	0.1904	0.0129	1	0.1904	0.0678		0.0129	(0.0060)	(0.0058)
Stb Idler wheel inner glass	0.1904	0.0129	1	0.1904	0.0678		0.0129	(0.0060)	(0.0058)
Port Rim, Drive wheel	0.2916	0.0198	1	0.2916	0.0679		0.0198	(0.0093)	(0.0090)
Stb Rim, Drive wheel	0.2916	0.0198	1	0.2916	0.0679		0.0198	(0.0093)	(0.0090)
Port Idler wheel outer glass	0.1727	0.0117	1	0.1727	0.0677		0.0117	(0.0055)	(0.0053)
Stb Idler wheel outer glass	0.1727	0.0117	1	0.1727	0.0677		0.0117	(0.0055)	(0.0053)
Port Idler wheel core	2.6148	0.0151	1	2.6148	0.0058		0.0151	0.0793	0.0822
Stb Idler wheel core	2.6148	0.0151	1	2.6148	0.0058		0.0151	0.0793	0.0822
Port Rubber wheel VBSS	2.9412	0.1063	1	2.9412	0.0361		0.1063	(0.0001)	0.0031
Stb Rubber wheel VBSS	2.9412	0.1063	1	2.9412	0.0361		0.1063	(0.0001)	0.0031
Port Bushing Idler wheel	0.0362	0.0030	1	0.0362	0.0829		0.0030	(0.0017)	(0.0017)
Stb Bushing Idler wheel	0.0362	0.0030	1	0.0362	0.0829		0.0030	(0.0017)	(0.0017)
Port 95304A263	0.0049	0.0002	1	0.0049	0.0408		0.0002	(0.0000)	(0.0000)
Stb 95304A263	0.0049	0.0002	1	0.0049	0.0408		0.0002	(0.0000)	(0.0000)
Port Axle, Idler wheel	0.4055	0.0396	1	0.4055	0.0977		0.0396	(0.0250)	(0.0245)
Stb Axle, Idler wheel	0.4055	0.0396	1	0.4055	0.0977		0.0396	(0.0250)	(0.0245)
Port Low 92905A089	0.0055	0.0015	1	0.0055	0.2727		0.0015	(0.0013)	(0.0013)
Port High 92905A089	0.0055	0.0015	1	0.0055	0.2727		0.0015	(0.0013)	(0.0013)
Stb Low 92905A089	0.0055	0.0015	1	0.0055	0.2727		0.0015	(0.0013)	(0.0013)
Stb High 92905A089	0.0055	0.0015	1	0.0055	0.2727		0.0015	(0.0013)	(0.0013)
						Totals	3.88	0.42	0.55

3.2 Maximum volumetric envelope

The 4500-cm^3 maximum volumetric envelope for the *Stingray* was determined by the requirement to fit in a MOLLE pouch. It had repercussions in terms of the wheelbase, width, and wheel diameter for the UGV, given that the wheels are the most prominent physical features of the robot. For practical purposes, the wheel diameter was dictated by the requirement to be able to cross a 5-cm-tall obstacle (i.e. the wheel diameter had to be approximately 10 cm to allow the wheel to climb over the 5-cm obstacle) and the width was mandated by the dimensions of the largest non-modifiable electronic component, which was the battery pack (and in short order, the radio-communication-modules assembly). As a result, the only free dimension was the overall length, which was set at 10 inches to provide an adequate amount of air inside the sealed UGV chassis for flotation, as well as providing extra stability and better obstacle-climbing capabilities. The final overall dimensions are shown in Figure 1.



Length: 253.9 mm (10.00 in)
Width: 205.5 mm (8.1 in)
Height: 95.5 mm (3.8 in)
Volume: 4492 cm^3
Threshold Volume: 4500 cm^3

Figure 1. Volumetric envelope for the *Stingray* UGV.

3.3 Flotation in seawater

The *Stingray* had to be capable of floating when immersed in seawater, both for recovery options as well as for operational reasons (capability of crossing standing water). At the initial kick-off meeting, these two requirements weren’t fully delineated and possibilities of including active flotation devices such as *Key Buoy*™ and *Water Buoy*™ systems were considered as viable candidates, with *Water Buoy*™ being selected as a possible solution (the *Key Buoy*™ didn’t have enough flotation volume and relied on a sponge expansion reaction that wasn’t seen as suitable for the kind of use the *Stingray* required). After the kick-off meeting, however, the active buoyancy-deployment-system idea was discarded, primarily due to the fact that it would have been impractical to develop a system that could discriminate between the desired water fording activities (driving on the floor of the flooded space) and the undesired fall into the sea during deployment event. (No reliable and practical solution was found that would allow the emergency buoyancy to activate in the latter case only.) Therefore, a passive, positively buoyant robot design was selected to accomplish both objectives. Instead of driving on the floor of a flooded space, the robot became a hybrid vehicle that can drive on the water surface as well as on land.

In order to achieve the desired results, the design team used a two-pronged approach where the UGV itself would be as buoyant as possible, through the integration of custom-design floats in the wheels and the maximization of the internal volume of the UGV chassis (without sacrificing ground clearance), coupled with the custom development of a high-visibility *Sling Flotation Device* (*SFD*) that would be wrapped around the UGV when an in-water operating environment was expected, but would not impede ground operation. The *SFD* would be similar to a personal flotation device in color (fluorescent yellow) and material (closed-cell foam), with openings to accommodate the camera and the multipurpose high-intensity LEDs. Figure 2 shows the *Stingray* with the *SFD*.

Figure 2. A *Stingray* prototype wearing a *Sling Flotation Device*.

Initial calculations showed that the system would have a density of 0.85 in saltwater (see Figure 3), yielding a positive buoyancy of approximately 15% (in reality, the final value from the prototypes was in excess of 20%). This value might seem relatively low for the purposes of teleoperated amphibious navigation using the driving camera alone, but is actually sufficient since the front of the UVG will lift upwards and allow for an unimpeded view for the operator due to the forward thrust of the paddle wheels.

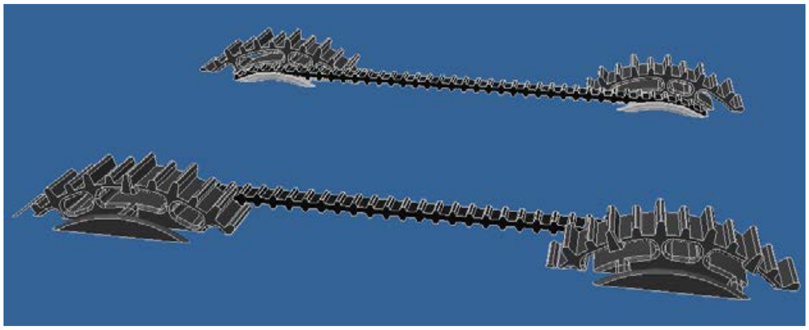


Figure 3. Initial flotation calculations for the *Stingray*.

3.4 Mobility in water

Once the UGV design had achieved the required goals of weight and buoyancy, the next challenge was to design a system that would be capable of mobility in the water. The original wheel design on Macro USA UGVs was a good starting point since the horizontal deep treads, initially designed mainly for traction and impact absorbance, had shown in prior testing the ability to perform as rudimentary paddle wheels.

The paddle wheel has existed as a marine propulsion system for over 200 years, yet there has been little development over the last 100 years. As a result of this, it was very difficult to find published guidelines and formulas to assist an engineering team in designing a new paddlewheel propulsion system from scratch. The team had to embark on archival research to find relevant text books and engineering manuals,[2-10] some dating back to the late 1830s, that would provide the required information, specifically with reference to efficiency, slip factor, and hull velocity. Nevertheless, a few assumptions and estimates had to be made in order to determine the feasibility of this approach (nominally the fact that part of the traction was from ducted paddles on the side of the wheel and some from body-belt teeth and wheel features that were unducted).

The first calculation was the overall propulsion area for the paddles, which derived from the outer tread and the ducted paddles (belt teeth were considered negligible).

The tread propulsion area was calculated using the original Macro USA *Beetle* UGV tread design (later modified) as follows (see light blue areas in Figure 4):

- Deep treads (21): 1242 mm^2 area per wheel
- Shallow treads (21): 630 mm^2 per wheel

The total tread propulsion area (TPA) is therefore 1872 mm^2 per wheel.

Characteristics of the TPA are an overall shallowness, the fact that the paddles are close to each other, and unducted, all of which determined the following assumptions:

- Significant amount of turbulence expected due to shallowness and close proximity
- Overall efficiency estimated at 40%

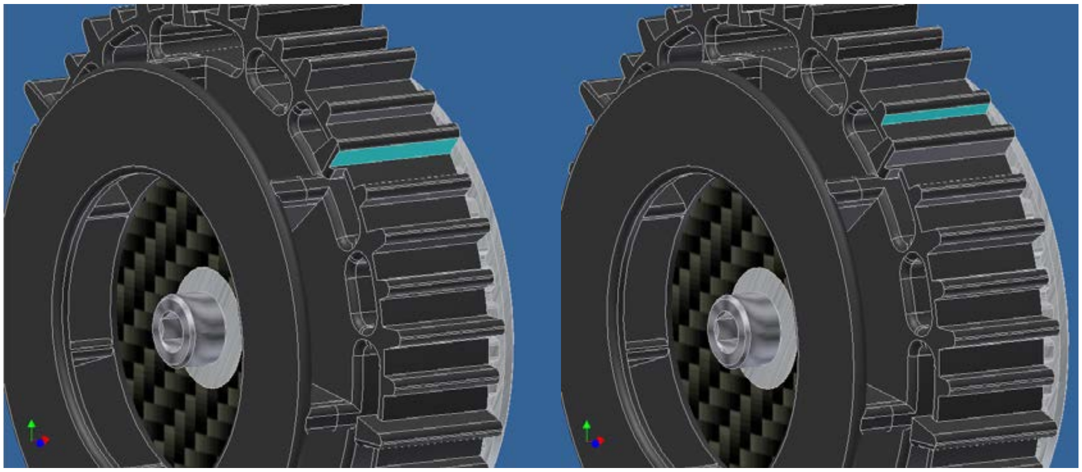


Figure 4. Tread propulsion areas (light blue): Deep treads (left) and shallow treads (right) for the *Stingray* UGV. (Note that the threads alternate between deep and shallow around the wheel circumference.)

Next, the ducted paddle propulsion area (DPPA) was calculated. The ducted paddles (7 for each wheel, see Figure 5) had an individual area of 114 mm^2 and a total area (per wheel) of 803 mm^2, characterized by significant depth, spacing that allows sufficient distance to reduce turbulence, and ducting for increased efficiency. As a result of these characteristics, the following performance assumptions were made:

- Reduced turbulence expected
- Overall efficiency estimated at 80% from published data on historic paddle wheels

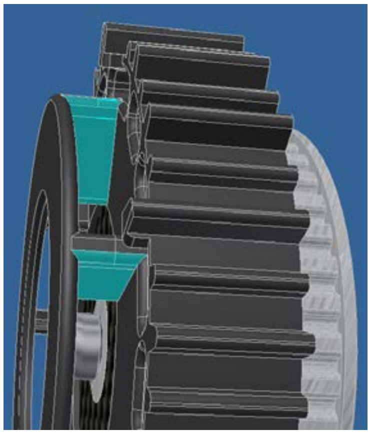


Figure 5. Ducted-paddle propulsion area (DPPA) for the *Stingray*.

Once the overall paddle area was calculated, the efficient wetted area was determined using the preliminary buoyancy calculation, which showed approximately a 14% volumetric emergence of Stingray from water (see Figure 6). Although suboptimal, this emergence allows for the horizontal component of the mass flow generated by the wheels to be effective (91 degrees of counter-rotating paddle are above water, Figure 6).

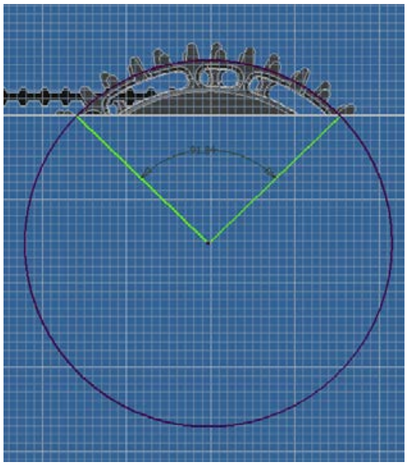


Figure 6. Paddlewheel emergence from water for the Stingray.

The amount of forward thrust generated by an individual paddle wheel is determined by the effective wetted area of the paddle wheel, based on the wheel emergence obtained from the buoyancy calculations. The portion of the paddle wheel above the centerline provides rearwards thrust while the portion below the centerline provides forwards thrust, with the net horizontal thrust being a function of the sine of the paddle angle (Figure 7). Maximum thrust would therefore be provided by a paddle immersed in water to the centerline and minimal thrust (which would be essentially zero) for a paddle completely immersed in water (discounting minute pressure differences due to water depth between the upper and lower halves of the paddle wheel).

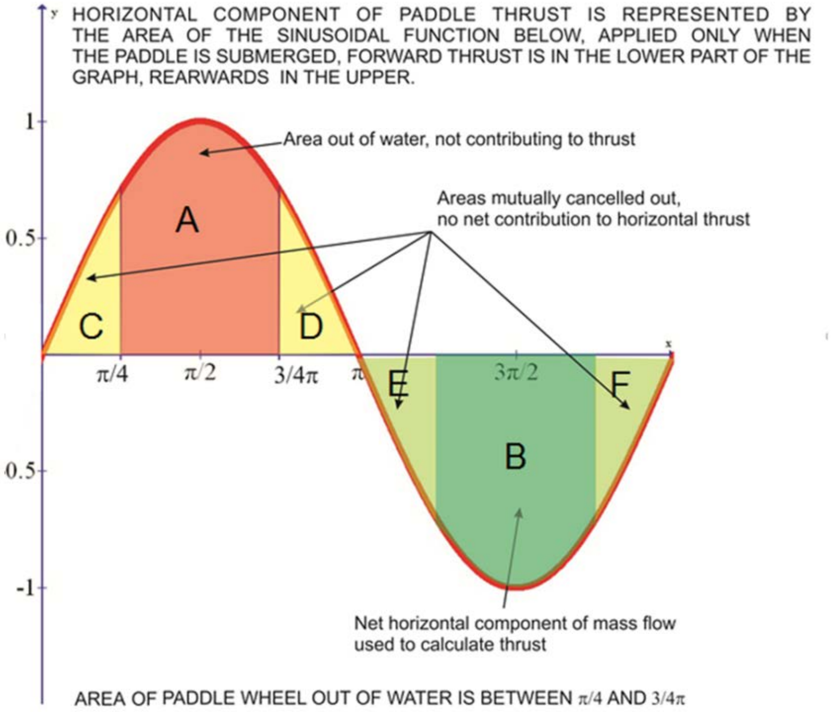


Figure 7. Paddle wheel effective wetted area graph.

To calculate the effective wetted area for the paddle wheels, the 91 degrees of emergence was simplified to $\pi/2$. The calculations for the integral of the net area of horizontal thrust are as follows:

$$A+C+D = \int_{0}^{\pi} \sin(x)\,dx = 2$$

$$A+C+D=-(E+B+F)$$

$$A = \int_{\pi/4}^{3/4\pi} \sin(x)\,dx = \sqrt{2}$$

$$C=-F,\ D=-E$$
$$C+D+E+F=0$$
$$B=-A.$$

The maximum horizontal mass flow with flotation at wheel hub is E+B+F=2 while the mass flow with flotation with 90 degrees of emerged wheel is $\frac{\sqrt{2}}{2}$, or 70.7% of theoretical maximum. Therefore the *Stingray* UGV paddle emergence was calculated as providing approximately 71% of the maximum possible thrust. This calculation results in a total of 626 mm^2 of efficient wetted area for one paddle at any given time (assuming 40% efficiency on unducted paddle area and 80% efficiency on ducted paddle area and applying a correction factor of $\frac{2}{\pi}$ to account for the rotational motion of the paddles in the water).

Once the effective wetted area was determined, the Mass Flow Thrust Equation was used to calculate the variable amount of thrust at different wheel speeds, assuming no difference in water pressure between entering water pressure and exiting water pressure.

$$F = \dot{m}V_e + (p_e - p_0)A_e$$

where: F is thrust
p_e-p_0 is considered null (no increase in pressure)
A_e is area of flow in m^2
Ve is exit velocity in m/sec
$\dot{m}$ is mass flow in kg/sec (Source: http://www.grc.nasa.gov/WWW/K-12/airplane/rktthsum.html)

Thrust was calculated at variable wheel speed between 1 RPM and maximum RPM, as shown in Table 2 below.

Table 2. Paddle wheels maximum thrust (single wheel).

Wheel RPM	**Mass flow (at maximum thrust and zero power)**		**Velocity (m/sec) (at tip of ducted paddle wheel)**	**Thrust**	
1	0.002441488	Kg/sec	0.003895575	9.511E-06	N
5	0.012207442	Kg/sec	0.019477874	0.000237775	N
10	0.024414884	Kg/sec	0.038955749	0.0009511	N
50	0.122074418	Kg/sec	0.194778745	0.023777502	N
100	0.244148836	Kg/sec	0.389557489	0.095110008	N
135	0.329600929	Kg/sec	0.52590261	0.173337989	N

Loss of thrust due to turbulence effects were not considered at this time except in the initial 40% and 80% efficiency assumptions for the paddles. The thrust values that were generated seemed relatively low, but based on initial testing and experience, considered sufficient to propel the *Stingray*.

To calculate the theoretical max speed for the *Stingray* in water, two factors were considered; the RPM of the wheel and tip diameter of the ducted fan, together with the typical values of slip (% of speed loss between paddle speed and vessel speed) that are found in literature for paddlewheel propulsion, as shown in Table 3 below.

Table 3. Paddle wheels maximum theoretical speed.

Maximum theoretical speed (using diameter of ducted paddle at 135 RPM):	**0.526**	**m/sec**	**1.89**	**Km/h**
Typical paddlewheel slip factor:	**34%**	**from multiple sources**		
Adjusted theoretical maximum speed:	**0.347**	**m/sec**	**1.25**	**Km/h**
NOTE: NO ADJUSTMENTS FOR HYDRODYNAMIC EFFECTS OTHER THAN SLIP HAVE BEEN APPLIED				

After obtaining the theoretical top speed, we calculated the theoretical hull speed, v_{hull}, to compare with the calculated theoretical maximum speed (if the hull speed is lower than the theoretical maximum speed, the Stingray could become a planing vessel— see Table 4) using the following hull-velocity formula:

$$v_{hull} \approx 1.34 \times \sqrt{LWL}$$

Table 4. Hull speed for the Stingray UGV.

Theoretical hull speed for Stingray:			
LWL = Length at waterline level	**0.832**	**feet**	**(measured from 3D model, excluding wheels)**
V_{hull} = Hull speed (displacement speed)	**1.22**	**knots**	**from formula**
V_{hull} in km/h	**2.26**	**Km/h**	
Adjusted theoretical maximum speed	**1.25**	**Km/h**	**from Table 3**

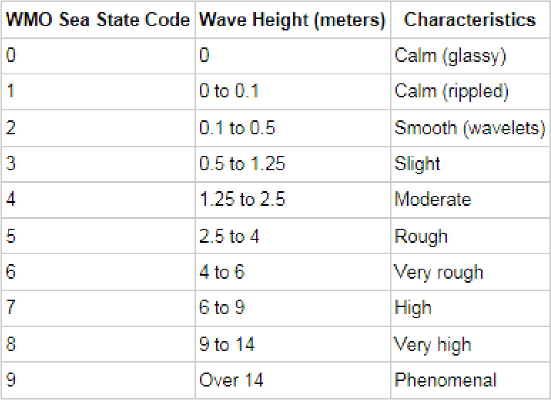
The calculated hull speed exceeds the adjusted theoretical maximum speed, thus avoiding planing possibilities. At these slow speeds, hydrodynamic drag effects were also assumed to be minimal.

3.5 Traction on wet, oily surfaces

The requirement for *Stingray* traction specified that the UGV should be able to achieve sufficient traction on wet, oily metal surfaces up to sea states 5 (see Table 5) on dhows (which are representative of the smallest vessels that are target of VBSS operations).

In order to be able to design and test to these specifications, the team members researched the possible effects of sea states 3 and 5 (threshold and objective levels) on vessels of the typical dimensions of dhows (estimated width of 30 feet) with the waves hitting the ships broadside (worst case for deck movement). The published literature[11] shows that those conditions would generate deck slopes of 5.5º for sea state 3 and 14º for sea state 5.

Table 5. Sea state and wave height.



WMO Sea State Code	Wave Height (meters)	Characteristics
0	0	Calm (glassy)
1	0 to 0.1	Calm (rippled)
2	0.1 to 0.5	Smooth (wavelets)
3	0.5 to 1.25	Slight
4	1.25 to 2.5	Moderate
5	2.5 to 4	Rough
6	4 to 6	Very rough
7	6 to 9	High
8	9 to 14	Very high
9	Over 14	Phenomenal

To determine the performance of the *Stingray* in the operational environment, a test rig was created (Figure 8) where a steel surface was left bare on one side and painted on the other (to simulate both scenarios) and wetted with oily water (to simulate conditions often found on ship deck). The rig was setup at a 30º slope to compensate for the fact that we are disregarding the deck’s angular velocity and acceleration, which are too difficult to realistically replicate.

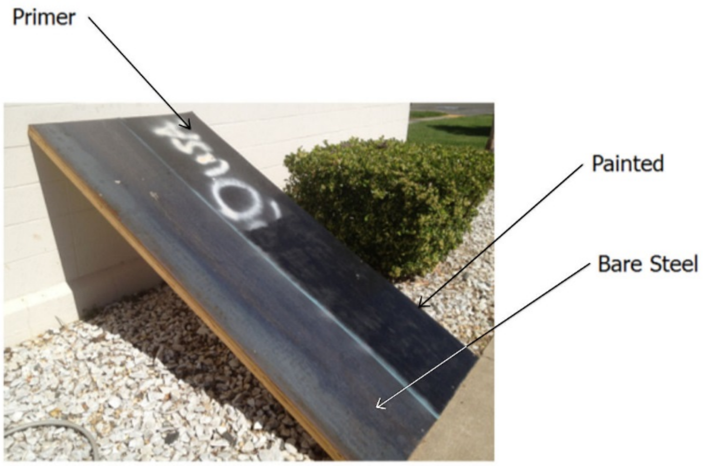


Figure 8. Traction testing setup.

Testing was conducted under both dry and wet conditions, and direction of travel was tested as follows (see Figure 9):

- Forward climb, the UGV traveled straight up the test fixture.
- Diagonal climb, the UGV traveled at a 45º angle to the forward climb.
- Transverse, the UGV traveled 90º to the forward climb.

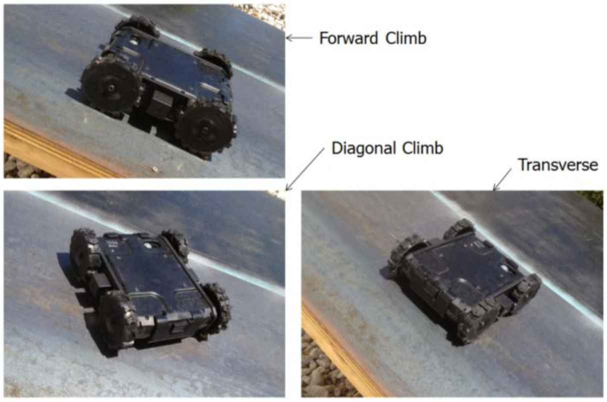


Figure 9. Traction testing: directions of travel tested.

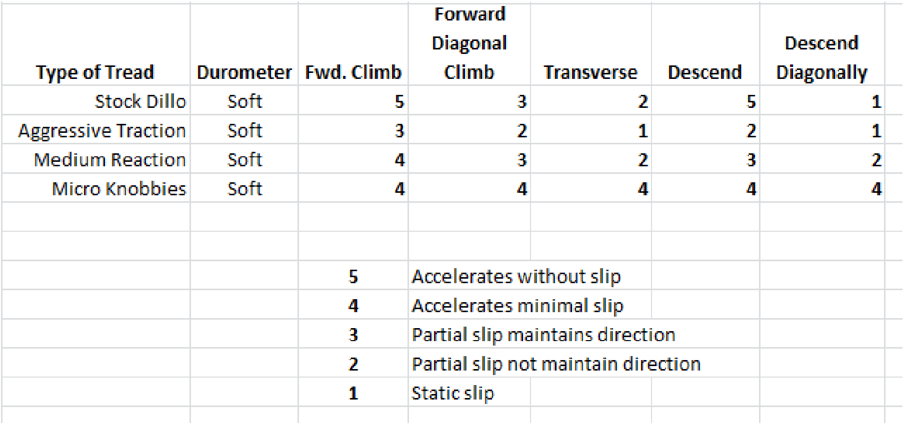
Four types of wheels were tested on the test rig, as shown in Figure 10:

- Stock *Armadillo* wheel, used on standard Macro USA product line.
- Aggressive tread, soft durometer rubber.
- Medium tread, soft durometer rubber.
- Micro-knobby tread, soft durometer rubber.

While all of the tread designs performed reasonably well under dry conditions, wet conditions posed the greatest challenge, as expected (see Table 6). The tread that performed the best overall was the micro-knobby design, which was chosen as the final *Stingray* tread design and implemented in the prototype units (Figure 11). To implement the micro-knobby design, the tread propulsion areas (Figure 4) had to be eliminated. Propulsion is now mostly produced by the ducted-paddle propulsion areas (Figure 5), resulting in some loss of thrust and maximum speed.

Figure 10. Types of tread design tested (aggressive, medium, micro-knobby, and stock *Armadillo*).

Table 6. Tread testing results under wet conditions.



Type of Tread	Durometer	Fwd. Climb	Forward Diagonal Climb	Transverse	Descend	Descend Diagonally
Stock Dillo	Soft	5	3	2	5	1
Aggressive Traction	Soft	3	2	1	2	1
Medium Reaction	Soft	4	3	2	3	2
Micro Knobbies	Soft	4	4	4	4	4
		5	Accelerates without slip			
		4	Accelerates minimal slip			
		3	Partial slip maintains direction			
		2	Partial slip not maintain direction			
		1	Static slip			

Figure 11. The *Stingray* with micro-knobby paddle wheels.

3.6 Impact resistance

The capability of surviving 5-meter (threshold) and 10-meter (objective) drops onto a steel deck was one of the key requirements for the *Stingray*. This was approached by team members using the experience and know-how derived from the standard Macro USA throwable robot line coupled with FEA of the *Stingray* designs using materials that were selected during the design process.

FEA was performed on all components and on the overall system with safety factors always in excess of 10 (Figure 12), which allowed the system to pass both the threshold and objective requirements once built.

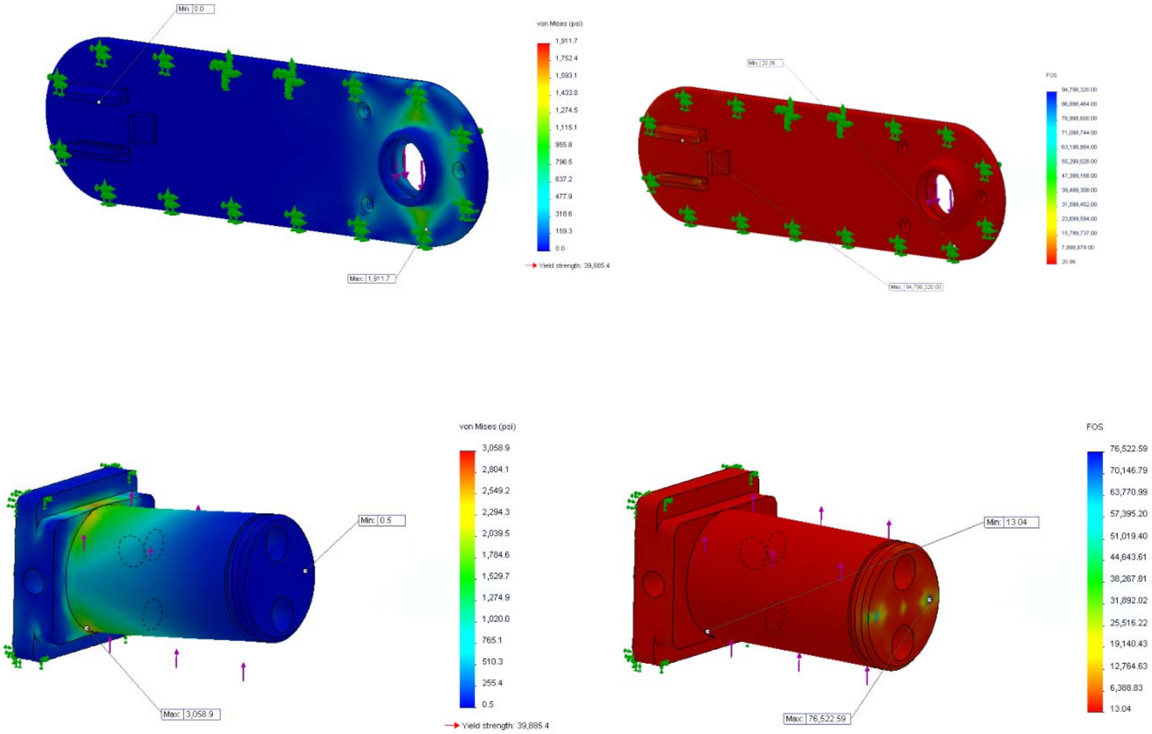


Figure 12. Examples of FEA analysis for *Stingray* components.

4. INITIAL RESULTS OF USER EVALUATIONS

SSC Pacific has been conducting user evaluations on the *Stingray* prototypes with various user groups. The systems have been tested by the US Coast Guard unit of the Joint Interagency Anti-terrorism Task Force South and the USMC III Marine Expeditionary Force, with additional evaluation by the Navy to be conducted at the PANAMAX'14 exercise scheduled for August 2014. Feedback has been very encouraging to date, with users often expressing desire to have a system for each squad, and envisioning non-VBSS applications for the system. Some of the features that were well liked include:

- Ease of operation
- Ruggedness
- Waterproof
- Availability of strobe distracter
- Control of two robots from one operator control/display unit
- Motion detection capability of the robot not currently under active control

User-recommended improvements, which SSC Pacific is currently looking for support to implement, include:

- Instant 360° view: Some users mentioned that it is difficult to keep up with the fast pace of VBSS and tactical operations by throwing the robot into a compartment and rotating the robot one revolution for a complete view of the room. A desire was expressed for an instant 360° view.
- Interchangeable wheels: For tactical operations other than VBSS, the users would like larger, more aggressive wheels that can cross over larger obstacles.
- Extended communications: A desire has been expressed for a communication relaying capability for the robots and OCU, as well as a reach-back capability linking the system to remote command centers.
- Audio: Robot-to-OCU audio is desired at a minimum, preferably two-way audio for remote negotiations. (This feature was part of the original design specifications, but was not implemented on the prototypes due to waterproofing problems.)

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