Continuous Autonomous Tracking and Imaging of White Sharks and Basking Sharks Using a REMUS-100 AUV

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***Abstract*-We present results from field experiments in which a REMUS-100 autonomous underwater vehicle (AUV) tracked multiple tagged sharks in the open ocean over periods of several hours. The Oceanographic Systems Laboratory (OSL) developed an algorithm that allows the vehicle to use information from an active transponder to provide a three dimensional track of the animal with high spatial and high temporal resolution. Field studies were conducted in the spring and summer of 2012. Two basking sharks and four white sharks were tagged and tracked for 1-3 hours. Here we present the engineering developments required to create the system.**

I. Introduction

Historically, the fine-scale movements of fishes have been studied using active tracking from boats (reviewed by Sundstrom et. al, 2001 [1]) and passive tracking with acoustic arrays (eg. Kneebone et. al. 2012 [2]). The former is typically hampered by logistical considerations (e.g. weather conditions, fuel) and provides poor spatial resolution (i.e. vessel movements are assumed to mimic those of the fish). Additionally, the vessel must constantly adjust to remain in close proximity with the tagged fish. Fish movements derived from the use of passive acoustic arrays also lack spatial resolution and are heavily dependent on the extent of receiver coverage (i.e. the fish is only detected when within range of the array). To overcome the shortcomings of these traditional methods, we modified a REMUS-100 Autonomous Underwater Vehicle (AUV) to locate, follow and approach a tagged animal.

REMUS (Remote Environmental Monitoring UnitS), is a family of AUVs , with depth ratings from 100 meters to 6000 meters, designed and developed by Oceanographic Systems Laboratory (OSL) of the Woods Hole Oceanographic Institution (WHOI) [3]. We used a REMUS-100 which is pressure rated for use up to 100 meters depth and is a versatile platform for underwater observation. REMUS can be easily reconfigured on a per mission basis to accommodate a versatile suite of sensors for science and military applications [4].
The objective of this work was to create a system that could provide high resolution three-dimensional position information regarding the animal under observation, collect associated environmental data and approach the tagged animal to provide visual data about its behavior and prey.

The idea of tracking an animal with an AUV is not unique. Unbeknownst to us, a similar system was also being developed at the same time using an AUV to track a tagged shark [5]. In that approach, they used a particle filter to produce a state estimate of the tag location. Our approach results in a direct measurement of the animal's location and depth yielding far greater positional accuracy in order to film a moving animal at close range.

The system consists of a transponder which is attached to the shark and the REMUS-100 vehicle (Fig. 1) which has been equipped with an omni-directional Ultra-Short BaseLine (USBL) receiver. The vehicle interrogates the transponder and derives range and bearing from the reply. This provided two-dimensional tracking. In order to resolve the third-dimension, we modified the transponder to telemeter depth information. We also added a release mechanism to facilitate retrieval of the transponder from the animal.

The vehicle firmware was modified by creating a new "objective", the basic building block of REMUS mission programming. This objective is designed to follow the transponder, and to do fly bys and fly overs, adjusting its speed to catch the animal when the range was long, and slowing to match the speed of the animal when it was nearby. Once the vehicle had passed the shark it would circle back and re-approach for another pass. This was a challenging problem, in that the target is capable of changing its heading, speed and depth randomly. Additionally, it was not sufficient to go where the shark had been, but REMUS also had to predict where it expected the target to be. This forced the vehicle CPU to continually recalculate the target position and estimate its current track, so that the vehicle could properly position itself to follow and approach. The vehicle always maintained a current estimate of its own position using existing REMUS self-navigation capabilities. The target position was then estimated based on the relative range and bearing as measured from the vehicle. Periodic navigation resets were accomplished by having the vehicle surface for a GPS fix.

Field tests were conducted in the waters off Cape Cod during spring and summer of 2012. Initial testing was accomplished by simply towing the transponder from a small boat.. We ultimately successfully tracked two basking sharks (*Cetorhinus maximus*) and four white sharks (*Carcharodon carcharias*), each for 1-3 hours. In addition to recording the animals' 3D tracks for the duration of the mission, the vehicle was able to follow closely along the track recording oceanographic measurements and approaching the animal to capture high definition video.

Figure 1(a). View from the boat showing the REMUS-100 shark tracking vehicle as it begins to track a tagged white shark. ©Big Wave Productions

Figure 1(b). View from the vehicle looking forward toward a tagged basking shark at the start of a mission. ©Big Wave Productions

II. Transponder Improvements

Each shark was tagged with a modified REMUS transponder (Fig. 2) tethered to an intramuscular dart. The vehicle uses the (USBL) acoustic navigation system to interrogate the transponder in order to estimate the range and bearing to the moving target every three seconds. The transponder was modified with an acoustic burn wire release, and also underwent software and hardware modifications in order to incorporate depth telemetry. The REMUS software was also modified to receive the depth information and utilize it during its approach to the moving target. Real-time transmissions of depth and position data allowed the operator to offset the vehicle depth above or below the depth of the shark if a different vantage point was desired while the mission was still underway. When the shark was working near the bottom, the vehicle's on board altimeter was used to maintain a minimum range above the bottom. When the vehicle's mission was complete, the transponder was programmed to accept an acoustic command at the end of each field trial to release from the animal and float to the surface for retrieval.

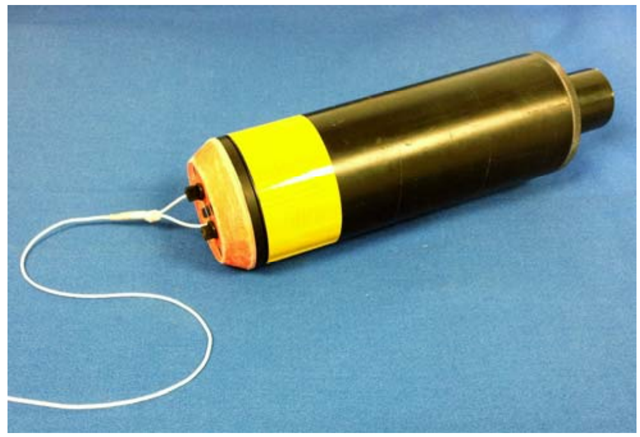

Figure 2. Transponder.

III. Algorithm

The REMUS vehicle software required a new algorithm to perform autonomous tracking, following, approach and fly-by of the randomly moving target. We developed a new mission scenario with adaptive behaviors. On start-up, the vehicle uses an initial assumption of the shark's location. However, this was typically an inaccurate initial position. To overcome this, once the vehicle was launched we would update the vehicle's estimate of the animal's location via acoustic modem. As it approached, the vehicle would "lock on" to the tag, start getting fixes, and autonomously determine the relative location of the animal using its on-board USBL acoustic navigation system. Once the vehicle has localized the animal's position, it begins estimating the animal's track, course and speed. Using continual updates, the vehicle autonomously re-plans the mission path to approach the tagged animal from behind, and eventually pass the animal in a pre-planned, user defined orientation. The vehicle can be configured to pass directly above the animal, directly below, to the left or to the right.

IV. Payload

Many different sensors have been integrated and used on the REMUS-100 system over the past 20 years [6], [7] and [8]. During this field test, the vehicle carried an omni-directional USBL array, GPS, an Acoustic Doppler Current Profiler (ADCP) for current data and speed over ground measurements, a Conductivity-Temperature (CT) probe, magnetic heading sensor, a WHOI micromodem, pressure sensor and four Go-Pro HD video cameras (Fig. 3). One camera was mounted on top of the vehicle looking forward. The other three cameras were mounted in a custom camera nose section; one looked left, one looked right and the third camera had a 45-degree mechanical pivot allowing it to look forward and slightly upward or downward.

Figure 3. Vehicle equipped with Go-Pro HD video cameras, acoustic navigation system and environmental sensors. ©Big Wave Productions

V. Field Tests

Field studies were conducted in the fall, spring and summer of 2012 off Cape Cod, MA and consisted of four phases.

A. Phase I: RHIB Following

Initial engineering field trials in the fall were conducted by towing a transponder below a moving RHIB and programming REMUS to use the follow objective to home in on it. The vehicle was told to swim at one meter depth in order for the operators to be able to visually track REMUS. This allowed the operators to effectively speed up/slow down the RHIB in order to emulate the random maneuvers of a fish and acoustically command REMUS to do the same in order to test its fly by capabilities.

B. Phase II: Dive Scooter Following

A second engineering trial involved a more dynamic and fish-like platform. A diver-occupied scooter was rigged with a transponder while REMUS was programmed to follow its maneuvers into a more realistic physical environment for sharks. The scooter swam inshore and offshore transects testing the vehicle's USBL homing capability in shallow water and its reaction time for turning offshore to reacquire the transponder. The scooter also varied its depth verifying that REMUS was capable of matching the changing depth of the transponder.

C. Phase III: Shark Following

In total, two basking (*Cetorhinus maximus*) and four white (*Carcharodon carcharias*) sharks were tagged with the active transponder and tracked for 1-3 hours (Fig. 4).

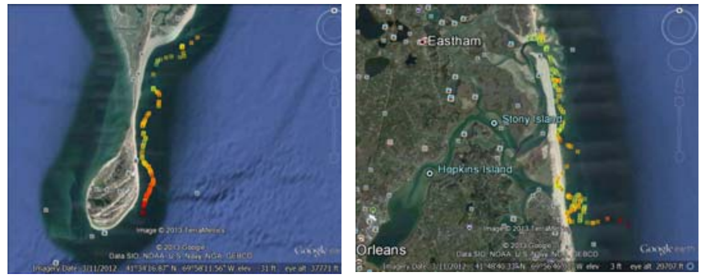

Figure 4. Sample tracks of two white sharks swimming off Monomoy (left) and Orleans (right).

For a typical mission, the AUV was launched immediately after the shark was tagged and given an initial position based on the assumed tagged shark position. . The vehicle would dive, immediately point itself in the direction of the shark and begin pinging the transponder and listening for replies. The USBL array interrogated the transponder every three seconds. From the response, the vehicle could estimate the range and bearing to the animal and the animal's depth. The vehicle combined the relative position of the target with the known position of the vehicle to provide accurate latitude, longitude, depth and time data for the shark over the duration of the mission. During the mission, the vehicle would telemeter back to the shipboard tracking station via its micromodem allowing operators to verify the positions of both the shark and REMUS. On board the ship, a separate handheld acoustic Ranger was used to independently verify the exact position of the shark and the REMUS. The ranger information along with acoustic fix ages received from the REMUS modem of its last known successful ping allowed operators to calculate how well the shark following was working.

Upon completion of each mission, an acoustic ping was sent to the transponder from the ship activating a burn wire. When released, the neutrally buoyant transponder would float to the surface. A handheld Ranger was used to locate the transponder. Batteries and the burn wire were replaced between each mission.

VI. Results

For each tracked animal we recorded the position of the vehicle, the relative position of the tag to the vehicle, the depth of the tag, the bathymetry along the vehicle track, the environmental data along the vehicle track and video of the animals.

Below (Fig. 5) we show an example of a vehicle track overlaying the animal position. The vehicle occupied each of the shark's positions within seconds or minutes. (Fig. 6) shows the vehicle travelling in close proximity to the shark.

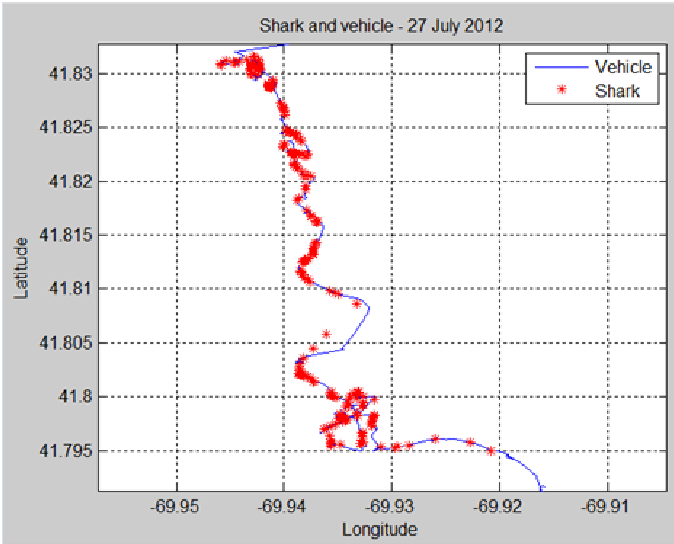

Figure 5. Each red asterisk represents the calculated position of the shark based on a received acoustic ping from the transponder.


Figure 6. The view from the camera atop REMUS as the vehicle travels with a white shark in the turbid summer waters off Cape Cod.

Occasionally, the vehicle would stop receiving responses from the shark's transponder for brief periods. The transponder is radially directional, and when towed, may orient to send the responses toward the surface and the bottom, not horizontally. Another possibility is that when the shark moved at faster speeds, Doppler shift in the transmitted signals meant the receiver on the vehicle had poor correlation, and rejected the results. We are developing improvements to deal with both issues.

A conventional REMUS as used in this project has a minimum speed slightly under one meter per second. Below that, the vehicle is less stable. Also, the vehicle itself has depth limits far less than that of the shark. However, the off-the-shelf HD camera housings were the limiting factor, and the vehicle was programmed to limit its depth excursion to their safe operating depth of 60 meters.

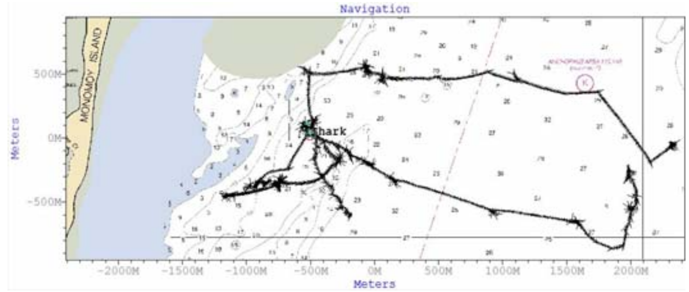

Figure 7. The arrows show the vehicle path as it approaches and occasionally flies over the shark.

As the vehicle followed the shark the bottom was profiled, allowing us to examine the shark's behavior with respect to bathymetry. We calculated the shark's altitude based on the known water depth and the shark's depth at points along the track. Additionally, REMUS collected conductivity, temperature and current data along the track which can readily be used to examine the extent to which these parameters impact the animal's behavior. As an example, temperature data are mapped with the shark's positions in the water column (Fig. 8). In this case, water temperature did not change dramatically given the shallow water, however this may not be the case when the sharks enter deeper waters.

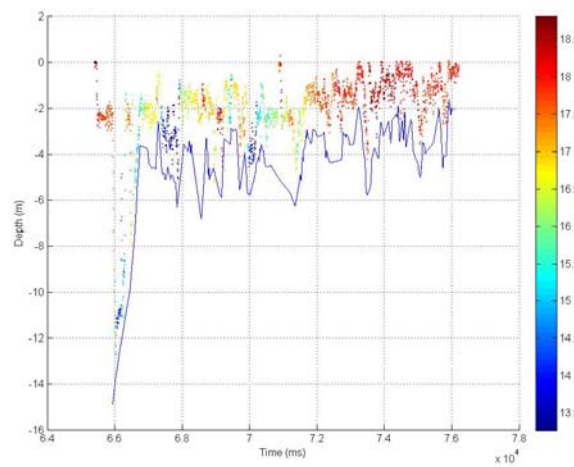

Figure 8. The shark's position in the water column is plotted over the bathymetry. The color of each point indicates the water temperature at that depth.

The great whites we tagged were seal hunters. Unlike the classic "Jaws" legend, they spent very little time near the surface. During our operations they spent most of the time near the bottom, where they could silhouette their prey against the sky. They frequently were in very shallow water that challenged the operating capabilities of the vehicle. It is clear that observing them from shore (for example at a swimming beach) would be difficult, and thus tagging and monitoring operations are essential for public safety

For us, the observers, it was very clear where the seal colonies were located, and while the sharks tended to congregate in those areas, they also ranged many kilometers outside this area.

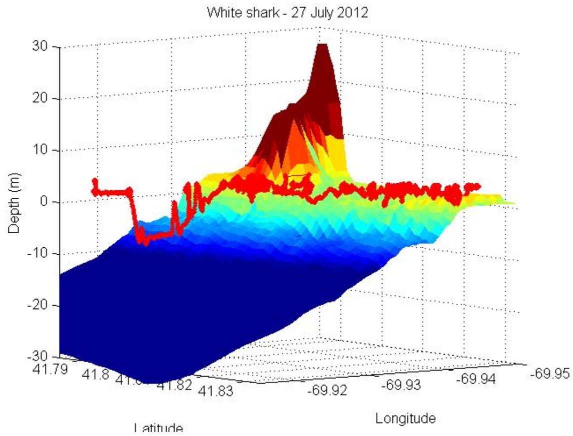

Figure 9. Three-dimensional plot of shark track superimposed on GEOSAT bathymetry set.

VII. Conclusion

The REMUS-100 tracking vehicle demonstrated its ability to autonomously monitor, follow, approach and image randomly moving tagged targets. The vehicle, which can easily be deployed in waters inaccessible to or unsafe for divers, is capable of producing highly precise tracks while collecting environmental data and behavioral imagery over periods of several hours. The visibility in waters off of Cape Cod was less than ten feet and in most cases, less than 5 feet. The achieved imagery from these tracks ultimately proves how close and for how long REMUS was able to follow and track sharks.

Moreover, the vehicle is versatile and can take on different payloads to meet science goals. We firmly believe that this technology offers a new and innovative tool for tracking the fine-scale behavior of marine animals.

Acknowledgment

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