

Simultaneous Tracking and Sampling of Dynamic Oceanographic Features with Autonomous Underwater Vehicles and Lagrangian Drifters

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1 Introduction

Studying ocean processes often requires observations made in a Lagrangian frame of reference, that is, a frame of reference moving with a feature of interest [1]. Often, the only way to understand a process is to acquire measurements at sufficient spatial and temporal resolution within a specific feature while it is evolving. Examples of coastal ocean features whose study requires Lagrangian observations include concentrated patches of microscopic algae (Fig. 1) that are toxic and may have impacts on fisheries, marine life and humans, or a patch of low-oxygen water that may cause marine life mortality depending on its movement and mixing.

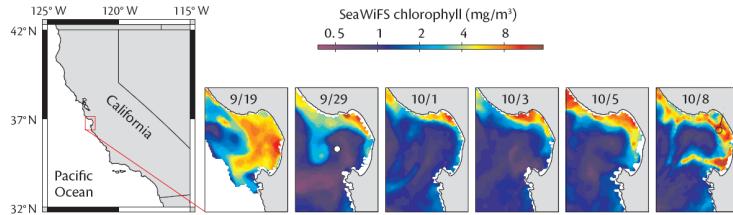


Fig. 1: Algal Bloom dynamics in Monterey Bay. Courtesy: MBARI

Recognizing the need for advancement of Lagrangian methods using multiple vehicles, the Controlled, Agile, Novel Observing Network (CANON) [2] initiative of the Monterey Bay Aquarium Research Institute (MBARI) began a 5-year development effort in 2010. CANON employs hardware and software advancements

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for autonomous underwater vehicles (AUVs) to better observe and sample dynamic ocean phenomena.

Drifters (Fig. 2 and 3) are often used as proxies for advection to study marine transport [3]. In this work, we describe a series of Lagrangian survey experiments carried out as a part of CANON, where an AUV performs surveys relative to a drifter used to tag a patch of water. We treat this as a *simultaneous tracking and sampling* task where a regular survey template (e.g. a 'lawnmower pattern' shown in Fig. 4a) is repeatedly performed *in the frame of reference of an advecting patch* that has been tagged by a GPS-tracked drifter. Starting with the scientific motivation for this effort, we first lay the groundwork through analysis of past data and simulations. Then, we describe multiple field trials that validate our approach.

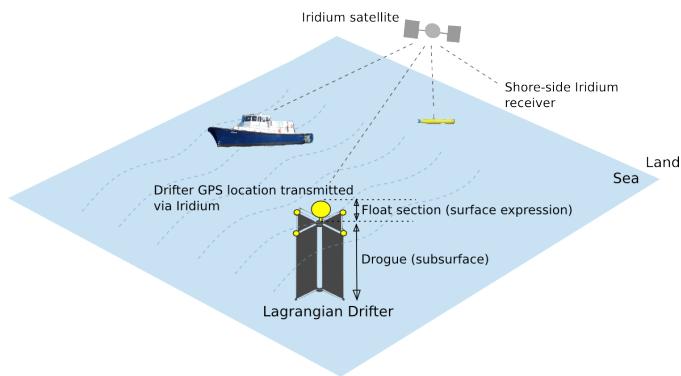
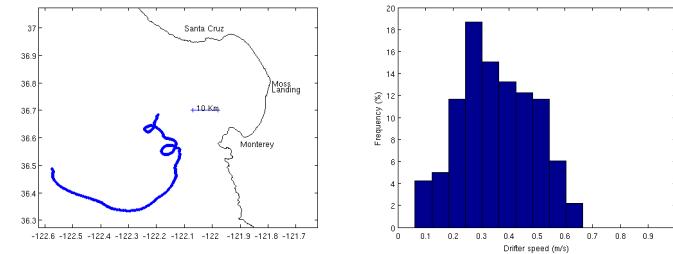


Fig. 2: Illustration of a Lagrangian drifter being tracked on shore and at sea. The drifter has a float section affected mostly by wind, and a drogue section which is dragged by the water mass. Drifter locations are transmitted via the Iridium satellite network.

Feature tracking with AUVs has been discussed in the context of multiple gliders in the Monterey Bay in 2004 by [4]. In [5], virtual drifters are deployed as patch proxies using the Regional Ocean Modeling System (ROMS), and gliders are used to track the boundary and centroid of the patch. In [6], a terrestrial multi-robot system using low-level control is used to localize and encircle a moving target in a lab environment. To the best of our knowledge, this work presents the first Lagrangian observation study where an AUV samples in the Lagrangian frame of reference of an advecting oceanographic feature tagged with a drifter.

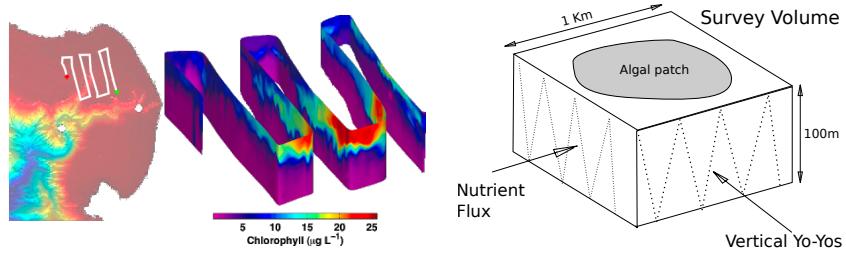
2 Experiment Design

Prior to the CANON field trials scheduled for September and October 2010, two science goals were identified for Lagrangian study of patches. First was to monitor nutrient budget through measurement of nutrient flux along the perimeter of a patch,



(a) Trajectory of a drifter advected close to the central California coast for a period of 3.5 days
 (b) Histogram of speed for drifter

Fig. 3: Characteristics of drifter trajectories



(a) Chlorophyll data reconstructed from a lawnmower survey in North Monterey bay. Courtesy: MBARI
 (b) Illustration showing the volume being studied, AUV yo-yo on the cuboid faces, and the nutrient flux measurements

Fig. 4: Example of patch mapping with a 'lawnmower' survey, and illustration showing measurement of nutrient flux (one of the goals of MBARI's CANON initiative)

and second, mapping the entire patch to understand its spatio-temporal dynamics. In the former, the focus is not on the dynamics of the patch, but, to understand what triggers the patch and hence, to study what exchanges happen between the patch interior and surroundings. The latter focuses on the activity *inside* a patch. The focus here is to study the dynamics of features of interest, e.g., in the case of an algal bloom being advected by ocean currents, the interest may be in mapping bloom growth and decay.

Motivated by the above goals, we devised approaches that differ *only* in the survey patterns used. For nutrient flux, we use surveys that focus on patch perimeter, and for patch mapping, we use templates that sample in the interior of a patch. Specifically, in this study we extend commonly used oceanographic survey templates with different sampling characteristics to the task of Lagrangian observation studies. In this section, we discuss our approach in detail and describe the implementation on AUVs. The results of field trials are discussed in Section 3.

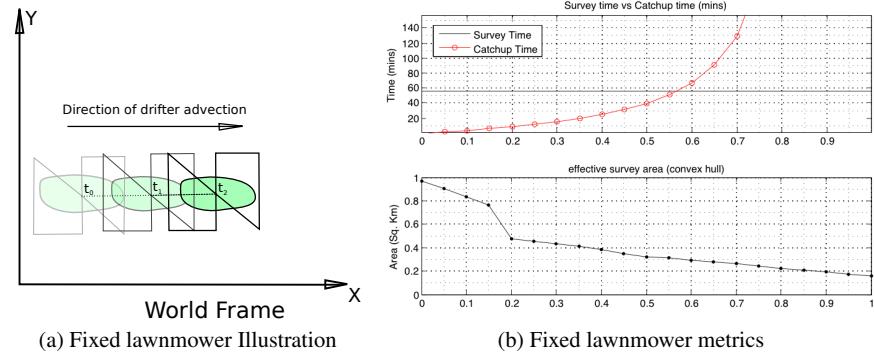


Fig. 5: The fixed-lawnmower survey template and metrics

2.1 Using fixed surveys

We started our study by performing a desired survey pattern (e.g lawnmower) relative to the world frame, centered at the initial observed patch center. Once complete, the survey is repeated at the new patch center. We will show two examples of this approach, tested in Monterey bay in June 2010 during a two-day field trial.

Fixed Lawnmower

The lawnmower template is one of the most commonly used survey pattern because of its ease of visualization and straightforward representation (Fig. 4a). We perform this template repeatedly to map a moving patch. Once the location of the patch center is marked by a GPS-tracked drifter (in the remaining paper, we will use patch center and drifter interchangeably), we plan a lawnmower survey around the last known patch center. After the survey is completed, the next iteration begins with an AUV catch-up step. Here, the AUV travels to position itself at the initial waypoint, relative to the new patch center (latest location of the drifter). Fig. 5 illustrates this scenario. Fig. 5b shows the relationship between drifter speed, AUV survey time, and AUV catch-up time for a simulation carried out for a 1Km x 1Km lawnmower survey. For the effective survey area, we consider the convex-hull of the survey region that overlaps with the 1Km x 1Km bounding box around the advecting drifter. For this analysis, the nominal projected AUV speed was set to 1.2m/s, with the top AUV speed of 1.75 m/s for the catch-up phase where the AUV does not perform yo-yos (projected speed and yo-yo are described in Fig. 9).

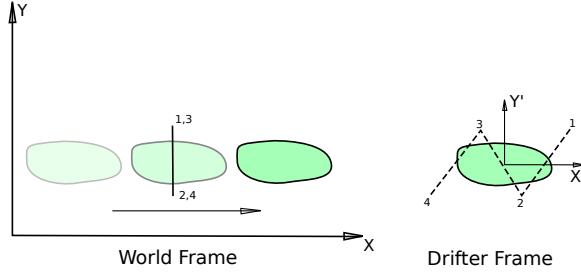


Fig. 6: Illustration of the slicer template

Fixed Slicer

We also tried an extension of a simple survey template, a slicer (Fig. 6). Here, an AUV alternately visits two waypoints while performing vertical Yo-Yos. This results in a survey along a fixed vertical plane. The goal is to allow an advecting patch to drift through this plane, in the process capturing a snapshot of a cuboidal volume of the patch. Fig. 6 illustrates this scenario looking from the top. The template is positioned on the expected path of the drifter and continued for a duration that allows the patch to completely pass through. The expected path is computed by linear extrapolation of the drifter trajectory based on its latest observed speed and course. After the drifting patch has passed through the template, the AUV performs a catch-up operation where it positions itself ahead of the patch. The AUV now performs a slicer again allowing the patch to pass through. This is repeated till the patch is outside the area of interest or the AUV mission time is achieved. Depending on the duration of the slicer and the speed of the drifting patch, the volume captured by the slicer will vary as shown in the following equation.

$$V = \frac{Wdv_d}{T} \quad (1)$$

Where W is the width of the slicer, d is the depth of yo-yos, T is the survey time (a function of AUV speed, pitch angle, and distance between waypoints) and v_d is the drifter speed. The slicer template was used for Day 1 of the June experiment and the results are discussed in Section 3.

2.2 Using Lagrangian surveys

The fixed lawnmower and fixed slicer presented above are extensions of existing survey templates repeatedly performed on an advecting patch. However, as shown in the analysis of the fixed lawnmower template (Fig. 5b), the effective survey area degrades and the catch-up time increases as the patch advection speed increases,

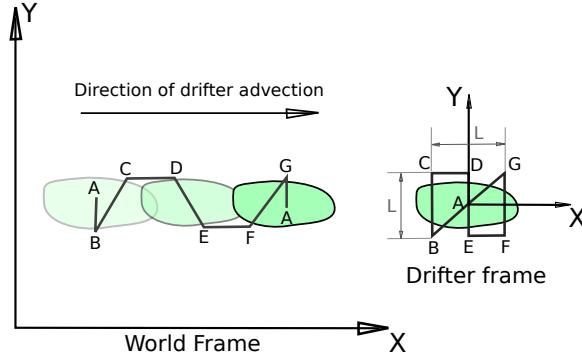


Fig. 7: Illustration of the Lagrangian lawnmower template

or the patch changes direction rapidly (observed in the June field trial discussed in Section 3). Based on these observations, in preparation for the September field experiment, we modified our approach such that the survey pattern is implemented in the Lagrangian frame of reference of the patch center. The template trajectory is transformed into the Lagrangian frame of reference of the drifter so that the survey pattern is performed relative to the drifter at all times. Fig. 7 illustrates this for the lawnmower template.

2.2.1 Lagrangian Box

We considered the box survey pattern for Lagrangian survey for the September field trial (Fig. 4b). This addresses the science goal of measuring nutrient flux around a drifting patch. The desired box dimensions were 1Km x 1Km with yo-yos of depth 100m, to be repeated every hour. Now we'll discuss the implementation of this survey on the AUV.

AUV Implementation

To implement the Lagrangian surveys on an AUV, we first need to compute the AUV trajectory in the world frame. We show two ways of doing this. First, where the AUV surveys a patch at a *constant speed in the Lagrangian frame* i.e. if seen from the patch center, the AUV appears to move at constant speed. Second, where the AUV maintains *constant speed in world frame*. The former is the ideal scenario given the science need of sampling the patch at a steady rate and uniformly distributed samples along the survey template, whereas the latter takes into account the operational constraints of the AUV. Currently, for standard AUV operations, waypoints are provided and the AUV travels between the waypoints at the specified pitch angle at a *constant speed*. Fig. 9 illustrates an AUV yo-yo in this mode of operation.

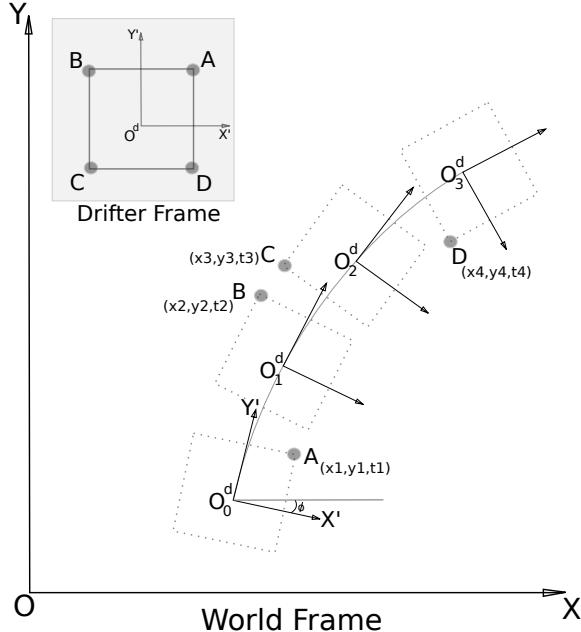


Fig. 8: Illustration of the transformation of box template waypoints from Lagrangian frame to world frame.

Here we discuss the two cases and then demonstrate how Lagrangian survey was performed during the September field trial.

Constant AUV speed in Lagrangian frame of reference

Here, the goal is to perform the survey template at constant speed relative to the drifter. This is the ideal science goal since we want to achieve a uniform sampling rate in the Lagrangian frame. In other words, we want the AUV to sample the advecting patch at a constant speed in the drifter frame of reference. This results in variable AUV speed in the world frame. We performed a simulation to study this variation with the lawnmower template. This simulation served two purposes. It helped us understand the nature of patch advection and allowed us to study the variations in speed and direction. Additionally, it helped us understand the complexity of implementing this mode operationally. The parameters for the lawnmower survey are width L (see Fig. 7), and survey period T in minutes. The maximum AUV ground speed is v_{max}^{auv} by design (maximum forward AUV speed during a yo-yo, projected on the ocean surface for simplicity). For the computation of trajectory in world frame, consider Fig. 8. Here, we show the box pattern with the four corner waypoints of the AUV trajectory. Given the desired speed at which we want the AUV to sample

in the Lagrangian frame, we have the corner coordinates denoted by $P_i^d = (x_i^d, y_i^d)$ and time t_i when they should be visited. If ϕ is the angle between the drifter frame and the world frame, and the origin of the drifter frame is $O_i^d = (x_i^o, y_i^o, t_i^o)$, we can construct a homogeneous transformation matrix H_w^d that transforms a point in the drifter coordinate frame to the world coordinate frame, given by,

$$H_w^d = \begin{bmatrix} \cos \phi & -\sin \phi & x_i^o \\ \sin \phi & \cos \phi & y_i^o \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Given P_i^d , a coordinate in drifter frame, the corresponding coordinate in world frame is given by,

$$P_i^w = H_w^d P_i^d \quad (3)$$

Given the current AUV coordinate in world frame, and the destination computed using Equation 3, we can compute the required yo-yo pitch angle, and AUV surge speed to achieve the target in the drifter frame at the desired time instant. The maximum required AUV speed in world frame is bounded by the following inequality,

$$|v_{rel}^{auv}| \leq v_{max}^{auv} - |v_d| \quad (4)$$

where v_d is the estimated drifter velocity and v_{rel}^{auv} is the AUV speed relative to the drifter. Given current estimated drifter velocity v_d , time-period T , the total survey length L_{total} , the required maximum AUV ground speed when the drifter and AUV are parallel and moving in the same direction is given by (the equality in Equation 4),

$$|v_{ground}^{auv}| = |v_{rel}^{auv}| + |v_d| \quad (5)$$

$$|v_{ground}^{auv}| = \frac{L_{total}}{T} + |v_d| \quad (6)$$

For the lawnmower template used in the simulation, $L_{total} = (4 + \sqrt{2})L$. Hence v_{ground}^{auv} is given by $\frac{(4+\sqrt{2})L}{T} + |v_d|$.

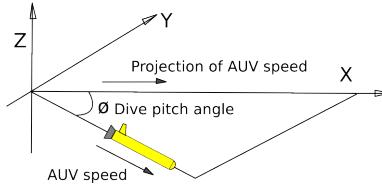


Fig. 9: AUV pitch angle and projected speed

Using the above formulation, a simulation was run on 3.5 days of drifter data logged in August 2006 to implement a Lagrangian lawnmower template (Fig. 7). During that period the drifter traveled 80 Km at a mean speed of 0.27 m/s (Fig. 3).

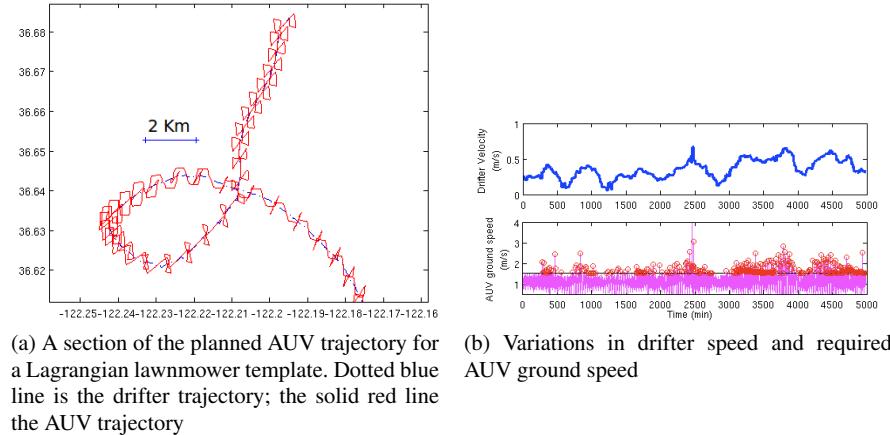


Fig. 10: Simulated AUV trajectory from historical drifter data

v_{max}^{auv} was set to 1.5 m/s, lawnmower width L to 500m, and T to 33 minutes based on AUV design and science needs. New drifter data was available every 10 mins. Drifter location was updated every minute by extrapolating the velocity estimate from the last available drifter location. Extrapolation error of the drifter trajectory results in the calculated AUV ground speed to exceed v_{max}^{auv} 15% of the time. This occurs when the drifter accelerates or changes direction. Results are as shown in Fig. 10.

Constant AUV speed in world frame of reference

As mentioned earlier, current AUV operation relies on waypoints, AUV surge speed, and yo-yo parameters (pitch angle and depth envelope) specified for missions. For the Lagrangian observation study presented in this paper, we wanted to extend existing AUV survey methodologies by making incremental modifications. In the case of fixed surveys presented earlier in this section, the standard mode of AUV operation is retained with just an additional catch-up step which can be specified as a waypoint and AUV surge speed (no yo-yos are performed during this step). Hence, for the five day patch following experiment planned for September, we considered an alternative to the ideal case where AUV moves at constant speed in Lagrangian frame. We used available AUV command primitives consisting of goal waypoints in the world frame, yo-yo parameters, and desired AUV surge speed. Given the desired survey pattern to be implemented in the Lagrangian frame, we compute the waypoints in the world frame that results in the desired survey in the Lagrangian or drifter frame. This is illustrated in Fig. 11.

Now we demonstrate the computation of waypoints via an example scenario shown in Fig. 12. The goal is for the AUV to travel from its initial location to the

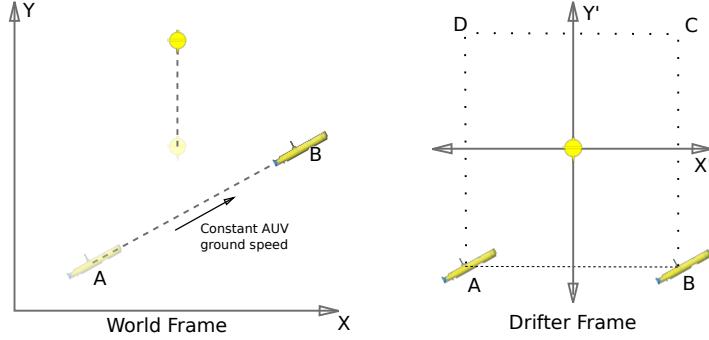


Fig. 11: Illustration showing the motion of AUV in world and drifter frames

drifter in the Lagrangian frame with constant ground speed s_d . The drifter advects along positive y -axis with speed s_d . Initial AUV location is $A = (-x_a, -y_a)$, initial drifter location is $B = (0, y)$. We want to compute C where the AUV reaches the drifter in the Lagrangian frame. \mathbf{I} represents the AUV displacement in the lagrangian frame, \mathbf{D} represent the drifter displacement in the world frame and $\mathbf{P} = \mathbf{I} + \mathbf{D}$ is AUV displacement in world frame. Hence, the AUV waypoint in the world frame is given by $C = (-x_a, y - y_a)$ where, y is unknown. Given that the drifter and the AUV travel for the same duration $T_d = T_a = T$, we can compute y as follows,

$$\begin{aligned}
 T_d &= T_a \\
 \frac{|\mathbf{D}|}{s_d} &= \frac{|\mathbf{P}|}{s_a} \\
 (s_a \cdot y)^2 &= s_d^2(x_a^2 + (y - y_a)^2) \\
 y &= \frac{-s_d y_a \pm \sqrt{(s_a y_a)^2 + (s_a^2 - s_d^2)x_a^2}}{(s_a^2 - s_d^2)}
 \end{aligned}$$

3 Field Trials

Fig. 12: Constant AUV speed example

Field trials were split into two separate experiments. A two-day experiment was carried out in June 2010 in Monterey Bay. In September 2010, a five-day off-shore experimentation was carried out with a science crew on two vessels following a drifter with an onboard genomic-sensor. In this section, we describe the logistical details for the trials and discuss the observations made.

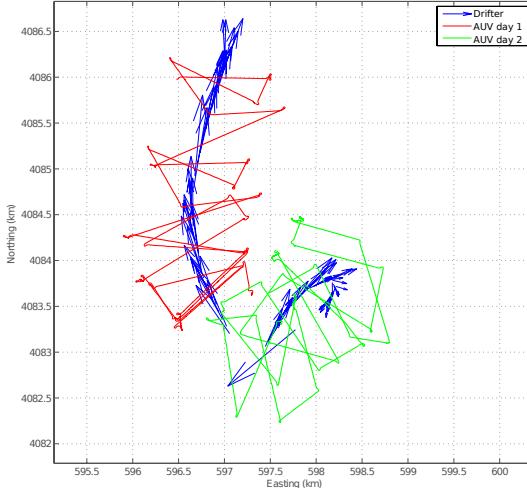


Fig. 13: AUV and drifter Trajectories of June 2010 drifter following experiment with the slicer and lawnmower patterns

3.1 June 2010 Drifter Following Experiment

In June 2010, a two-day pilot experiment was carried out in Monterey Bay. These were the first trials for the Lagrangian observation studies, and an important goal was to ensure the methodologies described worked smoothly within the logistical constraints of AUV deployment operations. This was critical for the Lagrangian observation capabilities required during the planned five-day September 2010 CANON experiment.

In Section 2.1, we showed how the slicer and lawnmower templates can be repeated to enable Lagrangian observation of an advecting patch. This is the simplest way to extend existing AUV operations and was the goal for the June 2010 trial. The first day focused on trying the fixed-slicer template, followed by experiments with the fixed-lawnmower on the second day. Each experiment was carried out for a period of ~ 7 hours. The experiment started with scientists choosing a point of interest within Monterey Bay, providing us with the desired patch center to be tracked. R/V Zephyr (a support vessel) deployed the drifter at the patch center, and MBARI's Dorado AUV (Fig. 15) in its vicinity. This process was followed on both days. Every 10 minutes, the GPS-tracked drifter transmitted its location to the vessel via Iridium satellite network. At the beginning of a survey iteration, an operator on the vessel transmitted the drifter location, course, and speed to the AUV Dorado. Although this step could have been automated, it was desired to have a human in the loop for the first trial for operational safety. A hybrid plan-execution controller T-REX [7–9] on the AUV computed the waypoints based on the desired template (slicer for Day 1, fixed-lawnmower for Day 2), and executed the survey. On completion of the survey,

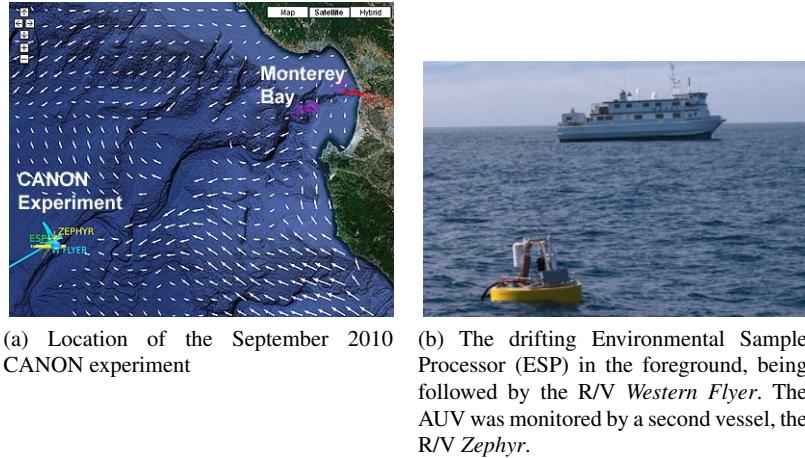


Fig. 14: The September 2010 CANON experiment occurred 160 Kms off California coast for a duration of five days. In this period, AUV Dorado performed a Lagrangian-box survey around an ESP-drifter.

the AUV was commanded again for the next iteration. This was continued for multiple iterations, each day. The AUV and drifter trajectories are shown in Fig. 13. As seen in the figure, on Day 2, the drifter showed a sudden change in direction, doing a complete 'U-turn' within an hour. This results in the AUV having to travel farther to position itself for the next iteration. This observation validated the simulation results described in Section 2.2.

3.2 September 2010 CANON Experiment

Based on the results of the June 2010 experiments, a longer five-day field experiments was carried out in September 2010, hundred nautical miles off the California coast (Fig. 14a). A specialized drifter was developed at MBARI with an Environmental Sample Processor (ESP) onboard allowing in-situ identification of micro-organisms(Fig. 14b). The experiment had multiple goals spread across crews on two vessels, R/V Western Flyer and R/V Zephyr. R/V Western Flyer crew visited the drifter every four hours to carry out a series of ship-based sampling experiments and lab analysis on water samples. R/V Zephyr focused entirely on Lagrangian observation studies with the AUV. The goal for the September 2010 experiment was to monitor the nutrient budget at the perimeter of a 1 sq.Km patch of water around the advecting ESP-drifter. To achieve this, MBARI's *Dorado* AUV was used to perform the Lagrangian-box described in Section 2.2 around the drifter. A number of logistical issues were kept in mind while designing and executing the experiment. Each iteration began with the latest drifter update (position and velocity) received from



Fig. 15: The *Dorado* AUV being loaded on the R/V *Zephyr* for the five day drifter tracking experiment in September 2010.

the drifter through an Iridium satellite link. This was transmitted to AUV Dorado for in-situ adaptation. T-REX in turn synthesized the four waypoints of the box survey. Given two vessels in proximity of the drifter at all times, once computed, these waypoints were not recomputed so that the ship crew had the expected surfacings before every iteration. The survey plan was hence known in advance for the duration of each survey lasting (~ 1 to 1:30 hrs). Fig. 16 shows the box pattern performed by the AUV relative to the drifter for one day of the five-day experiment.

3.3 Sources of error

Since waypoints are computed in advance for each iteration, errors during each survey can affect the quality of the resulting Lagrangian template. Change in drifter speed and course during an iteration results in the actual drifter trajectory being different from the AUV's internal projected drifter trajectory. Also, between surfacings, the AUV dead-reckons using its compass and the commanded pitch angle. This results in localization error that affects the quality of the Lagrangian survey. Additionally, for the operations during CANON, there was a lag of ~ 15 mins for drifter location data. This delay was both due to the update rate via Iridium from the drifter (~ 10 mins), and operational delay due to human in-the-loop commanding done for safety.

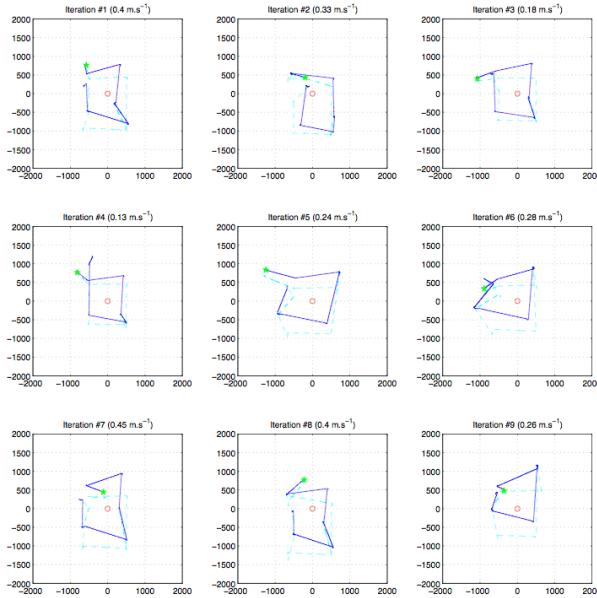


Fig. 16: AUV trajectories in the drifter frame of reference for Lagrangian box surveys during the September 2010 experiment, Day 4

4 Conclusion and Future Work

In this paper, we demonstrated methodologies to observe advecting oceanographic features with an AUV. A GPS-tracked drifter was used to tag a feature (or patch) of interest, and the AUV surveyed the volume of the patch using various survey patterns. A series of field trials were conducted targeting various methods. We observed that there are limitations of using extensions of static surveys repeatedly repositioned with the advecting patch. By ensuring a desired template is implemented in the Lagrangian frame of reference, we addressed the limitations, and an AUV was able to track a drifting patch continuously for a period of five days in a larger field experiment as part of MBARI’s CANON initiative. Our efforts were guided by working in a highly inter-disciplinary team with biological and physical oceanographers as well as operations personnel. The former articulated the design philosophy as well as helped formulate the appropriate survey templates shown in this work. The latter aided in formulating protocols for multi-ship operation in with the presence of an AUV and a drifter. The process of coming up with the experiments therefore involved a close effort to meet science, engineering and logistical goals. We are now working on two areas to improve such experiments. First, to

increase the level of autonomy by enabling the AUV to receive drifter locations directly to plan each iteration; one consideration is to ensure that the experiment occurs sufficiently offshore to discount any possibility of drifting towards shallow waters. Second, we are now considering more refined surveys where the AUV is able to compensate for drifter locations during the survey. Currently, the AUV plans a survey in advance, and no adaptation is performed during an iteration.

5 ACKNOWLEDGMENTS

This work was supported in part by the NOAA MERHAB program under grant NA05NOS4781228 and by NSF as part of the Center for Embedded Network Sensing (CENS) under grant CCR-0120778, by NSF grants CNS-1035866, CNS-0520305 and CNS-0540420, by the ONR MURI program (grants N00014-09-1-1031 and N00014-08-1-0693) by the ONR SoA program and a gift from the Okawa Foundation. We thank the David and Lucile Packard Foundation for supporting our work at MBARI and the crew of the R/V *Zephyr* for help with deployments.

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