New AUV Adaptive Behaviors for Subsea Data Exfiltration

Gwyneth Packard, John Collins*, Norman Farr, Carl Fiester, Alan Gardner*, Matt Grund, Jeff Kaeli, Chris McRaven, Leo Paul Pelletier, Mike Purcell, Dara Tebo, Jonathan Ware
Applied Ocean Physics and Engineering Department
**Geology & Geophysics Department*
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
{gepackard, jcollins, nfarr, cfiester, agardner, mgrund, jkaeli, cmcraven, lpelletier, mpurcell, dtebo, jware}@whoi.edu

Abstract— **This paper describes new adaptive behaviors native to the REMUS autonomous underwater vehicle (AUV). The new behaviors represent the expansion of the vehicle's capabilities to monitor vehicle and mission health and progress. We implemented the new framework to facilitate the application of REMUS vehicles to the data mule problem in general and specifically to the scenario of retrieving data from an Ocean Bottom Seismometer (OBS).**

Access to high-quality data from these off-shore stations would improve our understanding of the internal structure and rupture properties of faults, and could allow advanced warning of short-term seismic risk. However, retrieval of off-shore data remains complicated. Fiber optic cable stations are expensive to deploy; as is sending research vessels to retrieve data from autonomous stations. Oceanographic Systems Laboratory (OSL) collaborated with the Ocean Bottom Seismograph and Optical Modem Labs at Woods Hole Oceanographic Institution (WHOI) to develop a solution. [1]

Using an AUV to transport data from the sea floor requires specific autonomy to enhance vehicle endurance, reliability and communications quality awareness. The new capabilities described here address limitations of reactive vehicle monitoring strategies, which focus on problems rather than mission progress. Our new implementation features vehicle introspection infrastructure that allows the AUV to assess progress and make robust choices for performance improvement.

OSL developed a suite of REMUS capabilities to allow the AUV to make a long distance transit to the seafloor station, autonomously launch and monitor retrieval of the data, and make the transit back to deliver the data. Depending on the size of the data, data samples or meta data may be communicated by the vehicle over the horizon via Iridium before the vehicle performs the final transit.

To broaden the impact of the new vehicle introspection controls, we are currently organizing a system of mission progress metrics and plan to leverage that system to expose adaptive capabilities systematically across objectives.

Keywords—autonomous underwater vehicle, marine robotics, embedded software, vxworks, mobility, modularity, reliability, robustness, autonomy, embedded software, field demonstration.

I. INTRODUCTION

OSL has been a leader in development of AUVs for more than 25 years. OSL has continued to develop the REMUS family of AUVs including REMUS 100, REMUS 600, REMUS 2500 and REMUS 6000. The REMUS 100 is the design basis for the U.S. Navy Mk18 Mod 1 AUVs and the REMUS 600 provides the design base for the Mk18 Mod 2 AUVs. Both AUV systems are manufactured by Hydroid, Incorporated, a Kongsberg company.

The REMUS AUV software subsystem has been in continuous development at Woods Hole Oceanographic Institution for nearly three decades [2]. The software is currently instantiated as several *VxWorks* downloadable kernel modules, with support for multitasking, including task management, and

c

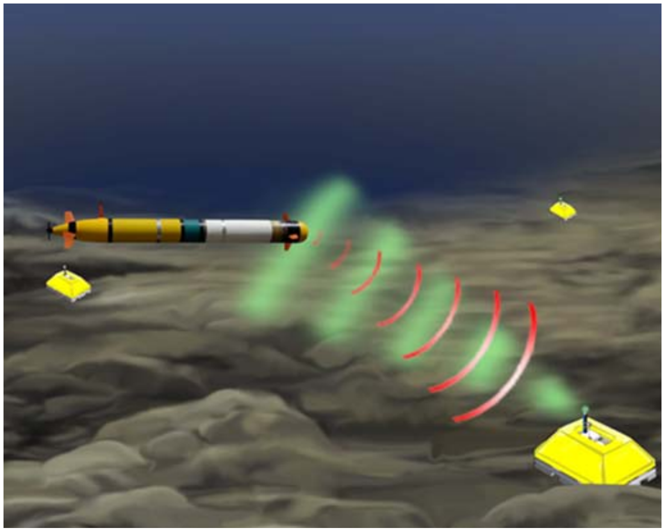

Figure 1 - A sketch of a REMUS 600, ranging acoustically to a bottom mounted data source, then uploading sensor data by high data rate underwater optical modem.

on-demand task spawning. WHOI is working to extend capabilities of the REMUS vehicles by creating tactical autonomous behaviors and integrating advanced sensors. Recently, OSL has developed an interface to enable a Robot Operating System (ROS) payload controller. [3] ROS is an open source middle-ware that provides elements of an operating system including message passing between system elements. [4]

A high data rate underwater optical modem, developed at WHOI, has been previously integrated and demonstrated with the REMUS AUV [5]. This paper describes the development of a robust autonomous data exfiltration *ie.* “data mule” mission capability for REMUS.

II. OPERATIONAL CONCEPT

A. *Architecture*

Recent improvements to the REMUS 600 AUV have significantly increased mission endurance, and system reliability [6]. The new electronics board offers significant advances in power control, allowing payloads to be turned off when they are not required, in order to conserve energy. The long endurance next-generation REMUS 600 not only makes it feasible, but also economical to launch an AUV from shore to retrieve data from an offshore bottom-mounted sensor.

The challenge for the project was to create a system that could autonomously retrieve the data from a station on the sea floor. The challenges this presented to the vehicle fell into the categories of endurance and control. The vehicle will be asked to make a long transit through new waters with potential hazards. The longer the vehicle is operating, the more likely it is that it will encounter a glitch in some system component. It needs to be able to recover and survive physical obstacles and software errors. The vehicle control challenges included autonomously locating the station, remaining close to the station throughout the transmission phase, establishing and monitoring the transmission phase, and safely shutting down the station before the return transit.

The REMUS system has the capacity to perform long transits, and to recover from a host of errors to continue its mission. However, with the continued enhancement of vehicle capabilities and sensor suites, we continue to rigorously develop safeguards to maintain that reliability in the face of growing complexity and risk. These safeguards include vehicle introspection, and offer the opportunity to create new pathways for mission recovery.

The solutions to the vehicle control challenges were also addressed by designing introspection elements and new infrastructure to make the elements modular. These elements provide communication paths between payload drivers and mission objectives while maintaining privacy of concern for those modules. Specifically, we put in place a message layer so that payloads and objectives could subscribe to system messages without the publisher requiring knowledge of the subscriber. Additionally, we made a place in the architecture for monitoring modules whose role it is to contain any case specific code without the payloads or objectives requiring any knowledge of the concept of operations. This structure makes the basic mission objectives easier to reuse and maintain.

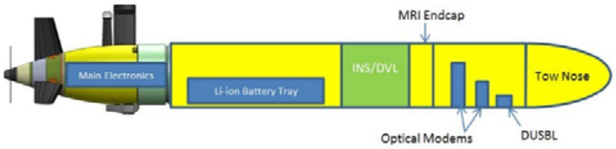

Figure 2 - Sketch of REMUS 600 AUV, showing subsystem configuration including optical modems and USBL transducer

B. *REMUS AUV Configuration*

The vehicle used for these field trials was a Next Generation REMUS 600 AUV configured as shown in Figure 2. The vehicle carried a single lithium-ion battery tray with 5400 watt-hour capacity, a navigation section containing a PHINS C7 INS and an RDI Acoustic Doppler Current Profiler (ADCP). The forward section was a wet section that housed the optical modem system, a downward looking USBL which was not used, and a standard REMUS 600 tow nose. Due to the core electronics design, the single battery tray was sufficient to power a 100km round trip transit and the data transfer at the station.

C. *AUV Mission Decsription*

The retrieval mission includes a long distance transit out to the reported position of an acoustic transponder, a loiter near the transponder while data is transferred, and a return transit. We created a new mission objective to perform the loiter. It included subscription to transponder position updates, and the ability to update the loiter center based on those position updates. Additionally, the objective had several end conditions: maximum time on station; signal from another vehicle introspection element; or user intervention via acoustic signaling.

III. NEW AUTONOMOUS BEHAVIOR

A. *Overall Tactics*

In addition to a new vehicle objective, we created monitor classes to sit between payload drivers and vehicle objectives. These monitor classes managed communication between payload drivers and vehicle objectives, and also handled control aspects such as sending the end signal to the loiter objective when the data transmission phase was complete.

B. *Acoustic Localization*

The Relative Loiter objective uses acoustic ranging for navigation, approaching and maintaining a set distance from an acoustic transponder. The vehicle queries the transponder with a ping and upon receiving the reply, it calculates a range based on two-way travel time and the measured speed of sound in the water. The objective handles both remote localization on approach and the terminal homing aspect of the mission. The vehicle transits toward the reported position of a transponder,

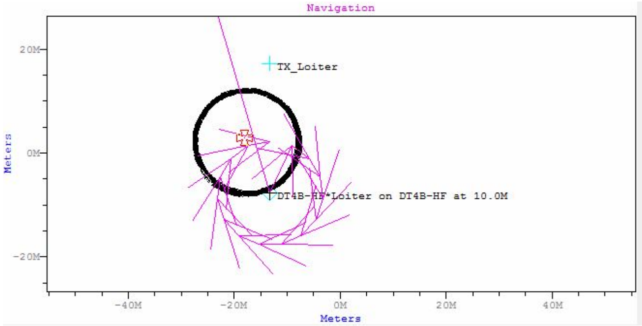

Figure 3 - Map showing vehicle path in black, along with planned path, (pink).

interrogating that transponder for ranges. When the vehicle receives replies, a new monitor task feeds them to an algorithm that generates a position from the input. Then, the monitor task publishes the algorithm's results for the rest of the system to use. The Relative Loiter objective subscribes to the position messages and uses them to update the navigation goal.

During the transit, an updated position represents a new end position. During the loiter, updates represent a new center of the loiter circle. As errors accumulate, or currents affect the vehicle trajectory, the station location in geo-coordinates will appear to drift in the vehicle frame of reference. However, navigating based on the acoustic ranges keeps the vehicle in physical proximity to the station even as navigation uncertainty builds.

C. *RANSAC Optimization*

To estimate position based on acoustic ranges, we used a modified version of the Random Sample Consensus (RANSAC) method to precisely determine the position of the transponder in the vehicle frame of reference based on the set of vehicle positions and acoustic ranges. Acoustic range data is prone to outliers. Correction for these outliers can be difficult without accurate knowledge of platform movement. RANSAC is able to simultaneously estimate a model and reject outliers. [7]

D. *Optical Link Quality of Service*

Given advancements by the Optical Modem Lab, the optical modem provides data transfer speeds rivaled only by fiber optic connections. The optical link is fast enough to allow a multi-node mission within the regular vehicle mission duration.

Additionally, the optical modem provided a break-through in delivering accurate timing to the station. [8] Significant, non-linear clock drifts increase with deployment time and present another of the main challenges to sustained OBS deployments. With recent advancements by the Optical Modem Laboratory, the optical link between the vehicle and the station provides more than data transmission. It provides time synchronization information, allowing the OBS to compare the station clock with the vehicle clock.

IV. DEMONSTRATION

A. *Method*

To carry out the data mule scenario, the vehicle begins with a Relative Loiter mission. Throughout the mission, the RANSAC manager is subscribing to acoustic ranges, seeding the RANSAC algorithm, and publishing the RANSAC results. Simultaneously, a data transfer monitor subscribes to the ranges; and when the vehicle gets within acoustic range of the station it takes care of waking the station and initiating the data transfer. During the data transfer, the data transfer monitor observes the data transfer statistics and when the transmission is finished, it shuts the station down gracefully and signals to the Relative Loiter that it is complete. The vehicle then transitions to the next objective. In the case of the demo, that was the return transit.

B. *Mission Area*

We tested this capability in Cape Cod Bay in June 2019. We deployed an OBS in 35m of water. Each mission was composed of a Relative Loiter objective followed by a transit objective to return to the start. For this demonstration, the vehicle transit distance from the mission start to the station location was 1km. We ran the demonstration at night to simulate the dark conditions that are found at the intended operational depth.

Figure 3 shows the geometry of the Relative Loiter mission. The offset between the planned path in pink and the vehicle path in black illustrates the difference between the estimated transponder position and the actual transponder position in the vehicle's frame of reference.

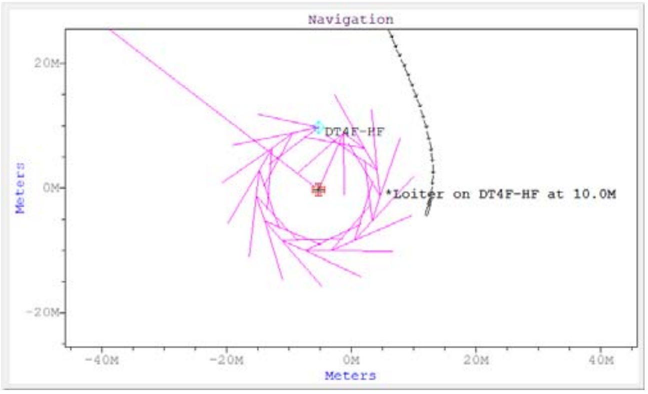

Figure 4 - Map showing the vehicle plan in pink, and the vehicle track in black. The vehicle goal is drawn in red, indicating the center of a circle that will bring the vehicle directly over the reported transponder position. The reported transponder position is shown in blue.

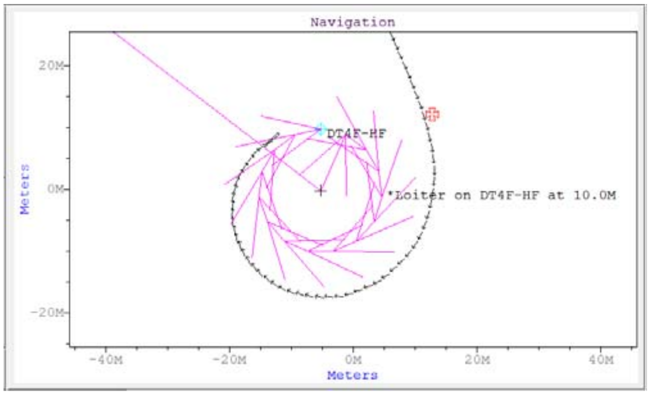

Figure 5 - Map showing the reported position of the DT4F transponder indicated by the blue diamond, and the vehicle's updated goal indicated by the red cross. The updated position represents the updated location of the center of the circle the vehicle will execute. The center of the circle is offset from the transponder position so that the vehicle will fly directly over the transponder during the mission.

C. *Results*

The first set of missions were run with the loiter set to a 10m radius; the loiter center was offset from the transponder position by 10m so that the vehicle would fly over the transponder. The second set of missions were run at 10m radius with no offset, so that the transponder was centered in the loiter circle. The last set of missions had 15m and 20m radii to test the extent of the optical link. In every case, the Relative Loiter behavior allowed the vehicle to maintain the programmed constant distance from the transponder.

Figures 4 and 5 illustrate the point in a mission where the vehicle has enough ranges to calculate the first position update. In Figure 4, the vehicle goal is to execute a circle around a position offset by 10m from the reported transponder position. In Figure 5, the vehicle has information that the transponder is actually to the east and north. The vehicle will perform a circle around the updated goal, which in this case represents a position offset by 10m from the actual transponder position.

Five of the June demonstration missions resulted in successful data transfers. In the first mission, the vehicle flew at high enough altitude that the vehicle could not maintain a good optical link; in this case, the length of the transmission was longer than the length of the user configurable time-out associated with the objective, and the mission ended before all the data was transferred.

In several cases, we found that poor acoustics had resulted in the station not properly receiving the shutdown command. When the subsequent mission began, the vehicle was not able to initiate a new session while the old session was in progress. This outcome is one for which we can implement safeguards. In the particular case of the demonstration, a faulty LBL transducer was found to be at fault for the intermittent acoustics; however, it is not difficult to imagine real world scenarios with sporadic acoustics, requiring an additional layer of verification to be certain the station is put into low power mode both to conserve energy and to enable future sessions.

V. SUMMARY

A. *Robust Data Exfiltration*

This project represents advances in several technologies combining to create a solution to a problem with societal impact. The problem we addressed is the use of OBS for affordable and efficient monitoring of off-shore sites to collect data with potential ramifications for risk prediction and mitigation. One of the major obstacles for this scenario was retrieval of the data without reliance on cumbersome fiber optic cable or expensive ship time.

The solution is an AUV that is equipped to independently transit to the off-shore sites, autonomously retrieve the data, and convey it back to users. Delivering that level of autonomy required new layers of REMUS vehicle introspection and control. We also introduced a novel position estimate in the form of the RANSAC algorithm operating on acoustic range information to provide transponder location updates throughout the mission.

We designed the new infrastructure to provide maintainability and the ability to easily expand vehicle introspection capability. These layers of communication and control lay the groundwork for the vehicle to be more independent in future applications.

B. *Future Work*

We can build on the capabilities developed in this phase of the work to make the vehicle and mission more robust. We can also implement autonomy modules to identify features of interest in the data; using the existing vehicle communication methods, data summaries or highlights could be sent over-the-horizon to users in advance of the vehicle's return with the rest of the data.

We can add layers of verification to the data transmission sequence, but more generally, we can put in place an introspection layer that monitors the progress of a vehicle mission. This would replace the time-outs that can interfere with a mission that is progressing more slowly than expected, allowing it to continue while progress continues.

Finally, we are continuing to expand the introspection layers to provide adaptive control; for example, having the vehicle speed up when it has no link and slow down when it has established a link. Here we can apply the system of performance metrics we are organizing to measure system performance, vehicle health, and mission progress; as we continue to expand the vehicle's ability to monitor its surroundings and plan against its observations.

This work has been supported by the U.S. National Science Foundation.

ACKNOWLEDGMENTS

The authors wish to thank the crew of the RV Discovery for their support of our in-water operations; and Hydroid Incorporated, a Kongsberg Company for initial support for development of the highly-integrated REMUS Core Electronics assembly.

REFERENCES

[1] C. McRaven, L.-P. Pelletier, J. Ware, A. Garder, N. Farr, J. Collins and M. Purcell, "Wireless Retrieval of High-Rate Ocean Bottom Seismograph Data and Time Synchronization using the WHOI Optical Modem and REMUS AUV," in *IEEE OCEANS*, Marseille, FRANCE, 2019.

[2] C. von Alt, B. Allen, T. Austin and R. Stokey, "Remote Environmental Measuring Units," in *Autonomous Underwater Vehicle Conference '94*, Cambridge, MA, 1994.

[3] E. Gallimore, R. Stokey and E. Terrill, "Robot Operating System (ROS) on the REMUS AUV using RECON," in *Proceedings of the 2018 IEEE OES Autonomous Underwater Vehicle Symposium*, Porto, Portugal, 2018.

[4] M. Quigley and e. al, "ROS: an open-source Robot Operating System," in *ICRA Worshop on Open Source Software*, 2009.

[5] N. E. Farr, J. D. Ware, C. Pontbriand and M. A. Tivey, "Demonstration of Wireless Data Harvesting from a Subsea Node," in *MTS/IEEE OCEANS*, San Diego, CA, 2013.

[6] C. Fiester, D. Gomez-Ibanez, M. Grund, M. Purcell, F. Jaffre, N. Forrester, T. Austin and R. Stokey, "A Modular, Compact, and Efficient Next Generation REMUS 600 AUV," in *MTS/IEEE OCEANS*, Marseille, FRANCE, 2019.

[7] J. Kaeli, G. Packard, C. Fiester, D. Tebo and a. M. Purcell, "A Range-Only Acoustic Localization Technique for Marine Robotic Applications," in *IEEE OCEANS*, Seattle, 2019.

[8] L. P. Pelletier, C. McRaven, J. Ware, A. Gardner, G. Packard, N. Farr, J. Collins and M. Purcell, "Delivery of Accurate Timing to Subsea Instruments via Optical Modem Technology with the Added Benefit of Optical Range Measurement," in *IEEE Oceans*, Seattle, 2019.