A Multi-AUV System for Cooperative Tracking and Following of Leopard Sharks

Dylan Shinzaki[1], Chris Gage[2], Sarah Tang[3], Mark Moline[4], Barrett Wolfe[5], Christopher G. Lowe[6], and Christopher Clark[7]

***Abstract*— This paper presents a system of multiple coordinating autonomous underwater vehicles (AUV) that can localize and track a shark tagged with an acoustic transmitter. Each AUV is equipped with a stereo-hydrophone system that provides measurements of the relative bearing to the transmitter, as well as an acoustic modem that allows for inter-AUV communication and hence cooperative shark state estimation and decentralized tracking control. Online state estimation of the shark's state is performed using a Particle Filter in which measurements are shared between AUVs. The decentralized control system enables the AUVs to circumnavigate a dynamic target, (i.e. the estimated shark location). Each AUV circles the target by tracking circles of different radii and at different phase angles with respect to the target so as to obtain simultaneous sensor vantage points and minimize chance of AUV collision. A series of experiments using two AUVs were conducted in Big Fisherman's Cove in Santa Catalina Island, CA and demonstrated the ability to track a tagged leopard shark (*Triakis semifasciata*). The performance of the tracking was compared to standard manual tracking performed using an directional hydrophone operated by a researcher in a boat. In an additional experiment, the AUVs tracked an acoustic tag attached to the tracking boat to quantify the error of the state estimation of the system.**

I. INTRODUCTION

The study of the behavior of marine species remains an important area of inquiry in marine biology. Past studies of the fine-scale movement patterns of fish have generally included fish tagging and tracking. Currently, there are several approaches to tracking fish. Tagging fish with satellite tags provides moderately accurate, long-term position information, but measurements can only be gathered when the fish is at the water's surface and accuracy depends on ocean conditions [1]. Acoustic transmitters work while underwater, but require additional tracking to determine position. Acoustic transmitters attached to fish can currently be tracked using hydrophones mounted to a stationary array or a manually controlled boat [2]. Stationary arrays can provide accurate information, but only when the fish is in range. A manually controlled boat can be repositioned as the fish moves, but is expensive in terms of labor and may not be feasible for wide ranging, migratory fish such as sharks.

Advances in technology have made it increasingly feasible for AUVs to provide an alternative approach. Previous work by the authors [3] presented a single AUV system for localization and tracking of a shark. The work presented here expands on this by presenting a system of multiple coordinating AUVs for localization and tracking of a shark. The contributions of this work include:

- A cooperative multi-AUV target tracking estimator that incorporates sensor measurement sharing through inter-AUV communication
- A decentralized multi-AUV control strategy that enables multiple AUVs to circumnavigate a common target at desired radii and with desired phase angle difference between AUVs, reduces the likelihood of collision, ensures multiple sensor vantage points, and has proven stability guarantees.
- Demonstration of the system in real shark tracking experiments conducted in Big Fisherman's Cove, Catalina Island, CA.

The paper is organized as follows. Section II describes the past work and related research on the topic. Sections III and IV describe the system of AUVs, the filtering strategy and the control scheme used to coordinate the AUVs. Sections V and VI describe the experiments performed at Catalina Island the show effectiveness of the described system.

II. BACKGROUND

Gathering highly detailed information about fish motion is often done by tracking an individual using acoustic telemetry. An acoustic telemetry system generally consists of a transmitter and a receiver. The transmitter, often called a "tag", is attached to the fish and emits an acoustic signal. The signal can encode information such as an identification number, velocity, acceleration, pressure and temperature. The signal can enable the fish to be localized using an array of omni-directional receivers or a receiver mounted to a mobile platform such as a boat [4], [5], [6]. Receiver arrays are comprised of multiple hydrophones, strategically placed in an area of interest. Fish positions are estimated based upon time difference of arrival of the transmission relative to neighboring hydrophones. The accuracy of the localization

[1]D. Shinzaki is with the Department of Mechanical Engineering, Stanford University, Stanford, CA, 94305, USA `shinzaki at stanford.edu`

[2]C. Gage is with the Department of Physics, Harvey Mudd College, Claremont, CA, 91711, USA `chris_gage at hmc.edu`

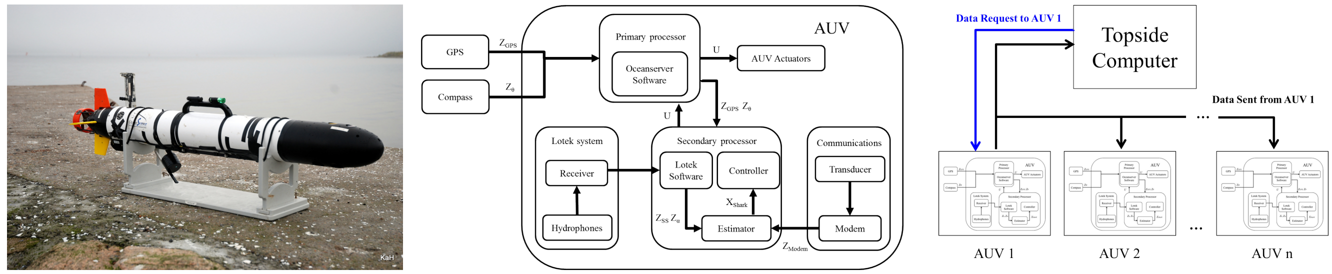
[3]S. Tang is with the Department of Mechanical and Aeronautical Engineering, Princeton University, Princeton, NJ, 08540, USA `sytang at princeton.edu`

[4]M. Moline is with the University of Delaware, , USA `mmoline at udel.edu`

[5]B. Wolfe is with Department of Biological Sciences, California State University, Long Beach, Long Beach, CA, 90840, USA `barrettwwolfe at gmail.com`

[6]C. Lowe is with Department of Biological Sciences, California State University, Long Beach, Long Beach, CA, 90840, USA `clowe at csulb.edu`

[7]C. Clark is with the Department of Engineering, Harvey Mudd College, Claremont, CA, 91711, USA `cmclark at hmc.edu`



(a) (b) (c)

Fig. 1. The OceanServer Iver2 AUV is shown in (a). Flow control within a single AUV, and between AUVs using communication, are shown in (b) and (c) respectively.

decreases if the fish is far away or outside of the boundaries of array [5]. Fish in estuaries along the western Atlantic such as winter flounder and shortnose sturgeon have been studied using acoustic tags and stationary arrays [6]. An alternative approach is to track the tag with a boat and onboard receiver. The boat is manually repositioned to allow for accurate measurements of the fish location. This approach tends to labor intensive and operationally expensive.

In general, much attention has been payed to the tracking of moving objects with mobile robots. E.g., mobile robots have been used to track moving humans in an indoor environment [7], [8], [9], [10]. In this work the focus is on underwater robot tracking systems. E.g., remotely operated underwater vehicles using visual sensors have been effective in tracking fish and jellyfish [11], [12]. In [13], a single AUV following predetermined paths, and equipped with two hydrophones, was used to take measurements from tagged Atlantic Sturgeon in the Hudson River. [14] presented a system of one robotic raft following a predetermined set of waypoints to triangulate the position of fish tagged with a radio tag in Minnesota. In [3], a single AUV with two hydrophones was shown to autonomously track and follow a tagged shark, using real-time state estimation and a control to drive the AUV towards the shark.

Robots are often used in groups when tracking to improve redundancy and performance. [15] presents the tracking of a moving target with a group of mobile robots with directional sensors and a control scheme to arrange the robots around the target. A similar project showed a group of robots sharing sensor measurements could achieve improved accuracy in tracking a target, especially in cases in which the target could be detected by some of the robots, but not others [16]. Coordinated tracking schemes have also been widely used with the control of groups of unmanned aerial vehicles because they often operate in noisy environments in which redundancy is needed. UAVs have been used to track moving ground targets such as forest fires and cars [17], [18].

Prior to this project, systems using AUVs to track ocean fish had been restricted to one AUV. This paper presents an acoustic based system for localization and tracking of a tagged fish using a system of multiple coordinating AUVs.

III. System Overview

The proposed Multi-AUV system includes two Oceanserver IVER2 AUVs (Fig. 1(a)), that are actuated by two pitch fins, two yaw fins, and a propeller. The AUV is equipped with GPS that provides latitude and longitude measurements, Z_{GPS}, used to estimate the AUV position. It is also equipped with a 3-axis compass which provides a yaw measurement of Z_θ. The flow control of the AUV is shown in Fig. 1(b). It consists of two processors that run simultaneously. The AUV's primary processor communicates with the IVER's actuators and sensors. The secondary processor interfaces with the primary processor and hosts any user programmed control, planning, and estimation. Each AUV is also configured with a Lotek MAP600RT stereo-hydrophone set and receiver. Acoustic tag measurements in the form of relative bearing and signal strength, Z_{ss} and Z_α, are provided by the Lotek System and allows estimation of the shark's position X_{shark}. The controller uses X_{shark}, Z_{GPS}, Z_θ, and Z_{modem} to determine a control input U that is sent to the actuators.

The Lotek hydrophones are mounted on a custom frame such that they are 2.4 meters apart with one near the front and one near the back, (see [3] for details). The hydrophones detect uniquely identifiable tags broadcasting at 76 kHz. Detections are converted to measurements of the relative bearing of the tag with respect to the AUV, Z_α. The bearing measurements are integer values between 8 to -8 that correspond to angles between $-\pi/2$ and $\pi/2$ radians. A measurement of 8 Lotek units indicates the tag is directly in front of the AUV and a measurement of -8 Lotek units indicates the tag is directly behind. Note that these units do not indicate whether the target is on port or starboard side.

Communication between the AUVs is facilitated using a WHOI Micro-Modem and an externally mounted transducer. The modem, connected to the secondary processor, receives incoming messages Z_{modem} from all other AUVs. These messages include the sending AUV's state estimate X_{AUV} and most recent Lotek measurement angle Z_α. Communication between AUVs is initiated from a topside computer, that sends a command to a single AUV instructing it to send its position, orientation and Lotek measurements to all other AUVs and the topside computer. The topside computer waits until it receives a reply or times out. It then sends the same command to the next AUV in the system, (see Fig. 1(c)). For the data packets transmitted in this work, a full communication cycle across n AUVs takes $10.0n$ seconds.

IV. Controller and State Estimator

A. State Estimation

For a system of n AUVs, let $X^i_{auv,t}$ represent the planar position, orientation, forward velocity, and rotational velocity of AUV i with respect to an inertial coordinate frame at time t, where $1 \leq i \leq n$.

$$X^i_{auv,t} = [x_{auv} \; y_{auv} \; \theta_{auv} \; \nu_{auv} \; \omega_{auv}]^i_t \tag{1}$$

Also, at time step t, the AUV may obtain Lotek sensor measurement $Z^i_{\alpha,t}$. Given AUV positions and Lotek measurements are broadcasted from all members of the AUV team, the collective measurement $Z^i_{modem,t}$ is:

$$Z^i_{modem,t} = [X^1_{auv,t} \; Z^1_{\alpha,t} \; X^2_{auv,t} \; Z^2_{\alpha,t} \; ... \; X^n_{auv,t} \; Z^n_{\alpha,t}] \tag{2}$$

The specific goal of this state estimation problem, is for each AUV i to use $Z^i_{modem,t}$ to generate at time t an estimate of the shark's position, orientation, and velocity states $X^i_{shark,t}$.

$$X^i_{shark,t} = [x_{shark} \; y_{shark} \; \theta_{shark} \; v_{shark}]^i_t \tag{3}$$

This problem is complicated by the fact that due to acoustic occlusions and reflections within the underwater environment, both Lotek measurements and broadcasted messages are not received with high likelihood. As well, the Lotek measurements are limited in resolution ($\approx \frac{\pi}{9}$) and have a sign ambiguity regarding the bearing to tag angle.

To accommodate these issues, a multi-AUV Particle Filter (PF) based estimation strategy that allows for non-Gaussian belief distributions and sharing of measurements through communication is proposed. To collectively represent the belief state, the PF uses a set of P particles, each with a state X^p_{shark}, and weight w^p. This set is denoted $\{X^p_{shark} w^p\}$. To initialize, the P particles are randomly assigned an orientation, velocity, and position. The orientations are randomly sampled from a uniform distribution from $-\pi$ to π. The velocities are randomly sampled from a uniform distribution from 0 to v_{max}, where v_{max} is a predetermined maximum particle velocity that is set using historical shark data. The position coordinates (x, y) are randomly sampled from a uniform distribution from $-L$ to L where L is approximately the range of the receiver system. The pseudocode for the particle filter can be seen in Alg. 1, where the time and AUV scripts are ommitted for clarity.

At each time step, the PF updates the particle distribution using two steps, prediction and correction. The prediction step propagates each particle forward in time using a stochastic motion model, (Alg. 1 Line 3). Much work has been done in studying models for individual movements as random walks including Brownian motion, Lévy flights, etc. [19], [20]. The motion model used in this project uses a random walk as described in Alg. 2.

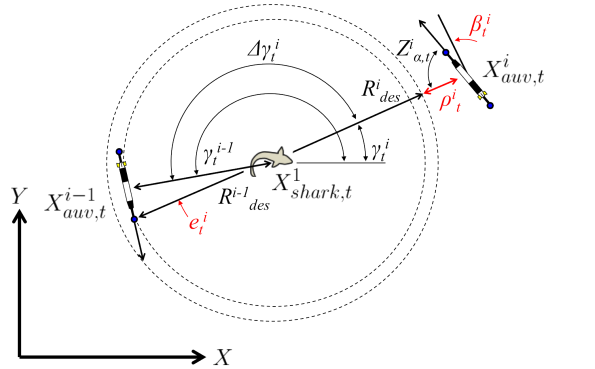


Fig. 2. A top down view of 2 AUVs cooperatively tracking and following a target. Hydrophones are shown as blue dots ahead of and behind the AUV. Control error variables are in red.

Algorithm 1 Shark_State_Estimator($\{X^p_{shark} w^p\}$, Z^i_{modem})

1: *//Prediction*
2: **for** *p=1:P* particles **do**
3: $\quad X^p_{shark} \leftarrow$ Motion_Model(X^p_{shark})
4: $\quad$ **if** Z_α is valid **then**
5: $\quad\quad \alpha^p_{exp} \leftarrow$ atan2$(y_{auv} - y^p_{shark}, x_{auv} - x^p_{shrk}) - \theta_{auv}$
6: $\quad\quad \alpha^p_{exp} \leftarrow g(\alpha^p_{exp})$
7: $\quad\quad w^p \leftarrow h(Z_\alpha, \alpha^p_{exp})$
8: $\quad$ **end if**
9: **end for**
10:
11: *//Correction*
12: **if** Z_α is valid **then**
13: $\quad$ **for all** p particles **do**
14: $\quad\quad X^p \leftarrow RandParticle(\{X^p_{shark}\}_{temp})$
15: $\quad$ **end for**
16: **end if**

If a valid measurement Z_α has been received by any AUV, an expected measurement angle α^p_{exp} is calculated (Alg. 1 Line 5) using the geometry of the positions of the AUV and particle. A sensor model function g converts the angle from radians to the integer based Lotek Units. A large number of ocean tests and function approximation techniques were used to experimentally determine g.

$$g(\alpha^p_{exp}) = -.19(\alpha^p_{exp})^3 + .066(\alpha^p_{exp})^2 + 5.4\alpha^p_{exp} - .28 \tag{4}$$

A comparison between the expected and actual Lotek measurement angle is used to recalculate the particle's weight, (Alg. 1 Line 7). The weighting function, $h(z_\alpha, \alpha^p_{exp})$, implements a Gaussian probability density function. The

Algorithm 2 Motion_Model(X^p_{shark})

//RandomWalkModel
$v^p_{rand} \leftarrow UniformRandom(0, v_{max})$
$\theta^p_{shark} \leftarrow UniformRandom(-\pi, \pi)$
$x^p_{shark} \leftarrow x^p_{shark} + v^p_{rand} * \cos(\theta^p_{shark}) * \Delta t$
$y^p_{shark} \leftarrow y^p_{shark} + v^p_{rand} * \sin(\theta^p_{shark}) * \Delta t$

TABLE I

ESTIMATOR AND CONTROLLER PARAMETER VALUES

Parameter	P	v_{max}	L	σ_α	K_ρ	K_β	K_γ	v_{nom}	$\Delta\gamma$	R^1_{des}	R^2_{des}	τ^1_R	τ^2_R	τ_γ
Value	1000	4 m/s	75 m	1 Lotek Unit	0.1	0.4	0.5	0.56 m/s	π rad	8 m	10 m	10 m	12 m	π/8 rad

weight has a minimum value of 0.001, and is given a greater value when the particle's expected Lotek measurement, α^p_{exp}, is closer to the measured Lotek measurement, Z_α.

$$h(z_\alpha, \alpha^p_{exp}) = 0.001 + \frac{1}{\sqrt{2\pi}\alpha^p_{exp}} e^{\frac{-(\alpha^p_{exp}-z_\alpha)^2}{2\sigma^2_\alpha}} \tag{5}$$

The correction step only occurs if a valid measurement has been received. In the correction step, the particle set is repopulated with particles chosen at random with probability proportional to their weight. This is implemented with the function *RandParticle* in Alg. 1 Line 14.

B. Controller

A decentralized target circumnavigation controller was designed for this system and is described in detail in [21]. The requirements of the controller include, 1) each AUV i circumnavigates a target or group of targets by tracking a circular path that is centered on the target, 2) the radius $R^i_{des}$of each AUV i's circular path is different and, 3) AUVs maintain a desired phase difference $\Delta\gamma_{des}$ with neighboring AUVs along this circular path. The first requirement ensures AUVs will follow the moving target while not altering the target's behavior. The second and third requirements minimize the likelihood of inter-AUV collision. The third also ensures multiple sensor vantage points of the target to improve state estimation. In this system (Fig. 2), the target to be circumnavigated and followed is set to be the lead AUV's shark state estimate $X^1_{shark,t}$.

Algorithm 3 $[\nu^i_{des}, \omega^i_{des}]$ = AUV_Controller(i, Z^i_t)

```
if i == 1 && |X^i_{shark,t} − X_{target,t−1}| > τ_{shark}
    Broadcast_Msg(X^1_{shark,t})
if new_Lead_AUV_message_received
    X_{target,t} ← In_Boundaries(X^1_{shark,t})
    ΔX_{target} ← X_{target,t} − X_{target,t−1}
    γ_{exit} ← atan2(−Δy_{target}, −Δx_{target})
if |γ_{exit} − γ^i_t| < τ_γ && r^i < τ_R
    [ν^i_{des}, ω^i_{des}] ← Track_Point(X_{target,t})
else
    [ν^i_{des}, ω^i_{des}] ← Track_Circle(X_{target,t}, i)
```

Algorithm 3 describes the logic used by the AUV to implement the circumnavigation controller. If the AUV is the lead AUV of the team, i.e. $i == 1$, then it will check if the shark position estimate has moved some minimum distance τ_{shark} from the last target position being tracked. If it has, the lead AUV broadcasts the new shark state to all AUVs in the team. Upon receiving this message, AUVs will reset their target point to be the location closest to the shark state estimate that is within a safe boundary zone. It also determines an acceptable phase angle γ_{exit} for which it is safe to depart the current circle being tracked and move to the next. By setting γ_{exit} to correspond with the AUV being at the point on the current circular path that is farthest from the new target point, AUVs will not collide when departing one circular path to track another. If the AUV is within some tolerance τ_γ of γ_{exit}, it will depart the current circular path and drive directly towards the new target point using $Track\_Point()$. Once the distance r^i between the AUV and new target is less than τ_R, it will invoke $Track\_Circle()$, i.e. the circumnavigation controller described below.

The circumnavigation controller assumes that the motion of AUV i can be modeled with discrete-time first order equations as shown in (6), (7), and (8). The size of the time step is Δt seconds.

$$x^i_{auv,t} = x^i_{auv,t-1} + \nu^i_{auv,t}\cos(\theta^i_{auv,t})\Delta t \tag{6}$$

$$y^i_{auv,t} = y^i_{auv,t-1} + \nu^i_{auv,t}\sin(\theta^i_{auv,t})\Delta t \tag{7}$$

$$\theta^i_{auv,t} = \theta^i_{auv,t-1} + \omega^i_{auv,t}\Delta t \tag{8}$$

At time t, let r^i_t be the distance between AUV i and the target. γ^i_t is the relative bearing of the AUV with respect to the target. $\theta^i_{des,t}$ is the desired yaw angle of the robot, which is tangent to the circle.

$$r^i_t = \sqrt{(x^i_{auv,t} - x_{target,t})^2 + (y^i_{auv,t} - y_{target,t})^2} \tag{9}$$

$$\gamma^i_t = \tan^{-1}(y^i_{auv,t} - y_{target,t}, x^i_{auv,t} - x_{target,t}) \tag{10}$$

$$\theta^i_{des,t} = \gamma^i_t - \frac{\pi}{2} \tag{11}$$

The system can be described in terms of error variables ρ^i_t, β^i_t, and e^i_t and is illustrated in Fig. 2.

$$\rho^i_t = R^i_{des} - r^i_t \tag{12}$$

$$\beta^i_t = \theta^i_{des,t} - \theta^i_{auv,t} \tag{13}$$

$$e^i_t = \Delta\gamma_{des} - (\gamma_{i,t} - \gamma_{i-1,t}) \tag{14}$$

For AUV i at time t, the controller defines control values $\omega^i_{des,t}$ and $\nu^i_{des,t}$ to drive the error variables to 0 as time goes to infinity. K_β, K_ρ, and K_γ are proportional controller gains for β, ρ, and γ respectively. v_{nom} is the AUV's nominal velocity.

$$\omega^i_{des,t} = -\frac{v^i_t\cos(\beta^i_t)}{R^i_{des} - \rho^i_t} + \frac{K_\beta}{\Delta t}\beta^i_t + \frac{K_\rho}{\Delta t}\rho^i_t \tag{15}$$

$$\nu^i_{des,t} = \frac{R^i_{des} - \rho^i_t}{R^i_{des}\cos(\beta^i_t)}(v_{nom} + \frac{R^i_{des}K_\gamma}{\Delta t}) * (e^{i+1}_t - e^i_t) \tag{16}$$

The authors show in [21] that desired velocities can be tracked by the Iver2 AUV (i.e. $\nu^i_{des,t} = \nu^i_t$, $\omega^i_{des,t} = \omega^i_t$), and that system dynamics analysis can prove the controller is stable when $0 < K_\rho$, $0 < K_\beta < 4$, and $0 < K_\gamma < 2/3$.

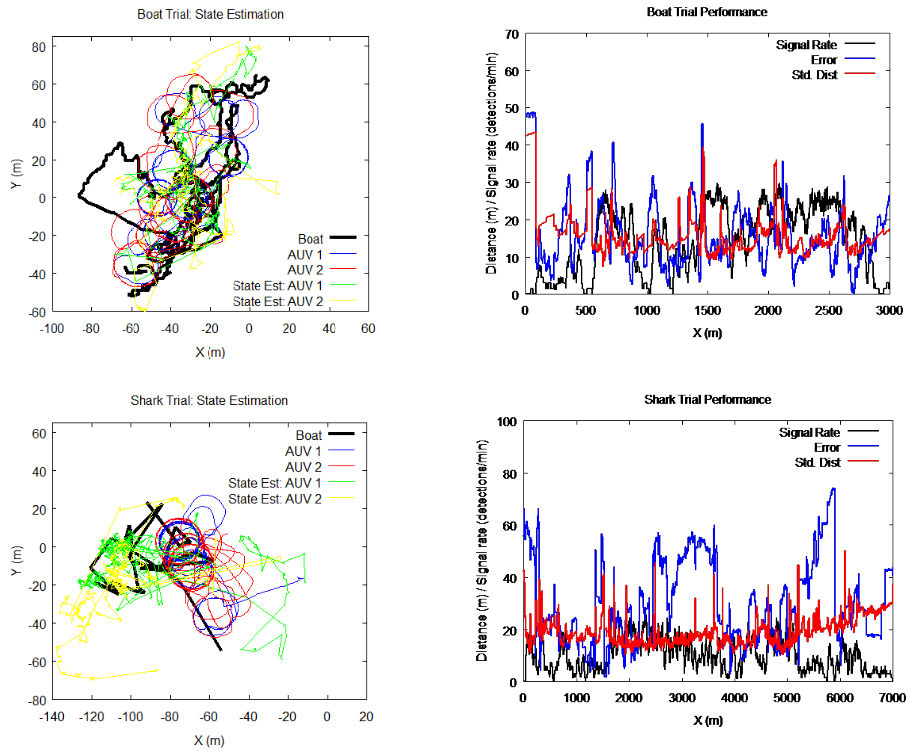


Fig. 3. State estimation trajectories from the boat trial (a) and AUV 1's error metrics plotted as a function of time (b). In (c), state estimation trajectories in the first hour of the Shark trial and the corresponding error metrics plotted as a function of time (d).

TABLE II

EXPERIMENT RESULTS

Experiment name	Avg error (m)	Min error (m)	Max error (m)	Min σ_x (m)	Max σ_x (m)	Min σ_y (m)	Max σ_y (m)
AUV 1: Shark Trial	31.42	1.68	95.96	5.57	35.84	4.92	31.80
AUV 2: Shark Trial	34.36	1.65	99.89	8.84	39.63	5.58	34.97
AUV 1: Boat Trial	15.90	0.14	48.79	4.64	30.65	4.99	34.79
AUV 2: Boat Trial	17.78	0.33	50.90	5.22	30.12	5.68	35.35

V. EXPERIMENTS

A series of verification experiments were performed in Big Fisherman's Cove located at Catalina Island, CA. The cove is adjacent to the USC Wrigley Institute for Environmental Studies. The cove contains fringing kelp forests and a large population of leopard sharks. AUV estimator and controller settings for these experiments are shown in Table I. Results from only two experiments are shown below for brevity.

The first experiment, is referred as the *Shark Trial*. Prior to the experiment, researchers attached an acoustic tag with known ID number to a leopard shark. At 10AM, July 19th, the two AUVs were deployed to cooperatively localize and track the shark based upon the signals from the tag. At the same time, researchers manually tracked the shark using a boat and directional hydrophone. The researchers repositioned the boat based upon the hydrophone measurement to move to the vicinity of the shark and approximate the shark position. This approach to manual tracking is a standard method for determining the movements of fish such as sharks [22]. Error in this experiment is measured as the distance between the AUV shark state estimate and the manual tracking shark state estimate. Notably, the true shark state is unknown.

The second experiment is referred to as the *Boat Trial*. Prior to the experiment, an acoustic tag was attached to a human controlled motor boat. At 1PM, July 19th, the two AUVs coordinated to localize and track the boat. The error in this experiment was measured as the difference between the AUV's boat state estimate and the boat's GPS measurements.

VI. RESULTS AND DISCUSSION

The paths of AUVs, boat, and targets as estimated by the AUV for the Shark trial and Boat trial are shown in Fig. 3(a) and 3(c) respectively. Real-time target state estimates were used for active AUV control during experiments, while offline processing of measurements were used to quantify performance statistics.

The statistics of the tracking error and standard deviation of the particle sets are tabulated in Table II. The tracking error and standard deviation of the particle sets of lead AUV 1, are plotted in Fig. 3(b) and 3(d). The experiment's location in the cove was near high densities of kelp which hinders the progress of the AUVs and can occlude acoustic communication. The plots include the signal rate, the rate at which the AUV receives valid measurements from the tag, averaged over the last 30 seconds. Decreases in signal rate tend to increase the error and the standard deviation of the particle set, e.g. in Fig. 3(b) near 500 seconds.

The Boat Trial error was much less than the Shark Trial error for two possible reasons. First, the shark was swimming in shallow areas outside the AUV safe boundary, and the boat could get closer to the shark than the AUVs. Second, the manual tracking method itself is not guaranteed to provide accurate truth measurements of the shark's location.

An advantage of using the AUV system over manual tracking is the increase in measurement sampling frequency. During the Shark Trial, the average sampling rate of the manual tracking system was only 0.5 measurements/minute, reflecting the time to find the shark signal and reposition the boat. As seen in Fig. 3(b), the AUV has a much higher signal rate (typically > 10 measurements/minute).

The standard deviation of the particle set indicates the uncertainty associated with the position estimate and thus the error. The proportion of time that the tracking error was less than the standard deviation of the particle is tabulated to compare the error and the standard deviation of the particle set. The lead AUV's error was less than the distance error 27.9% of the time in the Shark Trial and 52.3% of the time in the Boat Trial.

VII. Conclusions and Future Work

The presented results represent a novel attempt to use coordinating AUVs in the task of localization and tracking of a tagged fish. In trials in which the true position of the tag was known, the error associated with the tracking was shown to be of the same order of magnitude of existing approaches such as manual tracking.

Future work could expand upon this work to study other species of fish. In particularly, an AUV-based system could be a powerful tool in tracking the movements of highly migratory species of fish such as white sharks. Doing so would require improvements to the communication and sensor hardware. Additionally, usage of a tag that measures pressure and depth could allow the system can be modified to perform localization and tracking in 3 dimensions.

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