Fish telemetry and positioning from an autonomous underwater vehicle (AUV)

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Abstract *- We assessed telemetry of transmitter- tagged fishes from an autonomous underwater vehicle with an attached hydrophone/datalogger that procesed code-division-multiple-access acoustic signals. Geolocation estimates used synthetic aperture and relative sound strength mapping. Transmitters could be detected at all angles relative to the AUV heading and as far as 2 km distant. Signal reception patterns from tagged Atlantic sturgeon, a large nektonic fish, were similar to that of moored reference tags but those from tagged winter flounder, a small benthic fish, were reduced in range due to burying behavior.The effectiveness of synthetic aperture and signal strength mapping techniques to geolocate tags were sensitive to the AUV's path past or around the tag and complement each other as preferable solutions in different circumstances. Strategies of AUV search path for telemetry need to be explored further.*

Keywords - AUV; telemetry; sturgeon; flounder; synthetic aperture

INTRODUCTION

Tagging marine macrofauna with acoustic transmitters and following their progress through fixed hydrophone listening arrays or with mobile vessels is known as telemetry. Mobile telemetry remains an important telemetry tool because fish move and interact with habitat features on much larger or smaller scales than moored hydrophone arrays, especially in coastal or oceanic water [e.g.1,2,3]. Autonomous underwater vehicles (AUVs) are attractive as a complement or alternative to surface vessels for mobile telemetry. Robots, in general, could excel at deep or tedious missions such as tracking fish in continental shelf or deeper waters. AUVs in particular can simultaneously and continuously sample hydrography and benthic sidescan data for habitat delineation at depths relevant to the animals under study [4]. Freedom from a cable allows signal reception and processing at depth, below interfering thermoclines, without line-associated signal attenuation or vehicle pitch and along with complementary environmental data collection.

However, AUV use presents several unique challenges. A lack of real-time data transfer prevents en-route decision making. There are potential conflicts in choosing paths for best sampling of different variables (hydrography, benthic mapping, fish detection). Hydrophone position on the vehicle must not compromise effective navigation or produce undue drag, but should be oriented and placed so that the vehicle does not prevent tag reception. Finally, AUVs are potentially mechanically or electrically noisey and utilize a number of active sonic sensors and navigation tools that might interfere with transmitter tag reception.

We explored the signal reception patterns and geolocation solutions of an AUV during simultaneous telemetry and habitat mapping missions. We mapped signals from moored reference transmitters in known locations as well as from transmitters on two morphologically different species of fishes at liberty. This helps develop bounds of expectation useful for mission planning and data interpretation.

METHODS

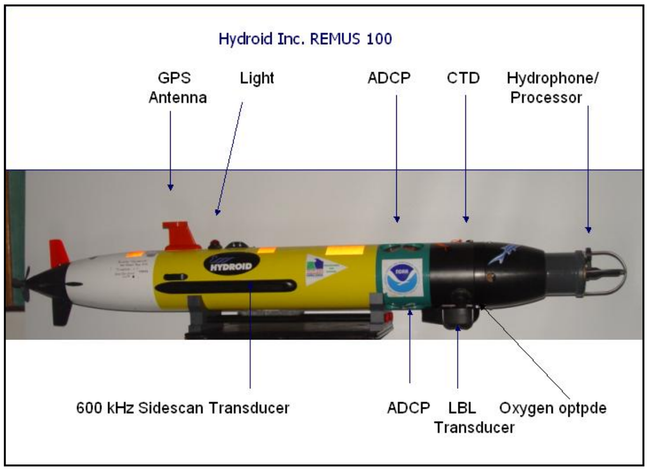
Platform

The Remote Environmental Measuring Units (REMUS-100, Hydroid Inc., Pocasset, MA) is an autonomous, propeller-driven AUV. The 36 kg (1.6 m length by 0.19 m diameter) vehicle hosts a conductivity/temperature/depth sensor (CTD, Yellow Springs Instruments, Yellow Springs Ohio, USA), a rapid response oxygen optode (Aanderaa Data Instruments, Bergen, Norway), chromatic dissolved organic materials (CDOM) optode triplet (Wetlabs, Inc., Philomath, Oregon, USA), chlorophyll a optode (Wetlabs, Inc.), port and starboard sidescan sonar (Marine Sonic Technology, Ltd., Whitemarsh, Virginia, USA), and upward and downward looking acoustic current Doppler profilers (ADCPs, Teledyne RD Instruments, Poway, California, USA), [5].

REMUS follows a user-programmed path. Navigation may apply dead-reckoning and/or transponder-based trialateration. Estimated fixes are calibrated by global positioning satellite (GPS) fixes taken while at the surface. Ballast is static. Depth and trim is achieved dynamically by control surfaces. REMUS has an endurance of 14 h at 1.5 m/s velocity or approximately 9 h at 2 m/s. It may thus supply a near-synoptic view of mesoscale hydrography [6]. REMUS AUVs are deployed worldwide in various scientific and naval missions, including under ice.

Telemetry Instrumentation

A hydrophone/processor (WHS_3050, Lotek Wireless, Inc., St. Johns, Newfoundland, Canada) was faired and mounted coaxially with the vehicle in place of its nose cone (Fig. 1). The package was minimally modified from its intended use as a moored wireless system by removing the battery case and drawing power from the AUV's guest port. Nominal power requirements of the WHS represent only 0.5 % of the AUV's 1 kWh battery budget over a 9 hr mission. The channel does not overlap with the operating frequencies of optional long-base-line navigation transducers (20-30 kHz), sidescan (600 kHz), or ADCP (1200 kHz).



“Fig. 1.” The REMUS AUV with co-axial hydrophone

Hydrophone and AUV clocks are synchronized before launch. The processor is capable of discerning 80,000 individual coded acoustic tags using code-division multiple access (CDMA). CDMA is robust against interference from motorized platform noise, echo from ice or hard reef, or code collision from multiple tags. Therefore, it is not necessary to stagger or vary signal bursts rates within or among tags, and signals may be trasmitted at short intervals. Accurate and invariant signal burst timing is a requisite for synthetic aperture geolocation [7,8]. Tags in the Lotek Inc. MAP series broadcast individually coded acoustic signals (76 kHz, 149 -162 dB re 1 µPa at 1 m) at programmable intervals (as low as 1.5 s apart) with an expected life span from 9 d to >3 y (depending on tag model and transmission rate). In addition, these tags may carry temperature, pressure, and motion sensors that acoustically broadcast their data.

Data Processing

Identified signals are stored with a time stamp and a value of sound pressure as relative signal strength (RSS) and optional sensor data. Data is retrieved from the WHS as a binary file and converted to a text file. The AUV likewise outputs a mission data file in ASCII text or MATLAB (Mathworks, Inc., Natick, Massachussets, USA) format that includes location, depth, speed, heading, sound speed, salinity, temperature, depth, flow, oxygen concentration and percent saturation, suspended materials backscatter, CDOM, chlorophyll a concentration and several vehicle performance variables at 1 s intervals. The position of the AUV at a given timestamp from the WHS (precise to <0.001 s) is interpolated from the navigation data of the AUV using MATLAB. This position is thus also associated with a particular RSS value for a given tag. Sidescan files are downloaded separately and processed in Sea Scan Review PC (Marine Sonic Technologies LTD) that allows queries of position, depth, altitude over bottom, and distance from AUV for user-selected targets through a graphic user interface.

RSS Mapping

While the RSS of any single acoustic reception at a given distance may vary over time due to numerous factors such as water density or sediment or bubble load, a series of reception values within a mission may be used as an indication of relative proximity. We explored the shape of the RSS distribution for its utility in approximating tag location on linear and simple non-linear mission paths. For non-linear mission paths, RSS was contoured in MATLAB using nearest neighbor interpolation to a grid of appropriate spacing (i.e. Kriging) to provide a graphic probability plot of tag location.

Synthetic Aperture

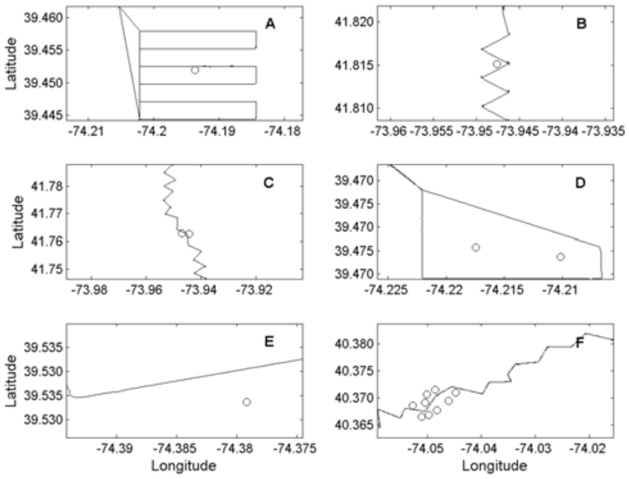
For more refined geolocation, the invariant timing of the tag broadcasts allows application of a synthetic aperture algorithm (SYNAPS, Lotek Wireless, Inc.). Synthetic aperture processing has been widely used for a variety of applications including with RADAR and SONAR instruments [9,10,11]. However, its use in ultrasonic bio-telemetry is novel, and it differs from previous applications in that it is not used to synthesize a picture (as in an echogram). Typical synthetic aperture processing system integrates the transmitter and receiver as one hardware unit, the transceiver. In the case of SYNAPS, however, the two operations are conducted separately; the signal is transmitted by the tag in the water and received by the moving WHS and assigned a time-of-arrival [8]. Execution of a turn within the period during which several receptions are made creates a synthetic array similar to a physical moored array used for trialateration and can resolve the position estimate to unimodality through a hyperbolic positioning algorithm. Iterative solutions using an initial detection set and additional detections provide mean square error criteria to evaluate dilution of precision (DOP). Sound speed uncertainty, a factor in determining precision, is supplied by the AUV’s navigation software, which calculates it from the CTD data.

Synthetic aperture does not become unstable in the presence of animal movement but increases the spacing of the solution grid, which is appropriate for a moving fish because a moving fish is not closely associated with a small static feature. Pitch and roll of the hydrophone are not issues in performance for calculating a position estimate by synthetic aperture, as they would be for imaging.

Assessment

We compiled data on transmitter-receiver coupling from 10 missions in riverine, estuarine, and coastal ocean environments. Stationary reference tags were deployed as controls in all included missions (Table 1, Fig. 2). Additionally, tagged Atlantic sturgeon (*Acipenser oxyrinchus*) and winter flounder (*Pseudopleuronectes americanus*) were at liberty in the study areas during three each of these missions respectively. Atlantic sturgeon are large (to 4 m, 100 kg) strong swimming migrant fish with a primarily marine habit but ascend large rivers to spawn. Winter flounder are small (to 0.04 m, 2 kg) flatfishes with a slow, benthic, oceanic habit but may move into estuaries to spawn. Specimens of both were tagged with Lotek MAP series transmitters in different areas for independent studies of habitat use and movement.

Together, these missions provided 1733 detection records of reference tags in known positions through which the AUV navigated at different times and different angles of approach (98 combinations of path and reference tag). This comprehensive data set was taken together to describe the reception pattern relative to the angle and distance between the vehicle (relative to its own heading) and the tag in varying conditions.



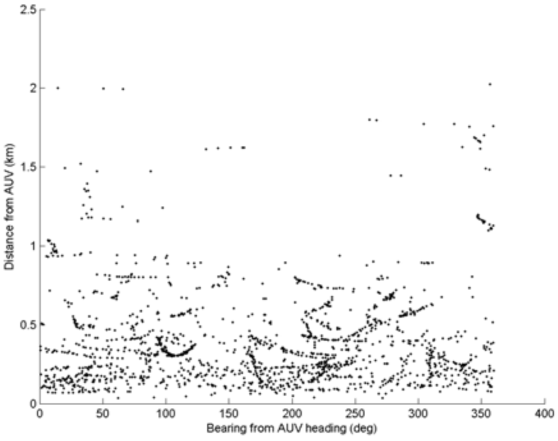
“Fig. 2.” Mission paths (plan view) and position of reference tags (open circles). A. AUV launch in the northwest corner, navigation to and through a grid at 1.5 and 1.8 m/s, followed by navigation along western grid margin to grid origin, grid repeat at 1.8 m/s, and return to launch point. B. Bank to bank zig-zag in Hudson River. C. Bank to bank zig-zag in Hudson River through Krum Elbow, repeated as two separate missions. D. Polygon mission path repeated twice, once with sidescan transducer disabled. E. Straight path past reference tag. F. Mission along navigable stretch of Navesink River Estuary from northwest launch point through fixed hydrophone array with reference tags and return to launch point. Mission was repeated three times.

A single linear navigation path will change the angle of the tag’s bearing relative to the vehicle’s heading as well as the distance to the tag. Irregular and zig-zag navigation paths approached and passed multiple moored tags or approached, turned and retreated from tags at different angles resulting in varying combinations of approach/depart angles and distances. For each position of the vehicle at a particular reference transmitter detection, the distance of that transmitter from the position of the vehicle was calculated in MATLAB using the Haversine formula, and the bearing was calculated and then rotated to reference the vehicle’s heading (Phi) as zero (bearing_1 = modulo(Phi – bearing_0), 360), thus providing an angle to the reference transmitter from the vehicle’s travel axis. This angle of approach/departure and distance were plotted against each other as well as against the power of reception (RSS) to graphically identify the domain of detections along these gradients. The power of reception was also plotted against AUV speed for a single mission with repeat tracks run at 1.5 and 1.8 m/s, and the effect of velocity on the number of detections was tested. All tests were single factor ANOVA with alpha = 0.05. All detections were mapped to graphically determine the position of tags for comparison with the known position, and the position of several reference tags was determined using SYNAPS and RSS mapping for comparison to the known position.

RESULTS

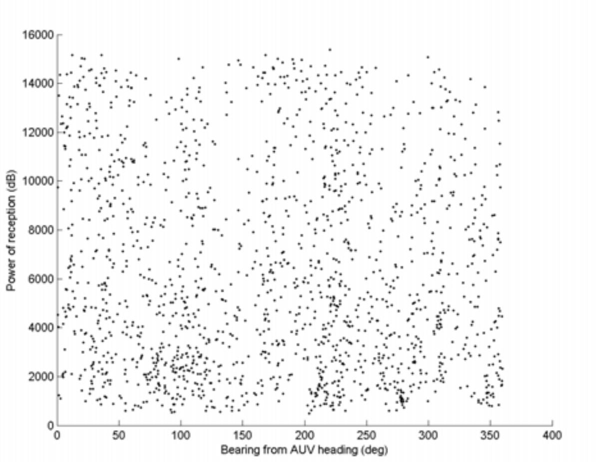
The AUV-mounted hydrophone detected moored acoustic transmitter tags as well as those on fish at liberty (Table 1). The distance and power with which tranmsitters were detected varied with environment and fish behavior. In the Hudson River, the AUV detected tags in excess of 2 km distant. Thus, signals from individual tags were detected during multiple path legs (AUV headings), allowing for creation of synthetic arrays that could calculate position estimates. However, location was determined with greater precision for stationary tags than sturgeon there, because the large fish could move significant distances during array creation. Winter flounder were detected from smaller distances than reference tags and fewer times per pass. However, maximum RSS of a detection set was often as high for these as for reference tranmsitters. This is consistent with flounder being buried or lying in depressions, during which sound is occluded to the side by sediment more than overhead. In this situation, the tags were often detected during only a single path segment (constant heading), therefore, appropriate synthetic arrays (low DOP) could not be constructed for several individuals or a set of iterative solutions was bimodal in reference to the vehiles travel axis. RSS mapping was useful for estimating flounder position along a single vector. Location estimates from RSS maps compared favorably with synthetic aperture solutions but tended to center along the vehicle path because the highest RSS values are always associated with a vehicle coordinate.

Reference tags were detected at all bearings relative to the AUV’s heading (Figs. 3, 4). There was a highly significant (Model 1 Regression, R^2= 0.2299, p<0.0000) relationship between RSS and distance to the reference tags described by y = -6630.1 *x + 8820.5. For the compiled set from all tags/missions, there was a slight negative relationship for angle at detection on RSS (Model 1 Regression, R^2= 0.0045, p=0.0051) described by y=-2.71*x+6741.5.



“Fig. 3.” Scatter plot of the distance between a transmitting tag and the AUV and the bearing between the tag and the AUV’s axis of travel.

The sign of these relationships was not consistent among individual mission/tag combinations. However, tags were more frequently detected as the vehicle approached, rather than departed from reference tag locations.



“Fig. 4.” Scatter plot of the signal strength received from a transmitting tag and the bearing between the tag and the AUV’s axis of travel.

“Table 1.”

Mission	Location	No. of tags Ref. (fish)	Detections Ref. (fish)
1	Great Bay, NJ	2 (0)	104 (0)
2	Ocean, NJ	2 (0)	91 (0)
3	Ocean, NJ	1 (0)	95 (0)
4	Navesink Estuary, NJ	7 (12)	328 (142)
5-7	Navesink Estuary, NJ	9 (16)	675 (365)
8	Hudson River, NY	1 (2)	131 (90)
9	Hudson River, NY	1 (2)	150 (118)
10	Hudson River, NY	1 (1)	118 (55)

Hydrography and bathymetry data was collected during all missions. Sidescan echograms from the Hudson River estuary missions showed 79 additional (untagged) Atlantic sturgeon and numerous unidentified fishes, but winter flounder, which are small and do not provide verticel releif from the bottom, were not imaged [3]. There was no difference in the powere of reception as a function of teh two tested speeds (1.35 and 1.8 m/s speed-made good) but the AUV detected more reference tag signals (64 at a rate of 0.63 detections per minute) at the higher speed than at the lower speed (26, signals at a rate of 0.28 detections per minute) over the same course.

CONCLUSIONS

This work demonstrates that an AUV can simultaneously telemeter tagged fish distribution and survey hydrographic and benthic habitat parameters. The use of AUVs to map individual fish movement relative to dynamic habitat features is especially promising for the continental shelf because of the expense and challenges of placing and maintaining instruments there on scales germane to mesoscale questions.

The time-invariant coding structure made synthetic aperture possible and proved to be robust to noise and interference that could typify some niche applications for this tool. The success of this “bolt on” integration makes it worthwhile to explore more complex models, such as integrating of the hydrophone’s circuitry with the AUV’s. That would lower the system’s mass and wetted area, allow different hydrophone orientations, and would facilitate direct communication and a single clock. This, in turn, would allow for reactive navigation (maneuvers cued by data events). Until then, paths must compromise between the detection range of the hydrophone for its transmitting tags, the spatial resolution being sought for fish positions, the suite of possible behaviors exhibited by the tagged fish in response to parameters under study, the resolution of the hydrographic features of interest, and the useful AUV battery life/mission length. Mission planners should therefore consider the size and shape of the search area, the path of the vehicle inside that area, including the spacing and shape of search segments, the vehicle speed, and the vertical profile of the path. While these may seem to be a long list of requirements, they do not differ from those needed to conduct searches from a manned surface vessel, although survey designs cannot be changed en-route. The particular strengths of the AUV is that they can be deployed in complement to a telemetry survey by a surface vessel without additional crew or significant additional sea-time and such an operation and that they can gather environmental data simultaneously.

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