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Human vs robot: Comparing the viability and utility of autonomous underwater vehicles for the acoustic telemetry tracking of marine organisms

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ABSTRACT

Currently, individual animal movement data can be obtained using a variety of methods, but each methodology is limited in either temporal or spatial resolution. A new method of active tracking was developed which utilizes autonomous underwater vehicles (AUV) equipped with stereo-hydrophones that can accurately estimate the position of a moving acoustic tag, while remaining at a distance. This technology was tested and compared to standard human-based active tracking technology to understand the benefits and limitations of this new technique. An AUV and a researcher independently tracked stationary and moving targets of known location in order to compare their spatial and temporal accuracy. Both methods were then used to track a leopard shark, *Triakis semifasciata*, in the field. The autonomous vehicle accurately positioned both stationary and moving tags with a positional error of <10 m. For stationary transmitters, the AUV and the researcher were comparable, but when tracking moving transmitters, the AUV had significantly better spatial accuracy. Throughout all trials, the AUV had a higher frequency of accurate location estimates than a researcher actively tracking. Based on these findings, the AUV was able to more accurately track and record the position of an acoustically tagged shark in the field. Using this new technology, researchers should be able to maintain or improve the spatial resolution of measurements when actively tracking acoustically tagged individuals and will be able to increase the temporal resolution of measurements while minimizing the potential influence of tracking on the behavior of the animal.

1. Introduction

Quantifying animal movement at fine spatio-temporal resolutions has provided insight into behaviors, such as social interactions, interspecies interactions, micro habitat selection, and activity levels (Berejikian et al., 2016; Cagnacci et al., 2010; Coulombe et al., 2006; Garcia et al., 2015; Mourier et al., 2012). Technology allowing for the coupling of spatial information to high resolution behavior information from data loggers (i.e. accelerometry, video), along with fine-scale adjacent environmental data, are providing opportunities to better understand the decision-making processes in animals (Hays et al., 2016; Hussey et al., 2015). Obtaining high resolution movement data (± 3 m) for mobile marine animals has been challenging though due to technology limitations. While tools like satellite telemetry (e.g., GPS fastlock) have been extremely effective in quantifying fine-scale movements of terrestrial and air-breathing marine animals, this technology has not been as effective for non-air breathing marine animals, due to the limited amounts of time these animals may spend at the surface or the poor positional resolution of archiving satellite transmitters (Hussey et al., 2015). As a result, acoustic telemetry tracking has been the primary tool for gathering movement information on non-air breathing mobile marine animals. Unlike satellite telemetry, acoustic telemetry requires a more proximate (<1 km) hydrophone and receivers to detect acoustic transmissions which are used to convey positioning information. Acoustic telemetry tracking can be applied using several techniques (active tracking, passive tracking, multi-lateration arrays, acoustic surveys) designed to estimate location of individuals, yet each technique has unique limitations, including degree of labor intensity, spatio-temporal resolution or scale (Bass and Rascovich, 1965; Grothues et al., 2010; Haulsee et al., 2015; Heupel and Webber, 2012).

Historically, active tracking, following an animal fitted with an acoustic transmitter from a surface vessel, has been the primary tool used to acquire high-resolution spatial movement information for mobile marine animals (Bass and Rascovich, 1965; Nelson, 1978, 1990). By closely following the animal, the tracker is able to use the position of the vessel as an estimate of the position of the animal. Depending

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on the proximity of the animal to the surface this localization technique could influence its behavior, so often trackers try to maintain distance between the vessel and the animal being tracked. Furthermore, oceanographic conditions, the position of the animal in the water column, the speed of the animal, as well as the trackers experience and skill level can all impact the spatio-temporal resolution of location estimate. These factors combined result in active tracking producing temporal resolutions between 5 and 30 min, spatial accuracies of between 5 and 30 m, and due to the labor intensity, temporal scales ranging from hours to days. While this provides a relatively fine spatio-temporal resolution, the resolution is often insufficient to be able to identify differences between Area Restricted Search (ARS - indicative of foraging) and resting. Despite these limitations, active tracking has remained one of the most common method to track the fine spatial movements, and habitat associations of an individual.

In order to extend the temporal scale and to simultaneously track more individuals over longer periods of time (days to years), researchers have turned to autonomous "passive" tracking systems to also obtain movement information. These systems rely on stationary omni-directional underwater receivers in arrays, grids, or strategically placed locations to detect movement patterns (Heupel et al., 2006; Heupel and Webber, 2012). These receivers can only determine whether a transmitter is present within its detection radius, which can vary considerably depending on habitat, oceanographic conditions, weather, and the power output of the transmitter. Yet, these systems sacrifice spatial resolution (>100 m) and frequency of position estimates compared to active tracking; however, this varies depending on the system.

More recently, there have been a variety of multi-lateration positioning systems developed to further generate fine-scale positions from a passive acoustic array (Biesinger et al., 2013; Ehrenberg and Steig, 2002; Heupel and Webber, 2012; Klimley et al., 2001; Steig and Johnston, 2010). These systems, such as the Vemco VRAP and VPS, HTI Model 290, and the Lotek MAP600 use differences in time-of-arrival of a detection on multiple acoustic receivers to estimate the position of a transmitter. By positioning stationary receivers in high densities, these multi-lateration arrays can provide fine positional resolution (<5 m) of multiple tagged individuals simultaneously (Andrews et al., 2011; Espinoza et al., 2011). Since many marine animals are often moving through complex, heterogeneous habitats, obtaining consistent positions is difficult due to the static nature of the array, resulting in consistent or intermittent "dead spots" within the array (Biesinger et al., 2013; Binder et al., 2016). In addition, changing environmental conditions and biofouling of stationary receivers can also effect position estimate frequency and accuracy (Clements et al., 2005; Heupel et al., 2008). These systems increase the spatial resolution of passive arrays, however, they still often lack the ability to obtain positions at fine temporal resolutions, and are not effective at tracking highly mobile species that move beyond the extent of an acoustic receiver array. In addition, due to the high density of receivers and costs of post processing these systems can incur significant costs over a traditional passive array with poorer positional accuracy.

In order to survey for tagged individuals dispersed over larger areas, researchers have been equipping autonomous underwater vehicles (AUVs, e.g. gliders and propeller driven vehicles) with passive acoustic receivers (Grothues et al., 2010; Grothues and Dobarro, 2009; Haulsee et al., 2015). These AUVs use a single passive receiver and move along preprogrammed paths surveying for tagged individuals while simultaneously collecting a wide array of oceanographic data (e.g., salinity, DO, light, chlorophyll, bathymetry, and video). These systems however, cannot generate precise locations while surveying areas and are not programmed to track individuals. In order to be able to track an individual, these AUVs need to be able to generate a fine-scale location of a tag in real time. Lin et al. (2013) developed a localization algorithm that could localize a transmitter from a pair of time-synchronized hydrophones. This method uses the difference in time of arrival to calculate an angle to the transmitter and a time of flight calculation to estimate distance to the transmitter, which are then incorporated into a particle filter to refine possible position estimates in real time.

This system was designed to be integrated into an Ocean Server Iver 2 AUV (Clark et al., 2013; Forney et al., 2012; Lin et al., 2014). This relatively small AUV (25 kg, 140 cm long) was designed to incorporate the position estimate from the paired hydrophone system designed by Lin et al. (2013) and programmed to alter its path in order to follow a tagged animal. This would provide an autonomous mobile system for locating and actively tracking acoustically tagged fishes (Clark et al., 2013; Forney et al., 2012; Lin et al., 2013, 2014; Xydes et al., 2013), providing similar positional accuracy as that of a stationary multilateration array, but allow flexibility to follow highly mobile species. Furthermore, by having the system be autonomous, it would have the potential to reduce the labor-intensive aspect of active tracking, and could be a useful tool to quantify the movements of animals.

In order to determine whether the 1) paired hydrophone localization technique and 2) incorporation into an autonomous vehicle may provide an accurate, efficient, land ess labor intensive tracking tool, comparison of the performance of these integrated systems with the historically standard method of active tracking is necessary. The goal of this study was to determine if the tracking AUV can provide more accurate position estimates and at a higher temporal resolution than a skilled human tracker.

2. Methods

A series of field trials were conducted in Big Fisherman's Cove, Santa Catalina Island, California to compare the positional accuracy and tracking efficiencies between a skilled human tracker in a surface vessel, using standard active tracking equipment and techniques and with a customized autonomous underwater tracking vehicle (AUV).

2.1. Human-based active tracking

Human-based active tracking was conducted aboard a 5 m Boston Whaler outfitted with a ship-borne acoustic receiver (Vemco VR100) and custom-built gunnel mount for easy, under-way use of a directional hydrophone (Vemco VH110). The acoustic receiver was maintained at a gain of 0 during all tracking trials. Researchers obtained "ground zero" locations by orienting themselves above the tag, determined by equal signal strength from all directions. The VR100 receiver records the time of detection, signal strength, tag ID, listening channel frequency, and GPS coordinates of the receiver. The tags used during all trials were Lotek MM-M-16-50-PM acoustic tags, which transmit predominantly at the 76.8 kHz frequency. While these tags were programmed to transmit a unique ID, pressure, and motion every two seconds, the Vemco VR100 could not decode Lotek coding, so were only used for geolocation tracking. All location estimates from human-based tracking are based on the coordinates provided by the GPS onboard the VR100.

2.2. AUV

During tracking trials two OceanServer Technology Inc. (Fall River, MA) Iver2 model autonomous underwater vehicles (AUVs) were used (Fig. 1). The Iver2 AUV is a torpedo-shaped robot that has a rear propeller to provide locomotion and four aft fins to control the pitch and yaw of the vehicle. The sensor payload includes a 3-DOF compass, wireless antenna, GPS receiver, and Doppler velocity logger (DVL) with the ability to expand to carry other environmental sensors such as temperature, salinity, chlorophyll, and sidescan sonar. The AUV uses a combination of GPS surface position and DVL to estimate position while operating underwater and can estimate their position with a precision of 0.3% of the distance traveled. The AUVs are designed to stay within a designed area dictated by the operators, in order to reduce the chance of colliding with objects such as moorings, kelp beds, and running aground. The vehicles are depth rated to 100 m, maximum speeds of 4 knots, and

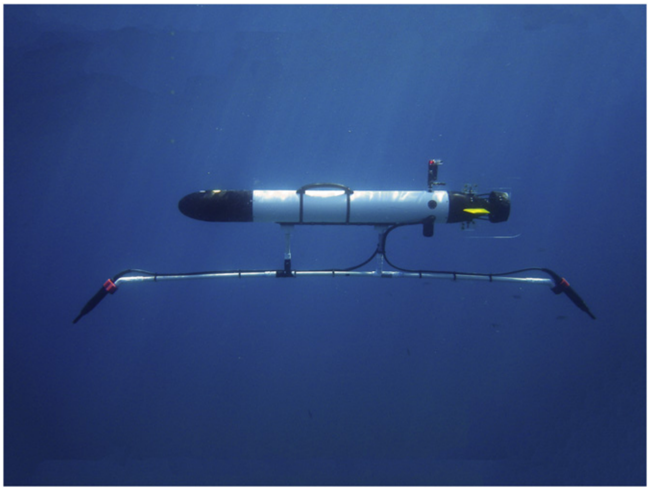

Fig. 1. Autonomous underwater vehicle. The OceanServer Iver II AUV used throughout all trials. The hydrophone rig is attached to the bottom of the AUV with each hydrophone suspended 0.4 m below the AUV and 2.4 m apart from each other.

battery limited operation times of 12 h. If multiple AUVs are deployed they can communicate with each other to coordinate their paths relative to each other, as well as with a topside modem, via a WHOI Micro-Modem and externally-mounted transducers. These vehicles are relatively low cost autonomous vehicles that are designed for coastal survey work and oceanic sampling.

To enable each AUV to acoustically track, they were outfitted with a Lotek (New Market, Ontario) MAP600RT receiver and an associated stereo-hydrophone set. The two hydrophones are mounted 2.4 m apart and suspended 0.4 m beneath each AUV. The Lotek MapHost software onboard each AUV records the unique tag ID, signal strength, pressure, presence of motion, and the time of detection with a resolution of 10^{-5} s for each receiver (Clark et al., 2013; Forney et al., 2012).

The separation of the hydrophones allows the angle between the AUV and the acoustic tag to be calculated by measuring the difference in time of arrival between the two hydrophones. When combined with the AUV heading and position, one can determine the bearing angle from the AUV to the tag. The AUV is able to estimate the distance to the tag by calculating the estimated time of flight (Lin et al., 2013).

The AUV incorporates the distance and angle measurements into a particle filter to further refine the location of the tag. All trials used 500 particles during each time step. Each particle represents a potential tag location that is assigned a weight based on the likelihood that the particle would produce the distance and angle measurements recorded by the AUV. The particles are resampled every 0.5 s to generate a new particle set, with particles of higher weights having higher likelihood of being randomly selected for the new particle set. The average location of all selected particles is calculated as the estimated tag location.

The two AUVs can be used independently or in conjunction with both simultaneously tracking the same acoustic tag. When both AUVs are tracking the same tag, they will coordinate their movements and share their estimated positions and tag measurements with each other. The communication bandwidth is limited when communicating through the WHOI acoustic modems and thus full sensor readings cannot be passed between the AUVs. Thus, if two AUVs were used simultaneously, the acoustic detection data from both AUVs would be downloaded and position estimates of the tag would be post-processed by passing detection data from both AUVs into one particle filter. For more information on localization algorithms and technical aspects see (Clark et al., 2013; Forney et al., 2012; Lin et al., 2013, 2014; Xydes et al., 2013).

Once an acoustic tag is located, the AUV is programmed to alter its path in order to follow the tag. The AUV currently has a motion planner that is comprised of two different steps: 1) drive directly towards the estimated location of the tag, and 2) once the AUV is within 10 m (or any pre-programmed distance) of the estimated tag location; it enters into a circle-tracking phase. During this phase, the AUV circles the estimated location of the acoustic tag or if the transmitter is out of the allowed tracking boundary, the AUV will circle the boundary area closest to the transmitter. This is designed to minimize the influence on the tagged animal while increasing the positional accuracy of the AUV. The AUV will continue to circle the same location until it has determined that the tag had moved a threshold distance of 10 m. By constantly shifting between these two phases, the AUV is able to indefinitely follow a tagged animal autonomously (Lin et al., 2014). Throughout all experiments the AUV was restricted to a small operational area approximately 30% of the area of the cove.

2.3. Stationary location trials

To compare the accuracy of both AUVs and researchers, how each method performed while tracking a stationary transmitter was determined. An acoustic transmitter (pulse rate = 2 s) was placed in four unmarked locations of various habitat and depths across the cove both inside and outside the AUVs operating area. The researcher tracking did not see where the tag was placed. The tag was positioned approximately 0.5 m off the seafloor. During deployment the true location of the tag was determined using a hand held GPS positioned directly above the tag (Garmin GPSMAP 76cx). The researcher used a shipborne acoustic receiver and directional hydrophone to find the tag and get as many "ground zero" locations within a 5 min period as possible. Immediately following the tracking session of the researcher, the AUV was deployed to autonomously find and record the location of the tag for five minutes.

After each method localized the tag for 5 min, the transmitter was moved to a new location and the process was repeated three more times for a total of four trials. The location of the transmitter in the cove was not randomly chosen but instead selected for locations of different habitats and depths in order to more holistically compare the accuracy of the human tracker and the AUV.

2.4. Moving location trials

In order to determine the accuracy of the AUV tracking a moving transmitter, two AUVs simultaneously tracked a tagged small vessel, towing an acoustic transmitter (pulse rate = 2 s), which was placed on a rope and suspended 2 m below the vessel. The vessel was slowly driven around the cove intermittently stopping and driving while its position was recorded for each acoustic tag transmission using an onboard VR100 and a VH110 directional hydrophone. This was repeated 4 times at different locations throughout the cove with each trial lasting between 20 and 40 min.

To investigate the accuracy of a researcher actively tracking a moving transmitter, an acoustic transmitter was fixed to the AUV and the researcher in a vessel tracked the submerged AUV. The AUV was preprogrammed to perform a mission while remaining at a depth of 3 m underwater while it moved at a rate of 1.5 to 2 knots. By remaining underwater, it prevented the researcher from visually tracking the AUV and the AUV only surfaced quickly (<10 s) two times on each mission to get a GPS fix (surfacing events were 10–15 min apart) potentially allowing the researcher to visually track the AUV.

2.5. Shark tracking

In July of 2013, a leopard shark (*Triakis semifasciata*) was externally fitted with an acoustic transmitter at the base of its dorsal fin. Immediately after tagging, the AUV was put in the water to track the shark approximately 100 m from the location in which the shark was tagged. Concurrently, a researcher in a small vessel actively tracked the same tagged individual using the VR100 receiver and directional hydrophone.

In order to minimize the influence of boat proximity on shark behavior, ground zero shark position estimates were only acquired every 10 min. As these were preliminary trials, tracking was not consistent over the three days of tracking and the AUV was repeatedly deployed for short periods of time (<4 h tracking durations).

2.6. Data analysis

All data were downloaded and analyzed in R v 2.15.2 (R Foundation for Statistical Computing, Vienna, Austria). Location estimation error was calculated as the linear distance in meters from the estimated location to the recorded true tag location.

A transmitter detection on the VR100 acoustic receiver does not automatically confer an accurate location. To obtain the most accurate position estimates, researchers who actively track must filter their detections based on a signal strength threshold, a proxy of distance to the tag. All researcher-derived tracking detections with a signal strength lower than a threshold of 90 dB were discarded. In contrast, the AUV can remotely derive the acoustic tag location and refine the estimate through its use of a particle filter, and thus, signal strength is not used as an accurate predictor of estimation accuracy. When particles are tightly clustered, the localization is accurate; when particles are spread-out, there is a greater potential area for the location of the tag and thus increased error. An approximation of the error from the particle filter can be determined (Eq. 1) by calculating the vector sum of the standard deviation of the particles in the east-west (σ_x) and north-south (σ_y) directions (Lin et al., 2014).

$$\varepsilon_t = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{1}$$

This approximation of error was used similarly to signal strength in human-based active tracking and was used to filter AUV detections by a threshold value of 15 to remove estimated locations with a low degree of certainty.

95% and 50% utilization distributions were constructed for the leopard shark that was tracked. Utilization distributions were constructed from both data collected from the AUV and from the human tracker. Utilization distributions were calculated using Brownian bridges kernel method in the adehabitat package in R to account and standardize for the temporal differences between the data collected from the AUV and the human tracker. These distributions were compared to each and percent overlap was calculated.

3. Results

When tracking stationary tags ($n = 4$), the AUV registered detections at a greater rate than the human (Table 1). After filtering the data to remove detections with a high estimated error, 46% of the human tracker detections were discarded as compared to only 24% of the AUV detections, providing 121% more geoposition estimates than the human tracker. Overall, the AUV provided similar spatial accuracy as that of a human tracker throughout all four stationary transmitter trials (two sample *t*-test, $t_{5.985} = -1.151$, $p = 0.29$). The AUV was able to maintain this spatial accuracy while operating at a significantly greater distance to the transmitter than a human tracker (Table 1, $F_{1,\ 764.2} = 229.04$, $p < 0.001$).

When tracking a moving transmitter (transmitter hung from the vessel or attached to the AUV), the AUV ($n = 4$, Fig. 2A–C) had a significantly smaller positional error than the human tracker ($n = 2$, Fig. 2D–F) (AUV: 6.1 ± 4.8 m, Researcher: 16.6 ± 9.7 m, $F_{1,\ 3.98} = 31.1$, $p = 0.005$), while generating significantly more detections per unit time of trial (AUV: 45.2 ± 10.5 detection/min, Researcher: 12.2 ± 9.1 detections/min, $t_{2.41} = 3.96$, $p = 0.04$). The positional accuracy of the human tracker was significantly worse when tracking a moving transmitter (16.6 ± 9.7 m) as compared to a stationary transmitter (10.3 ± 6.3 m, $F_{1,\ 3.88} = 5.52$, $p = 0.04$). In contrast, the AUV positional accuracy when tracking moving transmitters (6.1 ± 4.8 m) was not significantly different than tracking stationary transmitters (5.4 ± 3.3 m, $F_{1,\ 5.66} = 0.57$, $p = 0.48$). These results are not entirely comparable however, since two AUVs were tracking in tandem during moving trials, while only one AUV was tracking during stationary trials (Table 2).

Over a 3-day period the AUV performed four tracks for a total of 7.7 h (range 0.9–2.8 h, Table 3), during which time the AUV successfully localized and followed the tagged shark. Throughout the trials the AUV was able to average 27 geoposition estimates per minute when tracking the shark and these locations generated utilization distributions that overlapped considerably (95% utilization distribution: 84% overlap, 50% core utilization distribution: 68% overlap - Fig. 3). The mean estimated error was significantly greater for the AUV when tracking an actual shark than tracking a moving or stationary tag ($F_{2,\ 5.02} = 56.03$, $p < 0.001$).

4. Discussion

Overall, the dual hydrophone system coupled with the AUV performed better than the human in all tracking trials. Throughout all trials the AUV was able to maintain spatial accuracy that was equal to or better than a human tracker, while generating significantly more locations per unit time. This was especially true when tracking moving transmitters, as the human tracker had significantly fewer detections and a reduced accuracy, while the AUV maintained performance on par with tracking stationary transmitters. In addition, because the AUV is able to generate geoposition estimates without being in close proximity to the animal, it is able to continuously record information, while an active tracker usually only obtains high resolution location estimates at 5–10 min intervals. The distance the AUV maintains from the transmitter also makes it less likely to influence the behavior of the animal, unlike the active tracker who needs to hover directly over the animal to get an accurate location. By providing data on a fine temporal and spatial scale, the AUV enables researchers to better understand the habitat associations, movements and behaviors of individuals, while minimizing behavioral disturbance associated with tracking, particularly in shallow water, nearshore habitats. While this stereo-hydrophone system can be easily towed from a boat to achieve more accurate positions, the autonomous nature of the AUV can substantially increase active tracking efficiency.

The data collection efficiency of the AUV was highlighted when both methods were used to track an actual leopard shark. The AUV consistently generated over 20 geopositions per minute while maintaining a distance of >10 m from the shark, providing overlapping location estimates with the human tracker, yet providing over two orders of magnitude more locations per unit time. The difference between the UDs highlights one of the benefits of this technology, where the larger 95% UD of the AUV compared to the human tracker demonstrates that the AUV is likely better able to capture quick forays and movements that individuals make expanding the area an individual uses. Thus, the AUV more accurately reflects episodic animal movement and habitats that may be seldom used, while this information is lost due to aliasing

Table 1
Positional information on the accuracy and distance for a human and an AUV tracking moving tags. Trials between the Human and the AUV are not paired as each trial represents a different moving trajectory.

Method	Trial	Trial duration (min)	Number of detections	Number of locations	Positional error (m)	Distance to Tag (m)
AUV	1	42	5089	4030	5.1 ± 4	30.6
	2	45	5484	5424	6.8 ± 4.8	26.7
	3	31	3772	2794	8.8 ± 7.6	31.5
	4	18	2205	1685	6.6 ± 5.2	67.1
Human	1	22	1252	94	22.4 ± 9.5	25.7
	2	25	2885	418	14.1 ± 9.3	21.5

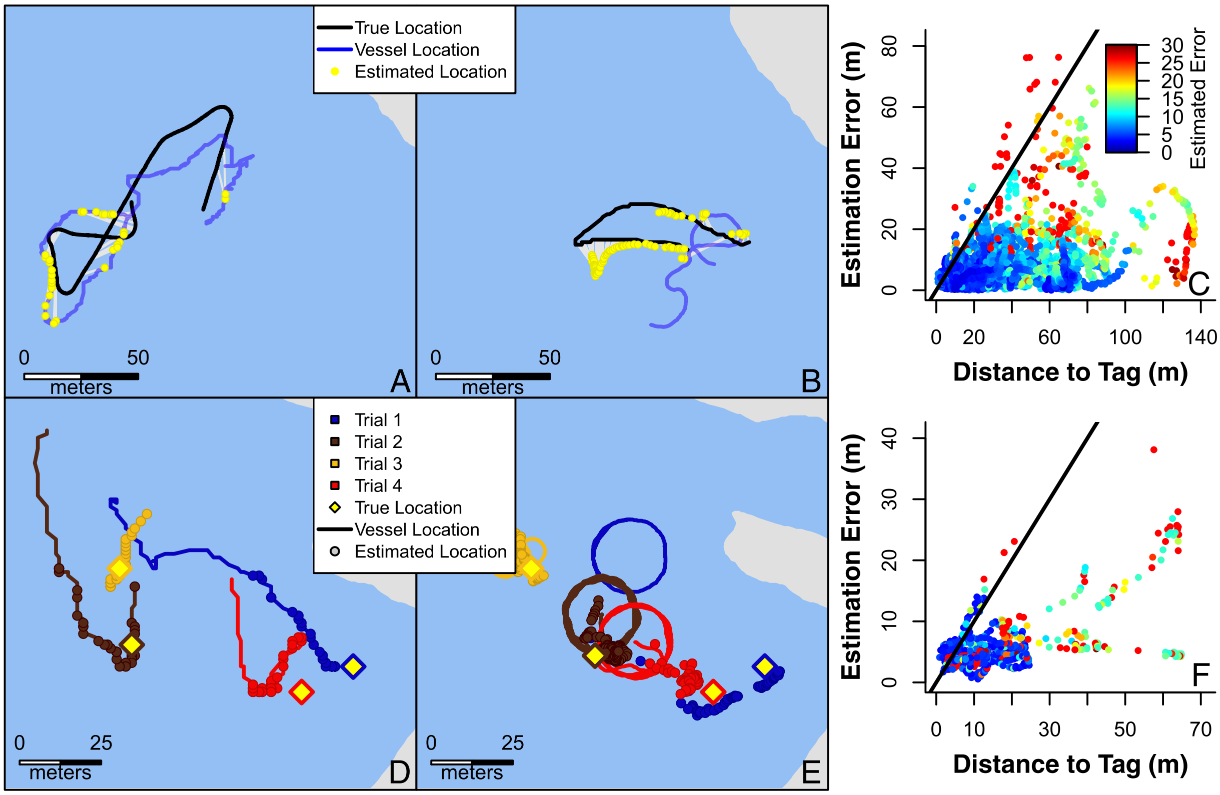

Fig. 2. Position estimates for tags of known location. Tracks of both the researcher (A) and the AUV (B) tracking moving objects of known position. D & E are respective tracks for the researcher and the AUV when tracking fixed objects of known position. Light grey lines represent the straight line comparing the estimated and true locations, blue lines represent the tracking vessel, while black lines represent the location of the acoustic transmitter. C & F are respective tracks for moving and fixed tags of the estimation error as measured by the distance between the estimated position and the true position for the AUV. Individual points are color coded by the estimated error produced by the particle filter in Eq. (1). The black line represents the line at which a researcher would produce localizations, as their distance to the tag is equal to their estimation error.

with a human tracker (positions every 5–10 min) (Frair et al., 2004; Johnson and Ganskopp, 2008). The AUV also had a substantially smaller 50% core UD than a human tracker, suggesting that the increased temporal resolution of the AUV better reflect the areas and microhabitats where individuals spend the majority of their time (Andrews et al., 2011; Fieberg and Kochanny, 2005). The larger core area from the human estimates might increase the likelihood of misidentifying microhabitat use.

There are still numerous challenges in using AUVs for full autonomous tracking. There is still a need for better obstacle avoidance, which is particularly problematic in areas with kelp that may grow seasonally and may pose problems for bounding AUV movements. While there are existing sonar-based obstacle avoidance programming used in other commercial AUVs, modifications are still required in order for the AUVs in this project to be fully autonomous for nearshore use. Incorporation of forward-facing image sonar may yield more accurate sensor-based data for programming obstacle avoidance of kelp, moored vessels and lines. In order to compensate for the limited obstacle avoidance, the operational area for the AUV in the cove was limited to a relatively small area, which occasionally caused the AUV to be a considerable distance (>100 m) from the tag.

While the Iver II model AUVs are considered low cost, they still amounted to over $50,000 USD each and thus present a significant upfront investment. The price of a commercially available AUV has dropped significantly over the past 10 years and with the increase in the use of autonomous tools, this trend is expected to continue. In addition, a hydrophone and tracking system, similar to the one presented in this paper, could be paired with a surface-based autonomous vehicle which could significantly reduce costs.

To better understand the behaviors of individuals, both fine-scale spatial accuracy and a high temporal resolution are needed and many of the current tools available are unable to meet these two criteria. Many current multi-lateration systems, such as the Vemco VPS system, can provide fine spatial estimates, comparable to the AUV and active

Table 2
Positional information on the accuracy and distance away of both a human and an AUV tracking objects of fixed locations. Both the AUV and the human tracked objects in the same location and thus each trial is paired.

Trial	Depth (m)	Method	Number of detections	Number of locations	Positional error (m)	Distance to tag (m)
1	2	AUV	77	36	10.7 ± 7.5	54.4
		Human	108	53	12.9 ± 10.9	13
2	6	AUV	275	253	5.3 ± 1.9	14.1
		Human	109	56	10.1 ± 8.8	5.4
3	8	AUV	281	222	4.4 ± 2.3	9.1
		Human	107	76	5.6 ± 3	4.3
4	3	AUV	61	18	10.1 ± 4.6	28.5
		Human	132	54	12.7 ± 2.5	9.6
Grand total		AUV	173.5	132.25	7.6 ± 4.1	26.5
		Human	114	59.75	10.3 ± 6.3	8.1

Table 3
Positional information on the estimated accuracy and distance away of the AUV when tracking a leopard shark.

Track	Duration (h)	Number of detections	Estimated error	Distance to tag (m)
1	2.9	4459	69.1 ± 7.7	33.5 ± 23.5
2	2.8	4588	76.1 ± 21.4	18.5 ± 12.6
3	1	2591	69.2 ± 14.4	21.2 ± 15.8
4	1.1	657	107.3 ± 49.6	47.8 ± 16.6

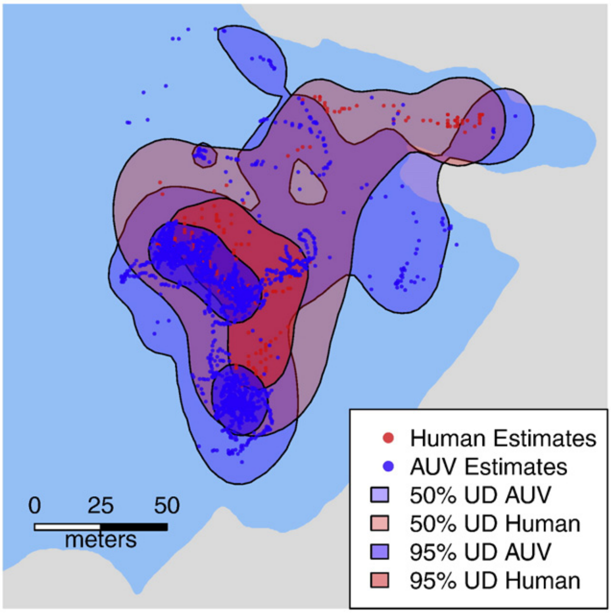

Fig. 3. Shark utilization distribution. Location estimates generated by the AUV (blue circles) and by the human tracker (red circles). The 95% utilization distribution for the AUV (light blue) and human tracker (light red) and 50% utilization distribution for the AUV (dark blue) and human tracker (dark red), showing high overlap between the two methods.

tracking (Andrews et al., 2011; Biesinger et al., 2013; Espinoza et al., 2011; Roy et al., 2014; Steel et al., 2014), but are often limited by the number of receivers needed to cover a particular area. In well-designed acoustic arrays, localization efficiency can be over 70%; however, efficiencies are more often significantly lower and can be <10%, based on the location of the tag, environmental conditions, acoustic array design, and density of acoustic tags (Biesinger et al., 2013; Espinoza et al., 2011; Farmer et al., 2013; Steel et al., 2014; Wilson et al., 2011). In addition, some acoustic transmitter manufacturers utilize a slower transmission rate as part of their coding schemes (between 30 s and 10 min), to extend the life of the tag and decrease the possibility of signal collisions. Thus, relocation estimates for each individual can be generated infrequently while the individual is within the array. Once the animal moves outside of the array there are no position estimates generated. For individuals with small home ranges that move infrequently, multi-lateration arrays can be an effective tool that can collect a large amount of information on individuals' fine-scale movements (McMahan et al., 2013; Piraino and Szedlmayer, 2014). For animals with large activity spaces, no defined home range, or where it is impractical to deploy a large acoustic array, these systems have limited benefits. In addition, for individuals that move frequently, multi-lateration systems might not provide enough high frequency sampling to reveal movement paths and behavioral patterns resulting in aliasing, due to reduced detection rates while tags are moving (Biesinger et al., 2013; Espinoza et al., 2011; Roy et al., 2014; Steel et al., 2013).

Quantifying fine-scale spatio-temporal movements is a high priority as increasing numbers of archival tags are deployed on animals (Bograd et al., 2010; Ropert-Coudert et al., 2009; Rutz and Hays, 2009). Use of archival data loggers on animals has recently greatly expanded to include video, sound, accelerometers, magnetometers, temperature, depth, and gastric pH sensors. Many of these data loggers record at high frequencies (>1 Hz), yet to be of greater value in understanding the behavior of animals, this sensor information needs to be better matched to spatial information which is often collected over a much more coarse time scale (min to days) (Cagnacci et al., 2010). Researchers have previously relied on satellite tags to provide spatial context to data derived from archival tags, but this has predominately been limited to marine mammals and turtles that must come to the surface to breathe, and are thus much less effective for fishes and sharks (Wilson et al., 2007). Placing high-frequency archival information in a spatial context is necessary to better interpret the data as surrounding conditions such as prey availability, conspecific density, and environmental conditions are known drivers of the movements and behaviors of an individual (Heupel and Simpfendorfer, 2014; Heupel and Simpfendorfer, 2008; Simpfendorfer et al., 2011). Thus for active, nomadic or wide ranging species an AUV-based system is able to accurately position individuals at a high spatio-temporal resolution. By having a mobile platform, large amounts of environmental variables can be collected *in situ*, which can place the movements of individuals in context as environmental variability (e.g., temperature, chlorophyll, dissolved oxygen, etc.) allowing for one platform to simultaneously provide the fine-scale movements of individuals and the environmental context in which they are making their movements.

The localization system used here does not have to be paired with an autonomous vehicle system. This localization system could be used as towable system or in a thru hull design in a manned vessel and provide fine spatio-temporal accuracy with the vessel operator following the tagged individual. Yet, by pairing the system with an autonomous navigation system, significant benefits are gained. It could be used in a manner similar to previous AUVs to survey for tagged fish, however, rather than drive past a detected individual, it could begin to track the individual providing fine-scale behavioral information. In a system such as this, large amounts of information could be collected on the broad scale location and presence of fish in habitats while also providing fine scale movements on tagged individuals.

The autonomous underwater vehicle tracking system presented in this paper was able to accurately follow an acoustically tagged shark *in situ* providing high quality information that was superior to that of a human tracker, all while remaining autonomous and reducing the man-hour investment required to collect data. Mobile autonomous tracking technology will likely become another tool for biologists to study the behavior of animals in the wild and allow researchers to pair fine-scale behavioral and environmental information to spatial locations.

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