Ocean Front Detection and Tracking by an Autonomous Underwater Vehicle

Yanwu Zhang, Michael Godin, James G. Bellingham, and John P. Ryan

***Abstract*—In this paper we present a method of using an autonomous underwater vehicle (AUV) to detect and track an ocean front created by coastal upwelling. In an upwelling water column, temperature, salinity, and other properties are more homogeneous over depth as compared with non-upwelling water which is typically stratified. We use the vertical homogeneity of temperature as the classifier for differentiating upwelling and stratified water columns. On 27 April 2011, the Tethys long-range AUV ran the algorithm to autonomously detect and track a front in a dynamic coastal upwelling region in Monterey Bay, CA. The AUV transected the front 14 times over two days, providing a very high-resolution depiction of the front.**

***Index Terms*—Autonomous underwater vehicle (AUV), ocean front, detection, tracking.**

I. INTRODUCTION

An ocean front delineates the boundary between water masses distinguished by different physical, chemical, and/or biological characteristics. Ocean ecosystems are greatly influenced by the structure and dynamics of fronts [1]. Ocean fronts also play an important role in air-sea exchange [2], [3]. Detection and tracking of ocean fronts is important for investigating the formation, evolution, and interaction of ocean water masses. Knowing the boundary between these water masses enables targeted sampling of the respective waters.

Coastal upwelling [4] is a wind-driven ocean process that brings cooler, saltier, and usually nutrient-rich deep water upward, displacing warmer, fresher, and nutrient-depleted surface water. The nutrients carried to the surface by upwelling have great impact on primary production and fisheries. Ocean life, from the microscopic to the largest animals, often aggregates at fronts.

The first use of autonomous underwater vehicles (AUVs) for studying ocean fronts was in the 1996 Haro Strait Frontal Dynamics Experiment. Two MIT Odyssey-class AUVs were deployed along with surface ships and drifters in a coordinated effort to map the tidal fronts. The AUVs conducted high-resolution surveys of temperature, salinity, and current velocity in the frontal regions [5], [6]. One vehicle also carried an acoustic tomography source [7]. During the experiment, the Harvard Ocean Prediction System (HOPS) ocean model was run to predict the front's location, which guided the AUVs' deployment. In recent studies of fronts at the periphery of the upwelling shadow in Monterey Bay [1], AUV-measured temperature, salinity, and current velocity proved very useful. In the above AUV missions, the vehicles did not possess the ability to autonomously detect the front.

In this paper, we present a method for an AUV to autonomously detect and track an ocean front created by coastal upwelling. The algorithm is given in Section II. In April 2011, the Tethys long-range AUV [8] ran the algorithm to autonomously detect and track an upwelling front in Monterey Bay, CA, as described in Section III. We propose future work in Section IV.

II. AUTONOMOUS DETECTION AND TRACKING OF AN UPWELLING FRONT

We have developed two approaches for detecting an ocean front using an AUV. The first approach, presented in a separate paper, involves the AUV recognizing locally enhanced gradients of ocean properties. This approach is required when accurate real-time localization of the front is needed. The second approach, presented in this paper, involves the AUV recognizing that it has departed one water column and entered another. The AUV will overfly the front, thus characterizing the water columns on both sides of the front. The key to this approach is a means of classifying the two different water columns.

In an upwelling water column, temperature, salinity, and other properties are much more homogeneous over depth as compared with non-upwelling water which is typically stratified. Drawing on this difference, we formulated a simple classifier — the vertical homogeneity of temperature $\Delta_{temp} = Temp_{shallow} - Temp_{deep}$ for differentiating upwelling and stratified water columns, where $Temp_{shallow}$ and $Temp_{deep}$ are temperatures at shallow and deep depths, respectively. Δ_{temp} is significantly smaller in an upwelling water column than in a stratified water column. The algorithm flows as follows.

- The AUV flies through the front on a sawtooth (i.e., yo-yo) trajectory (in the vertical dimension). We use $\Delta_{temp} = Temp_{5m} - Temp_{20m}$ as the classifier for distinguishing stratified and upwelling water columns. The 5 m shallow depth and 20 m deep depth are selected based on previous temperature measurements by AUVs in stratified and upwelling water columns in Monterey Bay. On each descent or ascent leg, the AUV records $Temp_{5m}$ and $Temp_{20m}$ when it passes those depths, and calculates Δ_{temp}.
- We set a threshold $thresh_{\Delta} = 1°C$. Suppose the AUV starts a mission in stratified water and flies towards upwelling water. When Δ_{temp} falls below $thresh_{\Delta}$, a

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detection counter $Count_{FrontDetected}$ counts 1. On the following yo-yo leg, if Δ_{temp} remains below $thresh_{\Delta}$, $Count_{FrontDetected}$ increases to 2; but if Δ_{temp} turns out to be above $thresh_{\Delta}$, $Count_{FrontDetected}$ is reset to 0. When $Count_{FrontDetected}$ reaches 6, the AUV determines that it has passed the front and has entered an upwelling water column, and accordingly sets $Flag_{PassedFront}$ to 1. The setup of $Count_{FrontDetected}$ is for robust detection of an upwelling water column (i.e., small patches of water with low Δ_{temp} will be ignored).

- The AUV continues flight in the upwelling water for $Dist_{continuaton} = 3$ km to cover the width of the frontal region, and then turns around to fly back to the stratified water. $Count_{FrontDetected}$ and $Flag_{PassedFront}$ are reset to 0.
- On the way back, when Δ_{temp} rises above $thresh_{\Delta}$, $Count_{FrontDetected}$ counts 1. When $Count_{FrontDetected}$ reaches 6, the AUV determines that it has passed the front and has entered the stratified water column, and sets $Flag_{PassedFront}$ to 1. Similarly, the setup of $Count_{FrontDetected}$ is for robust detection of a stratified water column (i.e., small patches of water with high Δ_{temp} will be ignored).
- The AUV continues flight in the stratified water for $Dist_{continuaton} = 3$ km, and then turns around to fly back to the upwelling water. $Count_{FrontDetected}$ and $Flag_{PassedFront}$ are reset to 0.
- The AUV repeats the above cycle of front crossing. As the front evolves over time, the AUV effectively tracks it.

Fig. 1. The Tethys AUV deployed in Monterey Bay. The orange tail section of the vehicle is the propulsion and control section, which also includes antennae for Iridium and Argos satellites, GPS, and line-of-sight radio-frequency communications. The yellow center section is the main pressure vessel housing vehicle electronics and batteries. The orange head section (submerged) is a wet volume housing a suite of science sensors.

III. FIELD PERFORMANCE

The Tethys long-range AUV [8], as shown in Figure 1, was developed at the Monterey Bay Aquarium Research Institute (MBARI). It has a length of 2.3 m and a diameter of 0.3 m (i.e., 12 inches) at the midsection. The propeller-driven vehicle can run at two speeds: 1 m/s and 0.5 m/s. Propulsion power consumption is minimized through a careful design of a low-drag body and a high-efficiency propulsion system. In addition, by using a buoyancy engine, the vehicle is capable of trimming to neutral buoyancy and drifting in a lower power mode. The Tethys AUV thus combines the merits of propeller-driven and buoyancy-driven vehicles. The vehicle's sensor suite includes Neil Brown temperature and conductivity sensors, a Keller depth sensor, a WET Labs ECO-Triplet Puck fluorescence/backscatter sensor, an Aanderaa dissolved oxygen sensor, an In Situ Ultraviolet Spectrophotometer (ISUS) nitrate sensor, and a LinkQuest Doppler velocity log (DVL).

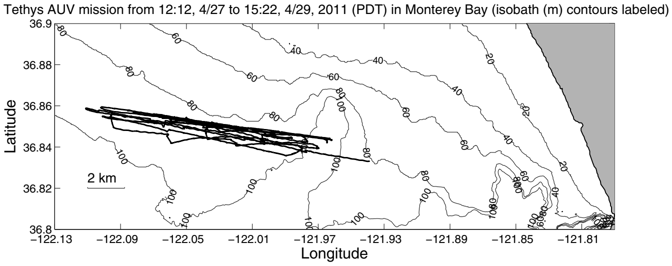

Fig. 2. The horizontal track of the Tethys AUV in the mission on 27 April 2011 (mission log No. 20110427T191236).

On 27 April 2011, the Tethys AUV ran the presented algorithm in Monterey Bay, CA during a Controlled, Agile, and Novel Observing Network (CANON) experiment (see http://www.mbari.org/canon/). The vehicle speed was about 1 m/s. The AUV's horizontal track is shown in Figure 2. The AUV flew on a yo-yo trajectory between surface and 50 m depth. The AUV transected the front 14 times over two days, providing a very high-resolution depiction of the front. The AUV-measured temperature in the 14 transects is shown in Figure 3. In each panel, the start and ending times of the transect is noted, and the arrow shows the AUV's flight direction.

As explained in Section II, we use $\Delta_{temp} = Temp_{5m} - Temp_{20m}$ as the classifier for distinguishing stratified and upwelling water columns. Temperature was lower and much more homogeneous over depth in the upwelling water column (on the west side) than in the stratified water column (on the east side). In each panel in Figure 3, the vertical bar marks where the AUV determined that it had passed the front (i.e., when $Count_{FrontDetected}$ reached 6). On the fourth transect, just after the AUV passed the front and entered the stratified water column (i.e., $Flag_{PassedFront}$ was set to 1), a propeller failure occurred and the mission ended. Then the AUV restarted the mission maintaining the direction ($Count_{FrontDetected}$ and $Flag_{PassedFront}$ were reset to 0). After $Count_{FrontDetected}$ reached 6 again, $Flag_{PassedFront}$ was set to 1 again, which explains the appearance of the second vertical bar.

As the front moved over time, the AUV closely tracked it (traced by the vertical bar). Note that when the AUV determined that it had passed the front into upwelling (or

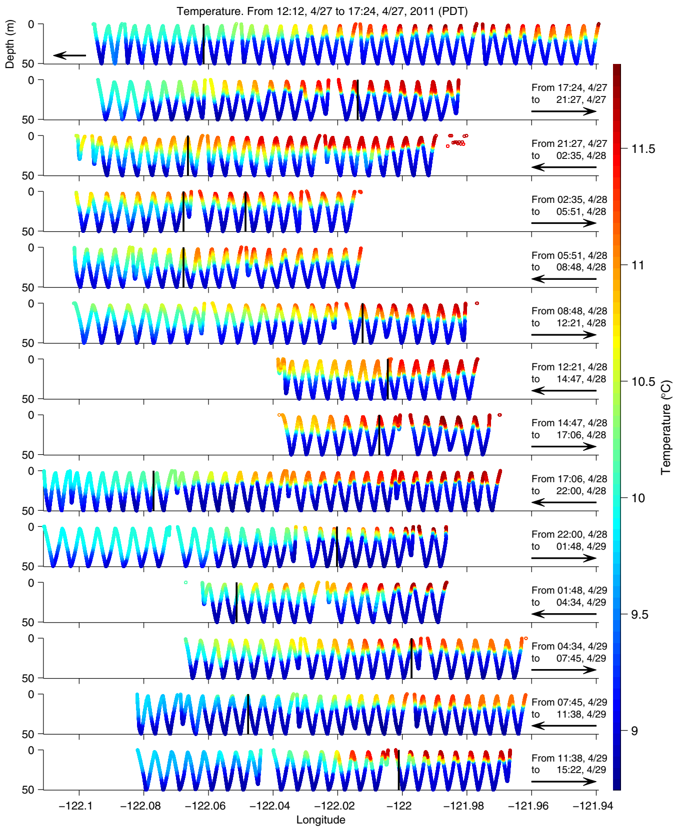

Fig. 3. Temperature measured by the Tethys AUV on the 14 transects across the upwelling front. In each panel, the arrow shows the AUV's flight direction, and the vertical bar marks where the AUV determined that it had passed the front (i.e., when $Count_{FrontDetected}$ reached 6).

stratified) water, it had already flown in upwelling (or stratified) water for 6 yo-yo profiles because of the requirement $Count_{FrontDetected}$ = 6. Hence the vertical bar's location was 6 yo-yo profiles later than the actual location of the front. A correction needs to be done in post-processing analysis of the front's motion over time.

Salinity measured by the AUV on the 14 transects is shown in Figure 4. Salinity was higher and much more homogeneous over depth in the upwelling water column (on the west side) than in the stratified water column (on the east side). Dissolved oxygen and chlorophyll concentrations are shown in Figure 5 and Figure 6, respectively. Note that the ISUS sensor was turned off in this mission. We are working on further analyses of the water column properties across the front, and also the evolution of the front in relation to atmospheric and oceanic conditions.

IV. CONCLUSION AND DISCUSSION

We have presented a method of using an AUV to autonomously detect and track an ocean front. In a two-day mission in April 2011, the Tethys long-range AUV ran the algorithm to detect and closely track an upwelling front. The 14 transects across the front provided high-resolution pictures of temperature, salinity, dissolved oxygen, and chlorophyll.

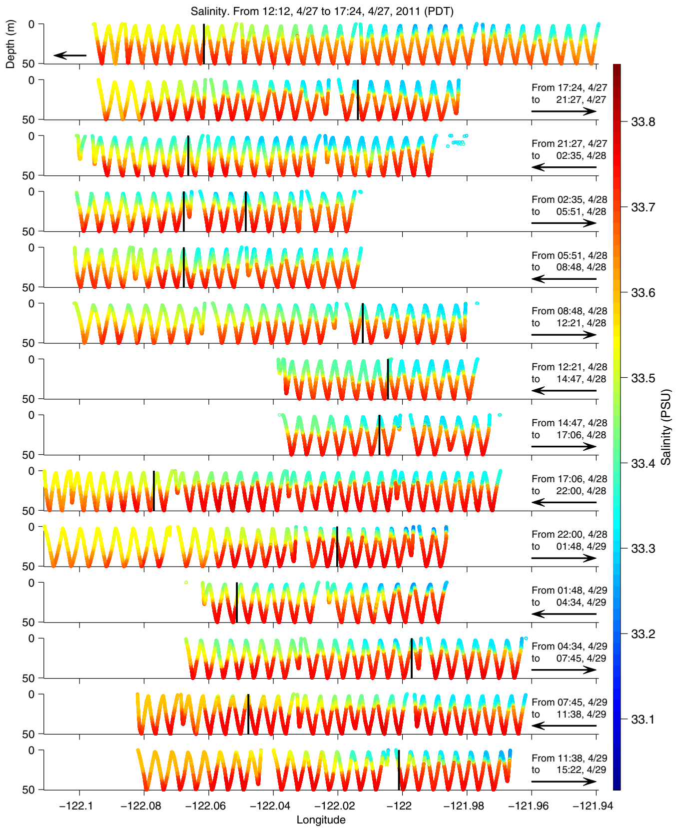

Fig. 4. Salinity measured by the Tethys AUV on the 14 transects across the upwelling front.

Given the successful test results on the Tethys AUV, we integrated the algorithm into the autonomous sampling software of the Dorado AUV (an earlier MBARI-developed vehicle with a larger sensor payload and a water sampling system). In an ensuing CANON experiment in June 2011, the Dorado AUV ran the algorithm to autonomously trigger water samplings in upwelling water columns. We are working on improving the method and expect it to find more applications in future studies of ocean fronts.

In the current algorithm, after the AUV has passed the front (i.e., $Flag_{PassedFront}$ is set to 1), the vehicle continues to fly for a pre-set distance $Dist_{continuaton}$ before turning around. The continued flight is for sufficient coverage of the front's width. Instead of pre-setting $Dist_{continuaton}$, we can let the AUV make the decision based on real-time calculation of the horizontal variability of temperature (and other properties if needed): when the horizontal variability remains high, the AUV should continue flight maintaining the direction; when the horizontal variability drops below some level, the vehicle should turn around. This way, the AUV can adaptively find a good balance between frontal coverage and temporal resolution of front tracking.

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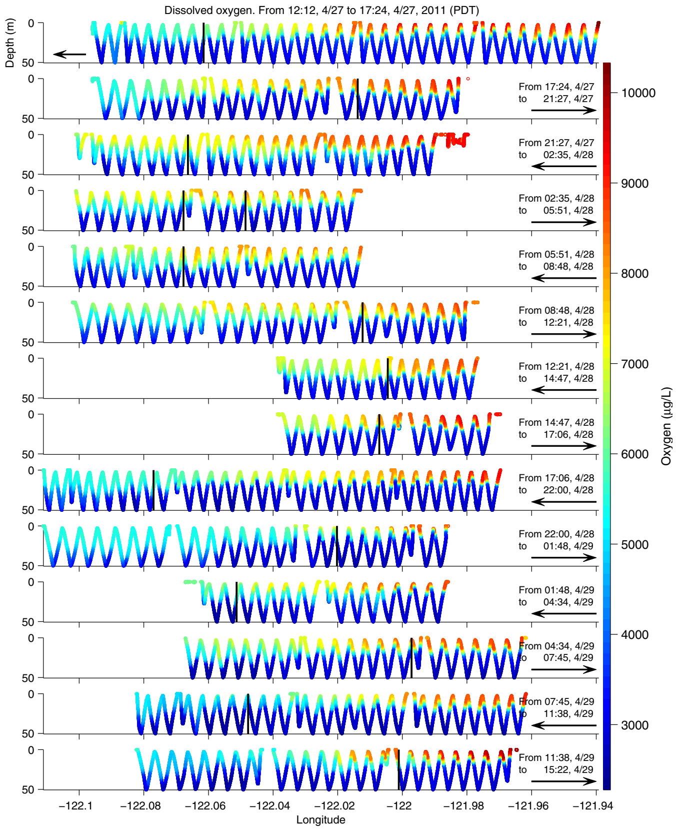

Fig. 5. Dissolved oxygen concentration measured by the Tethys AUV on the 14 transects across the upwelling front.

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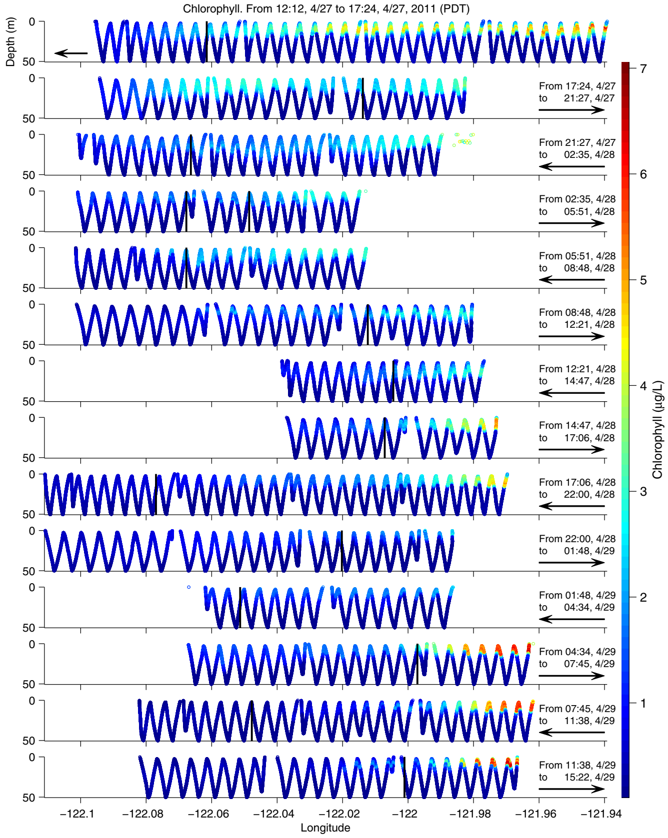

Fig. 6. Chlorophyll concentration measured by the Tethys AUV on the 14 transects across the upwelling front.

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