Two-Dimensional Mapping and Tracking of a Coastal Upwelling Front by an Autonomous Underwater Vehicle

Yanwu Zhang, James G. Bellingham, John P. Ryan, Brian Kieft, and Michael J. Stanway

Abstract—**Coastal upwelling is a wind-driven ocean process. It brings cooler, saltier, and usually nutrient-rich deep water upward to the surface. The boundary between the upwelling water and the normally stratified water is called the "upwelling front". Upwelling fronts support enriched phytoplankton and zooplankton populations, thus having great influences on ocean ecosystems. In our prior work, we developed and field demonstrated a method of using an autonomous underwater vehicle (AUV) to autonomously identify an upwelling front, map the vertical structure across the front, and track the front's movement on a fixed latitude (i.e., one-dimensional tracking). In this paper we present an extension of the method for mapping and tracking an upwelling front on both latitudinal and longitudinal dimensions (i.e., two-dimensional) using an AUV. Each time the AUV crosses and detects the meandering front, the vehicle makes a turn at an oblique angle to recross the front, thus zigzagging through the front to map it. The AUV's zigzag tracks alternate in northward and southward sweeps, so as to track the front as it moves over time. From 29 May to 4 June 2013, the Tethys long-range AUV ran the algorithm to autonomously detect and track an upwelling front in Monterey Bay, CA. The AUV repeatedly mapped the frontal zone over an area of about 200 km^2 in more than five days.**

Index Terms—**Autonomous underwater vehicle (AUV), upwelling front, mapping, tracking.**

I. Introduction

Coastal upwelling is a wind-driven ocean process that brings cooler, saltier, and usually nutrient-rich deep water upward, replacing warmer, fresher, and nutrient-depleted surface water. The nutrients carried up by upwelling have significant impact on primary production and fisheries. When a northwesterly wind persists in spring and summer along the California coastline, intense upwelling takes place at Point Año Nuevo (to the northwest of Monterey Bay, CA), and the upwelling filaments spread southward to the mouth of the bay. The upwelling process breaks down stratification and makes water properties more homogeneous over depth. In northern Monterey Bay, however, the water column typically remains stratified because the region is sheltered from upwelling-inducing wind by the Santa Cruz mountains, and sheltered from the upwelling filaments by the coastal recess. Hence an "upwelling shadow" forms in the northern bay. The boundary between the upwelling water and the stratified water is called the "upwelling front". Upwelling fronts support enriched phytoplankton and zooplankton populations [1], [2], thus having great influences on ocean ecosystems. Detection and tracking of an upwelling front is important for investigating the formation and evolution of the upwelling process, and enables targeted sampling of the different water types across the front.

All authors are with the Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039. Email of the corresponding author Yanwu Zhang: yzhang@mbari.org

In our prior work, we developed a method of using an autonomous underwater vehicle (AUV) to autonomously identify an upwelling front, map the vertical structure across the front, and track the front's movement [3], [4]. In upwelling water, the vertical temperature difference between shallow and deep depths is small due to the upwelling process; but in stratified water, the vertical temperature difference is large (warm at surface and cold at depth). Figure 1 illustrates the distinct vertical temperature structures in stratified and upwelling water columns, as well as in the narrow front between them. To characterize the difference between these temperature structures, and to differentiate between upwelling and stratified water columns, we set up a key classification metric — the vertical temperature difference between shallow and deep depths [5]. Based on this, we subsequently developed an improved metric — the vertical temperature homogeneity index, defined as follows [4]:

$$\Delta Temp_{vert} = \frac{1}{N}\Sigma_{i=1}^{N}|Temp_{depth\_i} - \frac{1}{N}\Sigma_{i=1}^{N}Temp_{depth\_i}| \quad (1)$$

where i is the depth index, and N is the total number of depths included for calculating $\Delta Temp_{vert}$. $Temp_{depth\_i}$ is the temperature at the ith depth. $\frac{1}{N}\Sigma_{i=1}^{N}Temp_{depth\_i}$ is the average temperature of those depths. $|Temp_{depth\_i} - \frac{1}{N}\Sigma_{i=1}^{N}Temp_{depth\_i}|$ measures the difference (absolute value) between the temperature at each individual depth and the depth-averaged temperature. The average difference $\Delta Temp_{vert}$ (averaged over all participating depths) is a measure of the vertical homogeneity of temperature in the water column. $\Delta Temp_{vert}$ is significantly smaller in upwelling water than in stratified water.

Suppose an AUV flies from stratified water to upwelling water on a sawtooth (i.e., yo-yo) trajectory (in the vertical dimension). Figure 2 illustrates the algorithm for the AUV to determine that it has departed from the stratified water column and entered the upwelling water column. On each yo-yo profile (descent or ascent), the AUV records temperature at the participating depths to calculate $\Delta Temp_{vert}$. When $\Delta Temp_{vert}$ falls below a threshold $thresh_{\Delta Temp}$ for a number of consecutive yo-yo profiles, the AUV determines that it has entered the upwelling water column. Conversely, suppose

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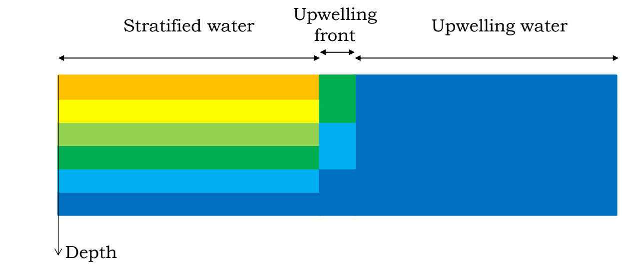

Fig. 1. Illustration of different vertical temperature structures in stratified and upwelling water columns, and in the narrow front between them. Temperature from high to low is represented by color ranging from orange to blue (i.e., the temperature decreases with depth).

an AUV flies from upwelling water to stratified water on a yo-yo trajectory. When $\Delta Temp_{vert}$ rises above $thresh_{\Delta Temp}$ for a number of consecutive yo-yo profiles, the AUV determines that it has entered the stratified water column. To avoid false detection due to measurement noise or existence of isolated water patches, the algorithm only sets the detection flag when $\Delta Temp_{vert}$ meets the threshold for a number of consecutive yo-yo profiles.

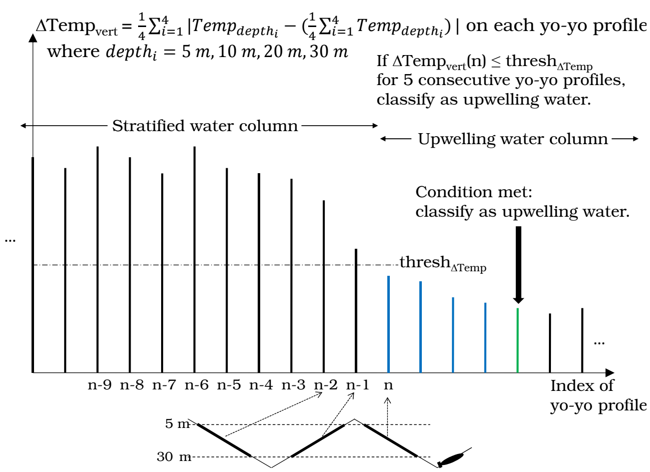

Fig. 2. Illustration of the algorithm for an AUV to determine that it has departed from a stratified water column and entered an upwelling water column.

In our one-dimensional front tracking algorithm, on each east-west AUV transect, the vehicle detects the front, continues flight for some distance (to sufficiently cover the frontal zone), and then reverses course. The AUV repeats this behavior to effectively track the front on a fixed latitude. In multiple experiments in Monterey Bay in 2011 and 2012, MBARI's Tethys AUV and Dorado AUV ran this algorithm to track upwelling fronts [3], [6] and acquire targeted water samples across the front [4], [5]. To obtain a complete spatial depiction of an meandering upwelling front, we need to extend the AUV tracking method from one-dimensional (on a fixed latitude) to two-dimensional (on both latitude and longitude).

II. Two-Dimensional Front Tracking Algorithm

Building upon our previous work, we have developed a method for mapping and tracking an upwelling front on both latitudinal and longitudinal dimensions (i.e., two-dimensional) using an AUV. A key change is that the AUV makes turns at an oblique angle (rather than reversing course) after detecting the front. This way, the vehicle zigzags through the front to map it. The AUV's zigzag tracks alternate in northward and southward sweeps, so as to track the front as it moves over time. The following steps describe the new algorithm, which is illustrated in Figure 3.

- The AUV starts the mission, say, from stratified water (where $\Delta Temp_{vert}$ is high), flying westward towards upwelling water (where $\Delta Temp_{vert}$ is low), on a yo-yo trajectory (in the vertical dimension). When $\Delta Temp_{vert}$ falls below $thresh_{\Delta Temp}$ for a number of consecutive yo-yo profiles, the AUV determines that it has passed the front and entered the upwelling water column.
- The AUV continues flight in the upwelling water for some distance to sufficiently cover the frontal zone, and then turns 135° to fly back to the stratified water.
- On the way back to the stratified water, when $\Delta Temp_{vert}$ rises above $thresh_{\Delta Temp}$ for a number of consecutive yo-yo profiles, the AUV determines that it has passed the front and entered the stratified water column.
- The AUV continues flight in the stratified water for some distance, and then turns $-135°$ to fly back to the upwelling water.
- The AUV repeats the above cycle, thus zigzagging through the front.
- The AUV's zigzag track is confined to a pre-set "operational zone" (based on bathymetry and logistical considerations). On each single leg of the zigzag track, if the AUV reaches the western or eastern bound without detecting the front, the vehicle will turn at the bound and begin the next zigzag leg. On a northward-sweeping zigzag, when the AUV reaches the northern bound, the vehicle turns around to start a southward-sweeping zigzag. Conversely, on a southward-sweeping zigzag, when the AUV reaches the southern bound, the vehicle turns around to start a northward-sweeping zigzag. The entire mission terminates once the prescribed mission duration has elapsed.
- As the front moves over time (due to variations of wind and ocean circulation), the AUV tracks it in two dimensions, thus producing a complete depiction of the dynamic front.

III. Field Performance

The Tethys long-range AUV [7], shown in Figure 4, is 2.3 m long and 0.3 m (i.e., 12 inches) in diameter at the midsection. The propeller-driven vehicle can run effectively from 0.5 m/s to 1 m/s. Propulsion power consumption is minimized through a careful design of a low-drag body and a high-efficiency

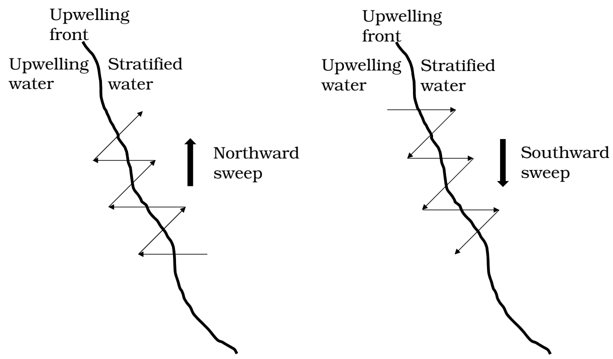

Fig. 3. Illustration of the AUV's two-dimensional front tracking algorithm. The AUV's zigzag tracks alternate in northward and southward sweeps between a northern bound and a southern bound.

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) of Model NavQuest 600 Micro.

The Tethys AUV navigates underwater by DVL-aided dead reckoning. The DVL measures the vehicle's velocity relative to the ocean bottom when it is within range. This velocity vector is rotated into the Earth reference frame using heading and attitude measurements, and then integrated in time to estimate the AUV's position. The vehicle periodically ascends to the surface for a global positioning system (GPS) fix to correct the AUV's underwater navigation errors [8].

Fig. 4. 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.

In late May 2013, due to a persistent northwesterly wind along the California coastline, intense upwelling developed at the Point Año Nuevo upwelling center (to the northwest of Monterey Bay) and the upwelling filaments spread southward to the mouth of the bay. An upwelling front formed in the bay, between the filaments of upwelling water on the west side and the stratified water on the east side (in the upwelling shadow).

The Tethys AUV ran the presented algorithm to autonomously detect and track the upwelling front from May 29 to June 4, as shown in Figure 5. Color on the AUV's track denotes the value of the vertical temperature homogeneity index $\Delta Temp_{vert}$ which is small in the upwelling water column (on the west side) and large in the stratified water column (on the east side).

The bounds of the AUV's "operational zone" are marked by the dashed lines in Figure 5. The northern and southern bounds were set to 36.88°N and 36.7°N, respectively. The eastern bound was the contour of 5 km offshore distance. The western bound was a line extending south-southwest at heading 150° from the northwestern corner [36.88°N 122.3°W]. The orientation of the western bound was set based on the typical spreading direction of the upwelling filaments originating from the Point Año Nuevo upwelling center.

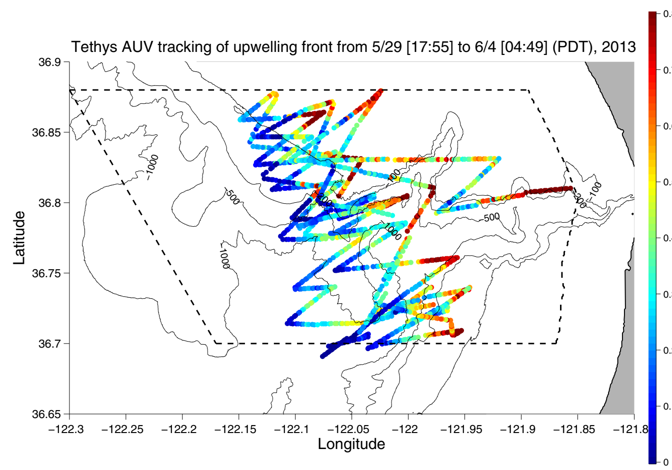

Fig. 5. From 29 May to 4 June 2013, the Tethys AUV autonomously detected and tracked the upwelling front in Monterey Bay. Color on the AUV's track denotes the value of $\Delta Temp_{vert}$ (small in the upwelling water column and large in the stratified water column). The bounds of the AUV's "operational zone" are marked by the dashed lines.

On May 29, the Tethys AUV started from stratified water near shore, and flew westward towards the upwelling water column. The AUV flew at a speed of 1 m/s, on a yo-yo trajectory between surface and 50 m depth. Previous temperature measurements in Monterey Bay indicated that vertical temperature difference between 5 m and 30 m depths provided a strong contrast between upwelling and stratified water columns. So the AUV used temperature measurements at 5 m, 10 m, 20 m, and 30 m to calculate $\Delta Temp_{vert}$ (see Equation (1)). For classification of the two types of water columns, we set the threshold $thresh_{\Delta Temp} = 0.3°C$, again based on previous AUV temperature measurements in Monterey Bay.

A close-up side view of one AUV transect from the stratified water (where $\Delta Temp_{vert}$ was large) to the upwelling water (where $\Delta Temp_{vert}$ was small) is shown in Figure 6. When

$\Delta Temp_{vert}$ fell below $thresh_{\Delta Temp} = 0.3°C$ for 5 consecutive yo-yo profiles, the AUV determined that it had passed the front and entered the upwelling water, and accordingly set the front detection flag, as marked by the blue triangle. The delay-corrected front location is marked by the red triangle. The AUV continued flight into the upwelling water for 40 minutes (about 2 km) to sufficiently cover the frontal zone.

The Tethys AUV autonomously tracked the upwelling front for more than five days, without any human intervention on any mission parameter during the mission. The AUV's zigzag tracks completed five "sweeps" between the northern and southern bounds, repeatedly mapping the frontal zone over an area of about 200 km^2. In total, the vehicle transected through the front 48 times, providing a high-resolution and long-duration depiction of the water properties across the front as well as the evolution of the front. The AUV encountered strong southward current during the front tracking mission. The upwelling front migrated westward as the AUV mission proceeded.

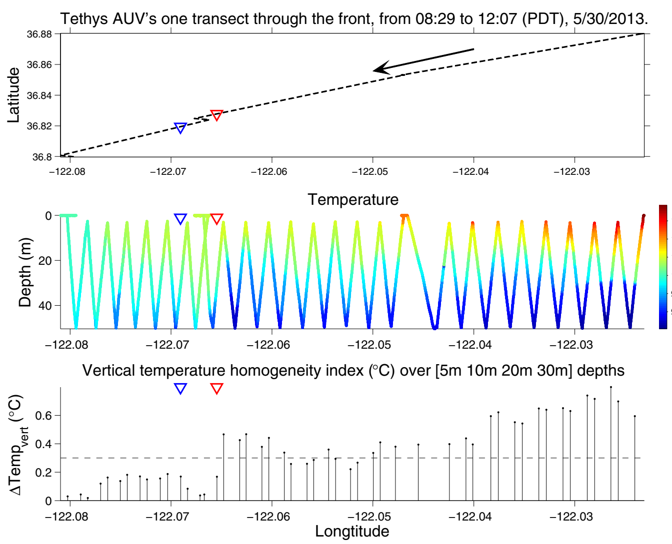

Fig. 6. Upper panel: the horizontal track of one AUV transect from stratified water to upwelling water. Middle panel: AUV-measured temperature between 5 m and 50 m depths. Lower panel: $\Delta Temp_{vert}$ used as the classifier for distinguishing between stratified and upwelling water columns. In each panel, the blue triangle marks the front detection location where the AUV determined that it had passed the front and entered the upwelling water column; the red triangle marks the delay-corrected location of the front. After detecting the front, the AUV continued to fly 40 minutes (about 2 km) into the upwelling water column before making a $-135°$ turn back to the stratified water column.

IV. Conclusion and Future Work

We have developed a method for an AUV to autonomously detect and track an upwelling front on both latitudinal and longitudinal dimensions to produce a complete depiction of the dynamic front. During a five-day mission in May/June 2013, the Tethys long-range AUV ran the algorithm to track an upwelling front in Monterey Bay, on zigzag tracks (in the horizontal dimensions) and yo-yoing between the surface and 50 m depth (in the vertical dimension). The AUV transects provided a high-resolution and long-duration depiction of temperature, salinity, chlorophyll fluorescence, and other water properties across the front, as well as the evolution of the front. We are working on further analyses of the physical and biological properties of the water columns across the front, and also the movement of the front in relation to atmospheric and oceanic conditions.

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