From the Lab to the Ocean: Characterizing the Critical Docking Parameters for a Free Floating Dock with a REMUS 600

Barbara Fletcher, Stephen Martin, Geno Flores, Anthony Jones, Anna Nguyen, M. Hunter Brown, Diane Leah Moore

Maritime Systems Division
Space and Naval Warfare Systems Center Pacific
San Diego, CA USA

Abstract— **Docking an autonomous underwater vehicle is a critical part of many current and envisioned Navy, commercial, and scientific missions. In the Defense Advanced Research Projects Agency's (DARPA) Tactical Undersea Network Architectures (TUNA) program, docking a vehicle is a key enabler for several of the proposed concepts of operation. To support the program, a series of risk reduction tests were performed 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 tubular structure. This docking demonstration and associated data will provide design support information for the various approaches being considered for implementing TUNA and other program solutions. At-Sea Testing was performed at San Clemente Island from 18-27 April 2016. Over the course of 3 days of testing, 42 test runs were performed with the vehicle in open water conditions. Of the 11 soft docking trials performed, there were six successful soft docks, one lasting in excess of 22 minutes. Of the 25 hard docking test runs, 6 were full docks and 5 were close-docks. Overall this test sequence showed that soft docking can be performed reliably in an at-sea environment, and that hard docking requires a hydrodynamic mass differential of 5 to 1 or greater.**

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 in open ocean conditions.

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 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

Underwater docks must provide enough opposing force and moment (inertial and/or using thrust) so that the AUV's ability to insert itself is not defeated by the rate at which the dock translates or rotates away from the AUV's approach vector. Intuitively, we expect that an AUV will dock more successfully into a massive dock than to a dock of about the same mass as the AUV. For many of the TUNA concepts, the mass of the dock could be the same or within ten times the mass of the AUV. To bound the minimum differential mass of the dock relative to the AUV, the San Clemente Island (SCI) tests employed a drifting dock with a hydrodynamic mass similar to the test AUV.

The vehicle dock was constructed from PVC pipe as shown in Figure 1 below. Components on the dock include Sensors, 1 LED Docking Beacon, 1 Ikelite housing Beacon Control Board, Two 240 Watt-hour Batteries, and 1 Benthos Standalone DAT. A method of adding more mass to the dock

This work was sponsored by the Defense Advanced Research Projects Agency Strategic Technology Office.

was required to support docking during the TUNA program hovering and docking tests at San Clemente Island (SCI). In preparation for the SCI tests, an experimental system was produced that allowed divers to increase and decrease the mass of the drifting dock. This system employed water-inflatable bags and an underwater pump system to increase the mass ratio between the dock and AUV to 5 to 1. This bag system increased the probability of docking the AUV during each attempt, while providing for the dock to be lighter when it was lifted in and out of the water.

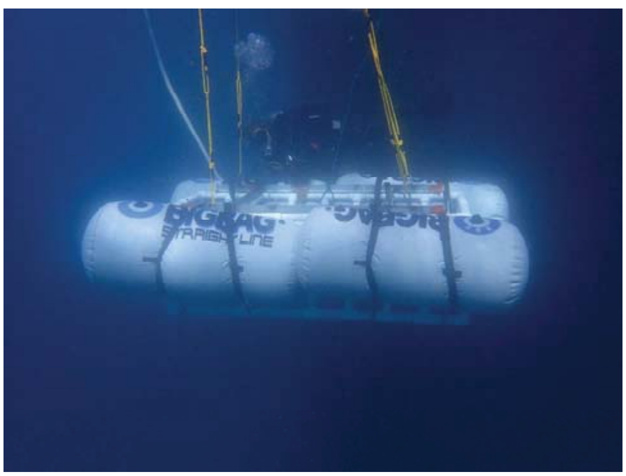


Figure 1: Hard Dock Hardware: bags deflated above, inflated below

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 (figure 3), and REMUS vehicle controller are all fed into the payload controller that then performs the necessary waypoint computation for docking. Details of the Hardware and Software Arcitectures can be found in [1].

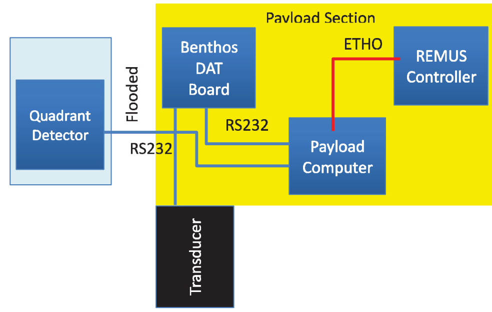


Figure 2: REMUS docking system architecture.

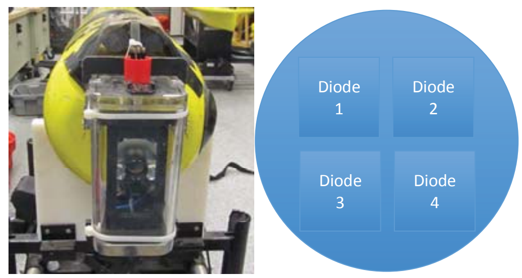


Figure 3: REMUS 600 with quadrant detector; detector photo diode layout

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.

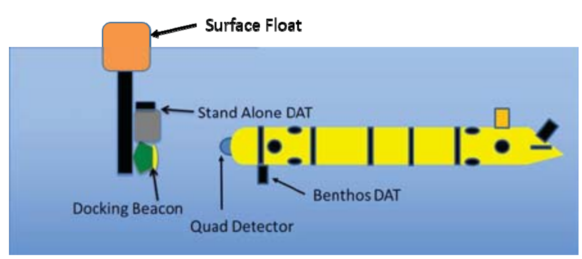


Figure 4: Soft optical docking system

B. *Execution*

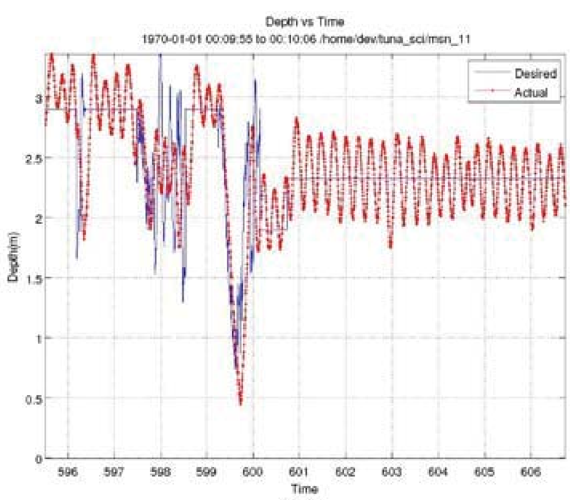
The hover / following behavior of a representative AUV (a REMUS 600) following a docking beacon was demonstrated using a beacon light mounted on a pole and lowered from the side of a boat. The dock was then moved laterally along the side of the boat, providing a target for the vehicle to follow. The 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

Over the course of 11 vehicle runs, there were 6 successful soft docking operations with the vehicle finding and following the light. Plots of the data are shown in Figure 5 below. The first graph shows the depth keeping capability, where the vehicle held the desired depth to less than +/- 0.25 m. The second graph shows the lateral translation of the vehicle following the moving dock, and the optical tracker errors recorded.

Failures to track were attributed to two main factors. The first is where the vehicle lost the light and then passed the target, making it unable to reacquire the beacon. This was the case in runs 5 and 6. The other major factor was vehicle control errors, where the vehicle went into an error mode of operation (false start, stuck in surf) and never got into a position to acquire the target. This was the case for runs 9 and 10.



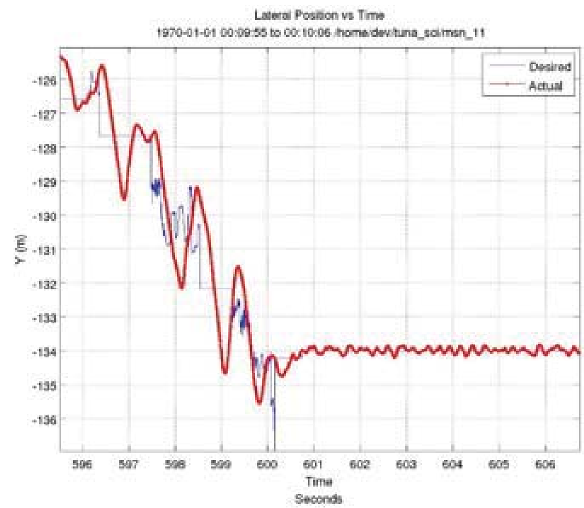


Figure 5: Plots of vehicle depth and lateral position while station keeping on optical beacon

D. Soft Dock Summary

A soft optical dock was repeatedly demonstrated with the vehicle at distances of 1-10 meters from the target (Figure 6). 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.

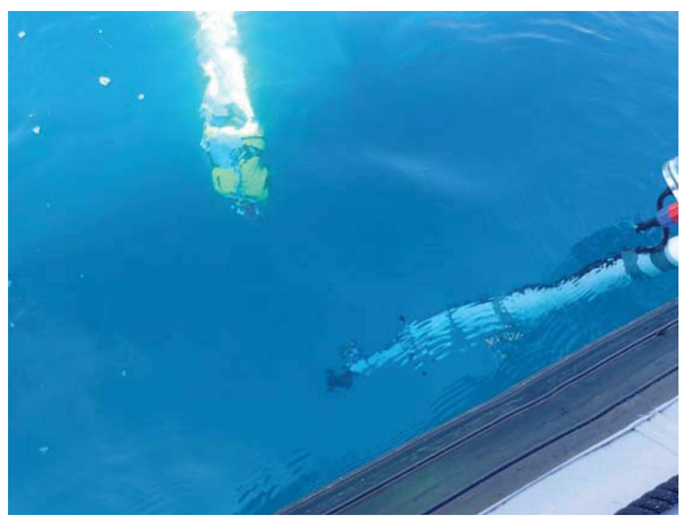


Figure 6: Optical soft dock

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 7. Factors influencing the docking process were determined and characterized. Some of these factors included the position update rates and dock characteristics.

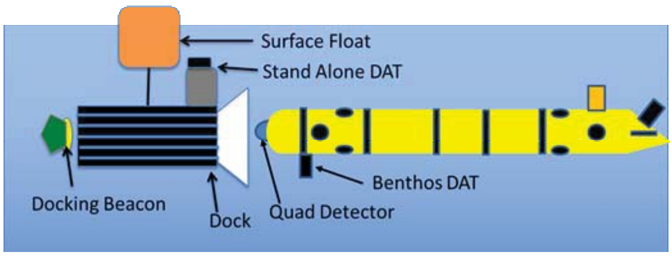


Figure 7: Hard dock system

B. Dock Preparation

Four "Big Bags" were attached to the dock as described in section II B. The air in the bags was evacuated to the degree possible using a shop vacuum. The dock was deployed into the ocean with the deflated bags attached using a crane on the NOTS SCI pier. Divers inflated and deflated the water bags on different occasions at both the pier and at-sea near the operations location. The bags and their attachment hardware survived dock towing operations and they survived lifting of the dock with substantial water still contained in the bags.

C. Execution

The basic operational sequence was as follows:

- Set REMUS vehicle at start position
- Vehicle is provided with dock orientation based on surface observation
- Vehicle descends to depth
- Relative acoustic position is determined
- Vehicle transits to 9 meters from beacon
- Vehicle detects optical docking beacon
- Vehicle transits to dock
- Vehicle docks

D. Results

25 vehicle docking runs were performed over 2 days of testing, with 6 successful docks and 5 close docks. During the first day of testing, 13 runs were performed with one successful dock and 3 close docks. At the end of the day, it was determined that there had been a bearing failure in the rear lateral thruster, adversely impacting the maneuverability of the vehicle. This was repaired and the vehicle returned to service for the next day's testing.

On the second day of docking testing, 12 standard runs were performed with 5 docks and 3 close docks. The primary cause of failure to dock during these runs was the shifting of the dock position while the vehicle was in transit. The vehicle typically had only the initial position / orientation of the dock, provided at the initiation of the mission. A sensor pack had been installed on the dock to provide updated information, but unfortunately communications were never established between the pack and the vehicle. This was later determined to be due to a bug in the Benthos DAT code, and there was insufficient time to correct the error before the end of the test period. This leaves the systems final docking percentage at the end of SCI testing at 41.7%.

Figure 8 shows the vehicle aligning itself with the dock and entering the dock during a successful docking evolution. Figure 9 shows a plot of the docking track, as the vehicle homed in on the target. Figure 10 shows the plots of the depth keeping performance, the lateral translation of the vehicle entering the dock, and the optical tracker errors recorded.

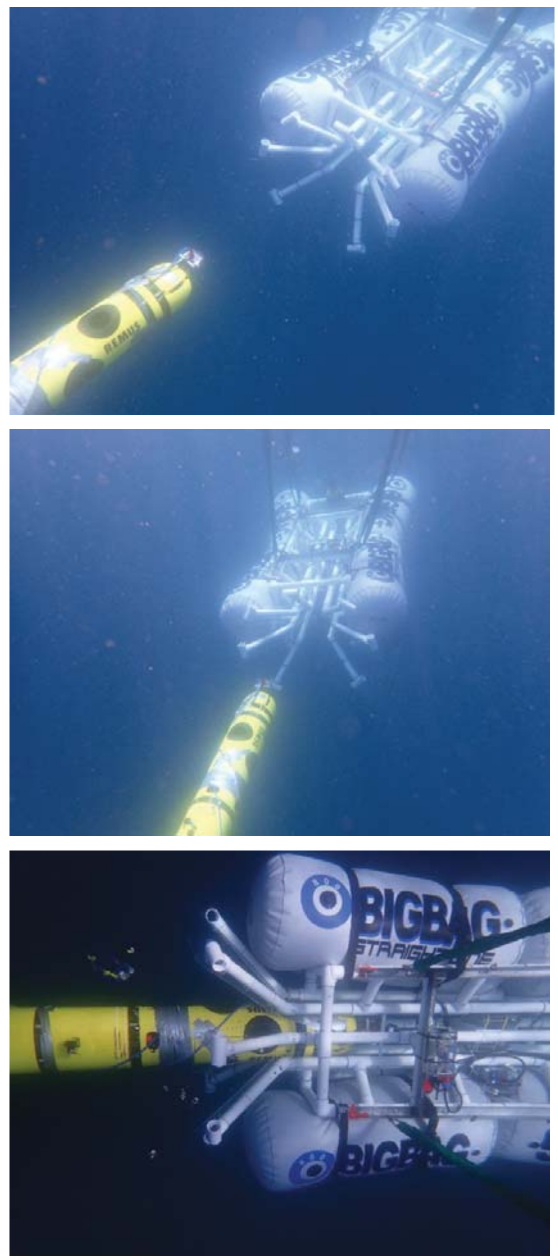


Figure 8: AUV Docking Process: approach, align, and dock

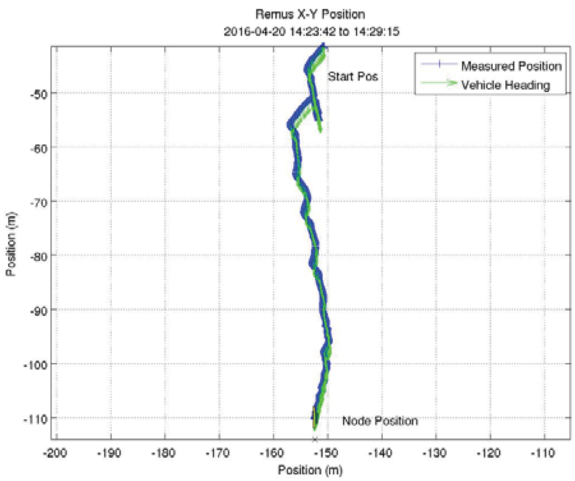


Figure 9: XY Plot of Hard Dock showing adjustment of position and dock

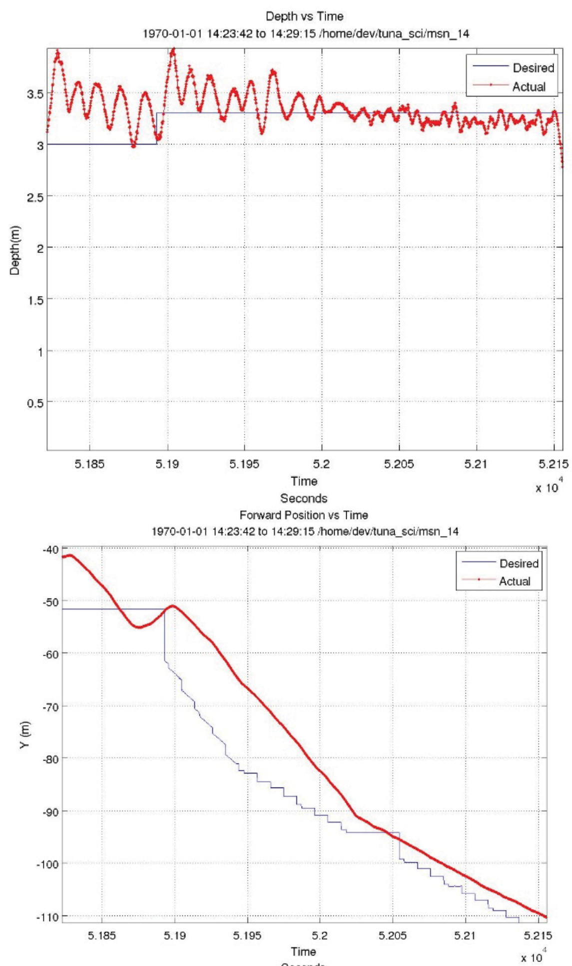


Figure 10: Plot of lateral position and depth during hard dock

E. Fin Control

During the second day of docking testing, an additional 8 test runs were made under fin control alone, not using the lateral thrusters to position the vehicle. This was of interest, as most AUVs do not have the hover capability of the system used in these tests. Software modifications were made to disable the thrusters, allocating all vehicle control authority to the fins.

Eight runs were made under fin control alone. The vehicle started at a position 20 m from the dock as shown in Figure 14. Due to the higher speed required to provide maneuverability, this resulted in a very dynamic situation. Additional distance from the dock was also necessary to provide the space required for fin maneuvers to be effective. Three close docks were achieved: in Figure 15 we show that the vehicle depth was still recovering from the transition from hovering to fin control mode, which is why the vehicle did not successfully dock. A review of the optical tracker data shows that the vehicle lateral error was sufficiently small that the REMUS could have docked if the depth had stabilized. Unfortunately, the testing had to be stopped due to the end of the test period, so we were unable to further tune the system to achieve the desired docking.

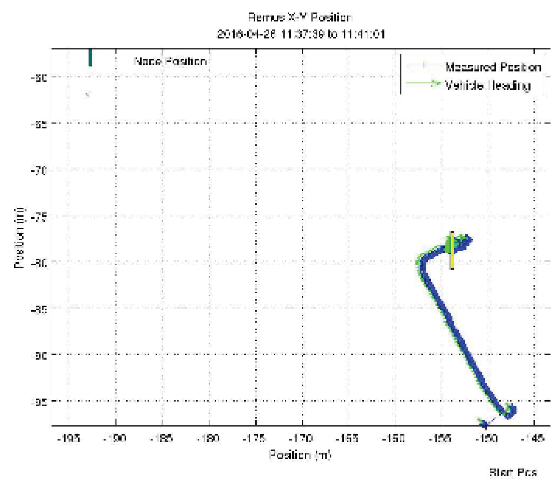


Figure 14: Track of docking approach under fin control

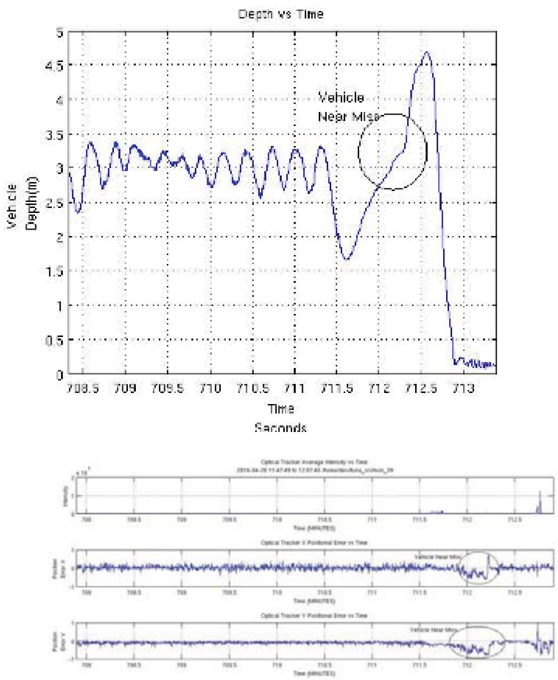


Figure 15: Plots of fin control performance: depth and optical tracker

V. Recommendations and Conclusions

A. Recommendations

1) Dock Design and Instrumentation

A major contributor to docking success with an unrestrained dock is the alignment of the dock and the vehicle. For the TRANSDEC and at-sea tests, information on the dock position and orientation was provided to the vehicle at the start of the run. In the benign test tank environment, this was sufficient to allow the vehicle to enter the dock. At sea, however, the dynamic sea conditions would sometimes cause the dock to drift out of alignment with the vehicle path. A sensor package was developed to allow the dock to communicate its position to the vehicle during the course of the test run, allowing the vehicle to adjust its path accordingly. Unfortunately, this system inoperable during the test period due to a software issue. In the future, the successful incorporation of this information to the vehicle will greatly aid in successful docking.

2) Vehicle Controls

The hovering capabilities of the vehicle were used for the bulk of the demonstration, as it provided a higher degree of control for alignment with the target and dock. Initial demonstrations using fin control indicate that docking would be feasible with additional tuning of the controls and the addition of high update rate dock position information.

3) Dock Controls

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 when increased to 5:1 or greater enabled successful docking. 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.

4) Follow-on Testing

While the feasibility of docking was demonstrated under at-sea conditions, additional testing would serve to further understand the systems involved and more closely approach operational conditions. Items to be further investigated would include the incorporation of real-time dock position , tuning of fin control operations, and increasing the ranges and offsets of the vehicle approaches.

B. Conclusions

The TUNA soft and hard docking behaviors have been repeatedly demonstrated under open ocean conditions. The soft optical dock was repeatedly demonstrated with the vehicle at distances of 1-10 meters from the target. The process worked well with an unrestrained target, not requiring any precision alignment. This navigation technique could also be employed at larger separations, particularly when ambient light is not an issue.

Hard docking was also demonstrated with a dock with added mass similar to that expected for an operational system. Performance can be improved with the addition of real-time dock position and attitude information to the vehicle. Docking with fin-control (no hover module thrusters operating) appears to be feasible, a mode which would be operationally preferable in many envisioned systems.

Acknowledgments

Thanks to all who supported and made these demonstrations possible, including our sponsors, Jim Walton, Robert Lee, and the SSC Pacific Navy Dive Locker.

The work reported was funded by the Defense Advanced Research Projects Agency under the Tactical Undersea Network Architectures (TUNA) program (John Kamp). The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government

References

[1] S. Martin et al., "Characterizing the critical parameters for docking unmanned underwater vehicles," OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, 2016, pp. 1-7.

[2] Stokey, Roger, et al. "A docking system for REMUS, an autonomous underwater vehicle." *OCEANS'97. MTS/IEEE Conference Proceedings*. Vol. 2. IEEE, 1997.

[3] Feezor, Michael D., et al. "Autonomous underwater vehicle homing/docking via electromagnetic guidance." *IEEE Journal of Oceanic Engineering* 26.4 (2001): 515-521.

[4] Cowen, Steve, Susan Briest, and James Dombrowski. "Underwater docking of autonomous undersea vehicles using optical terminal guidance." *OCEANS'97. MTS/IEEE Conference Proceedings*. Vol. 2. IEEE, 1997.

[5] Park, Jin-Yeong, et al. "Experiments on vision guided docking of an autonomous underwater vehicle using one camera." *Ocean Engineering* 36.1 (2009): 48-61.

[6] Allen, Ben, et al. "Autonomous docking demonstrations with enhanced REMUS technology." *OCEANS 2006*. IEEE, 2006.