Characterizing the Critical Parameters for Docking Unmanned Underwater Vehicles

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***Abstract*— Docking an autonomous underwater vehicle (AUV) is a critical part of many current and envisioned Navy, commercial, and scientific missions. Many missions require an AUV to dock with a subsea node that is not restrained through attachment to the seafloor or to a surface platform significantly larger than the system that is docking into it. Space and Naval Warfare Systems Center Pacific (SSC Pacific) recently performed a series of tests to characterize the docking process of an autonomous underwater vehicle (AUV) with a suspended dock. Two methods of docking were performed: a "soft" optical dock where the vehicle tracked and followed a suspended light emitting diode (LED) beacon and a "hard" physical dock where the vehicle entered a docking structure. This docking testing will provide design support information for future undersea systems.**

A REMUS 600 with a hover-capable thruster package was the base test platform. It was outfitted with a directional acoustic transducer (DAT) for acoustic AUV-Dock-relative navigation and an optical quadrant detector for terminal approach and homing. A basic dock structure was constructed of PVC pipe, and instrumented with both acoustic and optical homing devices.

Testing was performed at the SSC Pacific Transducer Evaluation Center (TRANSDEC) test facility. Key docking parameters evaluated during the testing included sensor update rates, vehicle kinematics, and dock inertial characteristics. SSC Pacific performed over 217 trials, with 105 successful hard and soft docks. There were 30 successful docks in 31 trials in the final hard dock series.

Keywords*— *docking, unmanned underwater vehicles, autonomous underwater vehicle

I. Introduction

Docking an autonomous underwater vehicle (AUV) is a critical part of many current and envisioned Navy, commercial, and scientific missions. Typical underwater docking approaches to date have involved a large fixed dock and a relatively small vehicle. As application of these vehicles expand, emerging missions may require an AUV to dock with a smaller docking fixture such as a subsea node that is not restrained by the seafloor or a large platform. Space and Naval Warfare Systems Center Pacific (SSC Pacific) recently performed a series of tests to characterize the docking process of an AUV with a suspended dock.

The SSC Pacific at-sea homing and docking tests were designed to demonstrate the capabilities and quantify risks involved in the docking capabilities. A REMUS 600 vehicle with hover capabilities was used to demonstrate the docking capabilities needed. Two types of docking were demonstrated: a soft dock and a hard dock. The objective of the soft dock was to demonstrate the capability of the AUV to hover and maneuver relative to a moving docking beacon. The objective of the hard dock was to approach and enter a physical dock. The critical parameters of update rate and mass characteristics of the dock were determined for accomplishing these docking behaviors. This docking testing will provide design support information for future undersea systems.

II. Experimental Set Up

A. Vehicle Platform

A REMUS 600 was used as the test platform vehicle outfitted with ducted thruster sections fore and aft to permit hovering and lateral motion. The vehicle is equipped with a Paroscientific pressure sensor to measure the vehicle depth, a Teledyne RD Instruments 300 kHz Doppler Sonar to measure the vehicle translational velocity, and a Kearfott Inertial Navigation System to estimate the vehicle position, and measure its rotational position and velocity.

B. Docking Fixture

A vehicle dock was constructed from PVC pipe. Components on the dock included an LED Docking Beacon, an Ikelite 5710 housing containing the beacon control board, two 240 Watt-hour batteries, and 1 Benthos standalone DAT. The dock was suspended below a catamaran float to allow adjustment of the dock position for the tracking soft dock tests. The dock and float are shown together in their pre-deployment configuration in Figure 1.

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Figure 1: Hard Dock Hardware

C. System Architecture

The development of additional AUV capabilities is challenging due to (1) COTS AUV controllers are closed to external developers and (2) the cost of integration of capabilities onto different commercial off-the-shelf (COTS) AUVs is prohibitive as the number and diversity of said platforms continues to expand. To mitigate these issues, the development of "backseat drivers" is widely used. We employed this approach as part of this risk mitigation with the system architecture shown in Figure 2. Data from the Benthos DAT, quadrant detector, and REMUS vehicle controller are all fed into the payload controller that then performs the necessary waypoint computation for docking.

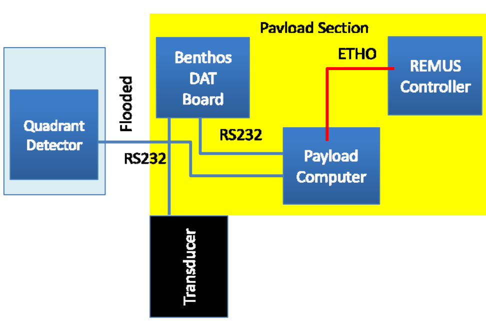

Figure 2: REMUS docking system architecture.

1) Hardware Architecture

Our docking approach required the integration of two sensors into the hovering REMUS 600: a Benthos DAT and an SSC Pacific developed quadrant detector.

The Benthos DAT is capable of supporting both acoustic position measurement (when employed as an ultra-short baseline system) and acoustic messaging. The Benthos DAT was calibrated at the TRANSDEC acoustic test facility to handle the unique electrical and mechanical environment of the REMUS 600, most importantly the air volume directly above the transducer. This approach ensured an azimuthal accuracy of ± 3 degrees and a complete 360 degree azimuthal field of view and an elevation field of +30 and -80 degrees.

The quadrant detector is used to home in on a docking beacon. The light emitted by the docking beacon is strobed at 40 Hz to distinguish it from ambient light. The quadrant detector was mounted into a 5710 Ikelite camera housing, and then zipped tied to a mounting bracket integrated into the standard REMUS forward tow point. It uses four photo diodes mounted in each of the 4 quadrants to measure light at 14 Hz emitted from the node-mounted beacon with a 30 degree field of view, as shown in Figure 3

To compute the vehicle relative x and y position error the following relationships are employed from the intensity measured by the diodes:

$$PX = {I_{Diode\,1} + I_{Diode\,2} - I_{Diode\,3} - I_{Diode\,4}} \Big/ {\textstyle\sum_1^4 I_{Diode\,i}},$$

$$PY = {I_{Diode\,1} + I_{Diode\,3} - I_{Diode\,2} - I_{Diode\,4}} \Big/ {\textstyle\sum_1^4 I_{Diode\,i}},$$

$$I_T = \sum_1^4 I_{Diode\,i}$$

where PX is the vehicle relative azimuthal error, PY is the vehicle relative elevation error, and I_T total intensity measured by the sensor. These parameters were treated as error parameters to the vehicle elevation and bearing relative to the dock. This is a critical component to the SSC Pacific Docking system.

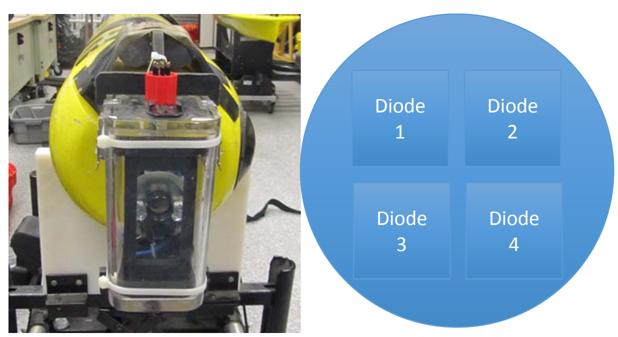

Figure 3: REMUS 600 with quadrant detector; detector photo diode layout

2) Software Architecture

Different from many other approaches [1-4] which treated docking as a low level control problem, we treated the underwater vehicle docking problem as a waypoint navigation problem. To implement this approach, we used the REMUS Remote Control (RECON) protocol to send waypoint commands to the REMUS native control system. This approach, although limited by a 2-3-sample lag between measurement of the vehicle position and the implementation of the command by REMUS, enabled SSC Pacific to implement a docking approach on a COTS AUV, which can more readily be applied to multiple platforms.

3) Docking Waypoint Algorithm

In this section we describe the algorithm used in commanding the REMUS 600 toward the dock. First we take the inertial position of the vehicle and convert it into its body frame relative position:

$$\vec{x}_b = {}^W_B R^T \vec{x}_w$$

where $\vec{x}_w$ is the vehicle world inertial world position, $\vec{x}_b$ is the vehicle body position, and ${}^W_B R$ is the rotation from world to body coordinates. Second the body relative position is converted into a body relative azimuth, elevation, and range relative to the docking beacon:

$$\phi = \cos^{-1} x_{b3},$$

$$\theta = atan2(x_{b2}, x_{b1}),$$

$$r = \sqrt{x_{b1}^2 + x_{b2}^2 + x_{b3}^2}$$

where ϕ is the elevation, θ is the azimuth, and r is the range. Third the optical azimuth and elevation are subtracted from the estimated azimuth, elevation of the vehicle relative to the dock, creating a desired azimuth, and elevation:

$$\theta_d = \theta - PX * SF,$$

$$\phi_d = \phi - PY * SF$$

where ϕ_d and θ_d are the desired azimuth and elevation of the vehicle relative to the dock and SF converts optical error to radians. The range is modified to increment the vehicle closer to the dock.

$$r_d = r + \Delta r$$

where Δr defines the change in range with vehicle update, which sets the vehicle forward velocity, and r_d is the desired range for the new desired vehicle position. Finally, the desired azimuth, elevation, and range are converted back into a desired position which is provided to the vehicle controller to enable docking of the system:

$$\vec{x}_{wd} = {}^W_B R \begin{bmatrix} cos\,\theta_d\, sin\phi_d \\ sin\theta_d\, sin\phi_d \\ cos\phi_d \end{bmatrix} r_d$$

III. Soft Dock

A. Objective

The objectives of the soft dock experiments were to collect data on the performance of the AUV when it hovers and maneuvers to vector into a moving docking beacon. The AUV "soft dock" system is depicted in Figure 4.

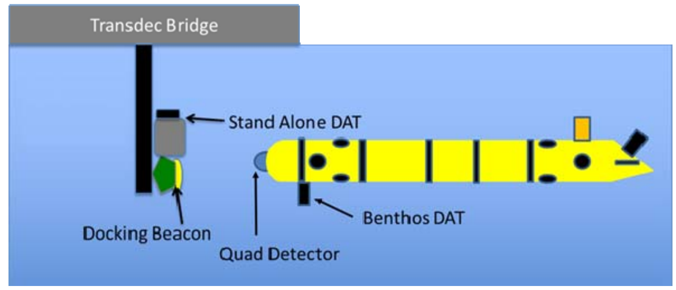

Figure 4: Soft optical docking system

B. Soft Dock Sequence

The hover / following behavior of a representative AUV (a REMUS 600) following a docking beacon was demonstrated using a beacon light mounted to the dock and lowered from the bridge at TRANSDEC. The dock was then moved laterally along the bridge, providing a target for the vehicle to follow. The basic operational sequence was as follows:

- Set REMUS vehicle at start position
- Vehicle descends to depth
- Acoustic position is determined by AUV
- Vehicle transits to 9 meters from dock
- Vehicle detects optical docking beacon
- Vehicle transits to beacon in 0.5 meter increments
- Beacon is moved laterally to show the following behavior of the system

C. Results

The vehicle was able to successfully find and follow the target light. Figure 5 below shows the vehicle position moving back and forth following the moving target, and incrementally moving towards the target. Figure 6 shows the depth keeping capability, where the vehicle held the desired depth to less than ± 0.25 m. Figure 6 also shows the lateral translation of the vehicle following the moving dock up to ± 2 meters.

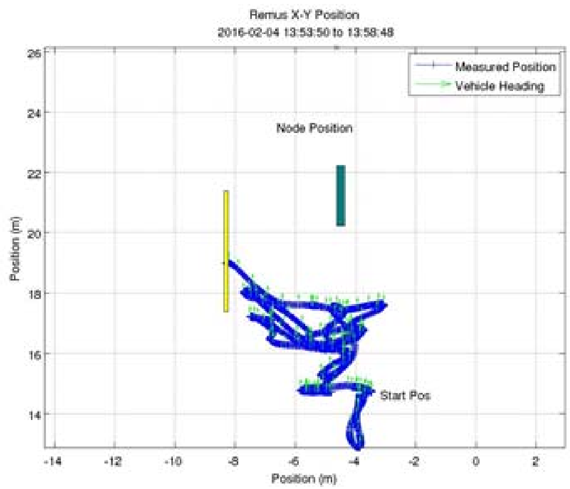

Figure 5: XY plot of vehicle tracking beacon

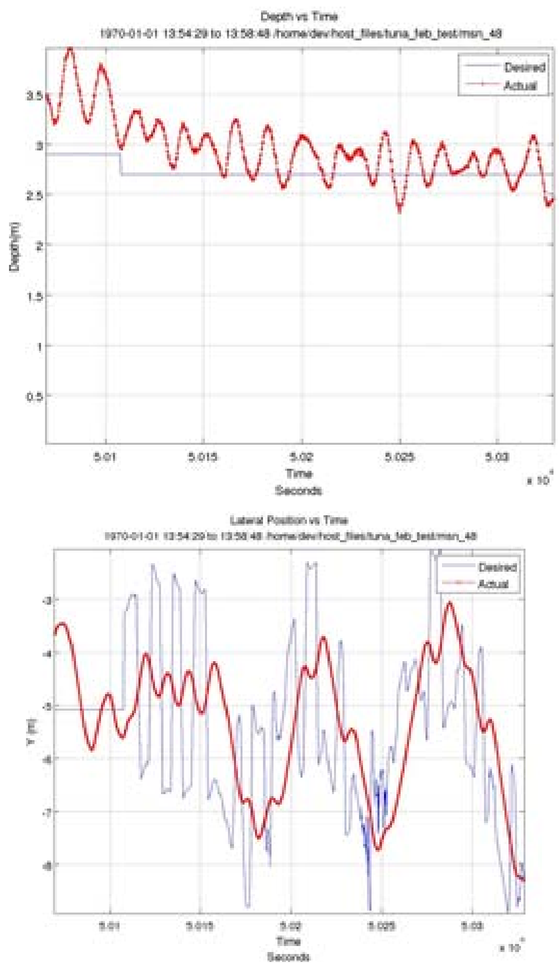

Figure 6: Plots of vehicle depth and lateral position while station keeping on optical beacon

D. Issues and Lessons Learned

The acoustic environment of TRANSDEC proved to be a major consideration. Initial location of the dock and homing was performed using the DAT on the vehicle and the dock. There are shadow zones in the acoustic environment in TRANSDEC such that the vehicle must be positioned to allow hearing of the dock. This limited the range and relative positions that could be tested between the vehicle and the dock. This is not anticipated to be an issue for testing and operation in an open water environment.

E. Soft Dock Summary

A soft optical dock was repeatedly demonstrated with the vehicle at distances of 1-10 meters from the target (Figure 7). The process worked well with an unrestrained dock, not requiring any precision alignment. This navigation technique could also be employed at larger separations, particularly when ambient light is not an issue.

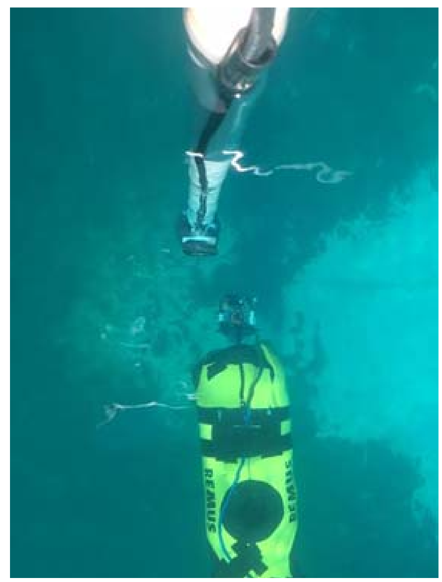

Figure 7: Optical soft dock

IV. Hard Dock

A. Objective

The hard dock for physical capture experiments objectives included collecting data on the performance of the AUV when hovering and entering a physical dock as shown in Figure 8. Factors influencing the docking process were determined and characterized. Some of these factors included the position update rates and dock characteristics.

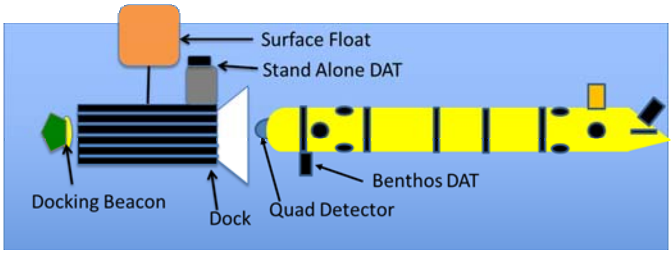

Figure 8: Hard dock system

B. Hard Dock Sequence

The docking behavior of a representative AUV (a REMUS 600) into a hard dock was demonstrated using a dock attached to a float on the bridge at TRANSDEC. The basic operational sequence was as follows:

- Set REMUS vehicle at start position
- Vehicle descends to depth
- Acoustic position is determined by AUV
- Vehicle transits to 9 meters from dock
- Vehicle detects optical docking beacon
- Vehicle transits to dock
- Vehicle docks

Two major parameters were evaluated in regards to the hard dock: update rate of the position information to the vehicle and the dock physical characteristics. The position update rate was varied by subsampling the quadrant detector sensor data to the desired rate.

C. Results

Over the course of 4 test periods, 217 docking runs were performed with 105 successful docks (Figure 9) Most notable was the final demonstration sequence, where there were 30 successful docks in 31 runs. Figure 10 shows the track of the vehicle as it aligned with the dock and then entered it. Figure 11 shows the desired vs. actual lateral and depth position of the vehicle throughout the docking process. During the terminal docking phase, the vehicle was within 0.2m of the desired position.

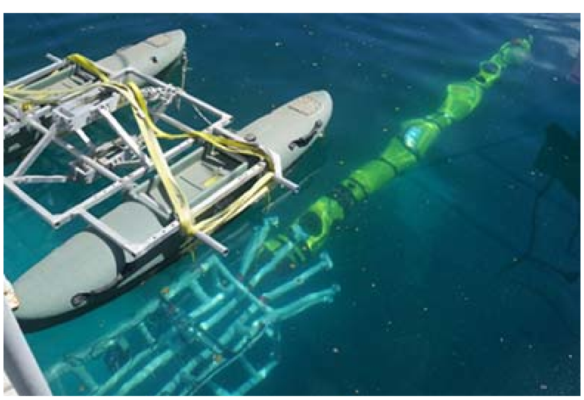

Figure 9: Successful hard dock

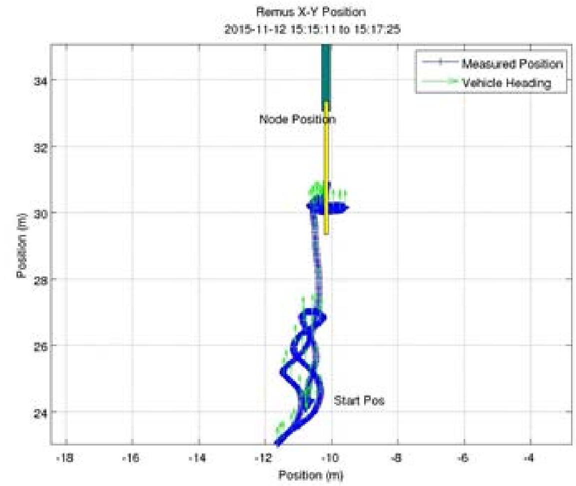

Figure 10: XY Plot of Hard Dock showing adjustment of position and dock

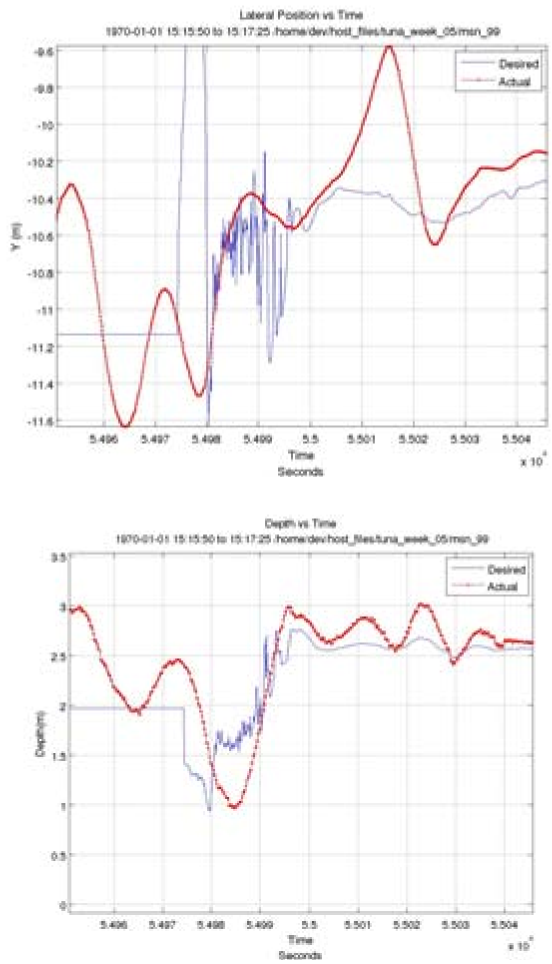

Figure 11: Plot of lateral position and depth during hard dock

D. *Issues and Lessons Learned*

During the course of the docking development, critical parameters were determined for successful docking with an unrestrained dock. These included the update rate of the vehicle vs. dock location and the mass characteristics of the dock itself.

1) *Update Rate Variation*

Previous experience with docking vehicles indicated the need for a sufficiently high update rate for terminal homing and docking. A series of runs at different rates and speeds was performed in an effort to quantify the benefit of update rate. Table 1 lists the runs and docking performance. 100% docking was accomplished at the slower 0.25 m/s forward speed for all update rates tested (10 Hz, 2 Hz, and 1/2.5 Hz). 87.5% docking was accomplished at 0.5m/s forward speed (nominal 1 knot) for the 10Hz and 2Hz update rate. However, there were no successful docks at the higher vehicle speed with the slower update rate of 1/2.5 Hz (=0.4Hz).

TABLE I. RESULTS OF UPDATE RATE AND SPEED ON DOCKING

Update Rate	Vehicle Speed m/sec	Dock
10 Hz	0.25	Y
10 Hz	0.25	Y
10 Hz	0.25	Y
10 Hz	0.25	Y
10 Hz	0.5	Y
10 Hz	0.5	Y
10 Hz	0.5	Y
10 Hz	0.5	Y
10 Hz	0.5	Y
10 Hz	0.5	Y
10 Hz	0.5	N
10 Hz	0.5	Y
2 Hz	0.25	Y
2 Hz	0.25	Y
2 Hz	0.25	Y
1/2.5 Hz	0.25	Y
1/2.5 Hz	0.25	Y
1/2.5 Hz	0.25	Y
1/2.5 Hz	0.5	N
1/2.5 Hz	0.5	N
1/2.5 Hz	0.5	N

Things to note include the operation of the REMUS control interface. The REMUS RECON interface transmits the REMUS position at 9Hz, with the state information processed at 1/9s delay of receipt. The REMUS then processes the sent command 1/9s later. These delays must be taken into account when considering the real-time control required for precision operations such as docking.

2) *Dock Characteristics*

For test purposes, the dock and vehicle in water mass were roughly equivalent. When the dock was fixed, there were no major issues with the dock in the docking process. However, when the dock was unrestrained and free to move, there were multiple interactions with the moving vehicle. Docking was successful when the REMUS was perfectly aligned with the dock, but any offset resulted in the vehicle pushing the dock around. Weights and a Plexiglas plate were added to increase hydrodynamic mass from (100 kg to 440 kg), but it was insufficient resistance for effective docking if there was any misalignment. Future testing, particularly in open water, will require a dock with a significantly greater mass.

E. *Hard Dock Summary*

Testing demonstrated the utility of high update rates (> 2 Hz) for terminal homing and docking operations. This was shown for both the low speed approaches possible with a hovering vehicle and for the higher speed approaches required when a 3 dimensional hovering capability is not available.

V. RECOMMENDATIONS AND CONCLUSIONS

A. *Recommendations*

1) *Navigation and Controls*

The update rate testing demonstrated the utility of higher update rates (>2 Hz) on docking success, particularly at greater vehicle speeds. High frequency acoustics on a hovering vehicle may support an update rate sufficient to dock at low approach speeds. However, these tests suggests that a high update rate optical system such as used in these tests is a more reliable method of providing the timely feedback required to support docking, particularly at higher approach speeds. The Field of View of the docking sensor is also important, especially in final 3 meters of docking process.

2) *Mechanical Design*

Docking success with an unrestrained dock is largely dependent on the alignment of the dock with the vehicle and the mass of the vehicle. This can be improved over the test configuration in several ways. The differential mass between dock and vehicle can be increased to 5:1 or greater, rather than the 1:1 version tested. Adding actuators such as thrusters on the dock could mitigate this issue as well. Finally, the use of smooth and flexible entry cones can assist in docking by minimizing the opportunity for the vehicle catching on the structure.

3) *Follow-on Testing: Open Water*

The tests reported on here were all performed in a benign tank environment. While this provided excellent access to the vehicle and dock, it also posed limitations in the range of operations and the acoustic conditions available. The next step in the testing will be to take the vehicle and the dock to open water and perform docking from longer ranges and greater offsets.

B. Conclusions

Reliable and consistent docking of an AUV into an unrestrained dock is possible provided that attention is paid to both the control and mechanical design of the system. The following critical docking parameters have been identified:

- Close-in docking requires sensor update rates greater then 2Hz, preferably at least 10Hz.
- The minimal in-water mass ratio between a subsea dock and AUV is 5 to 1.
- It is possible to dock an AUV using the back-seat driver protocols, but that will induce lags in the control loop, which affects the types of environments that docking is possible.

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