Autonomous Front Tracking by a Wave Glider

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***Abstract*—Coastal upwelling brings cooler, saltier, and nutrient-rich deep water upward to the surface. Upwelling fronts support enriched phytoplankton and zooplankton populations, thus having great influences on ocean ecosystems. We have developed a method to enable a Wave Glider (an autonomous surface vehicle) to autonomously detect and track an upwelling front. Unlike an autonomous underwater vehicle (AUV) which runs on a yo-yo trajectory to measure vertical profiles of water properties, a Wave Glider's measurements are confined to the surface (from the "float") and a fixed depth of only several meters (from the submerged "glider"). However, an upwelling front presents a strong surface signature that a Wave Glider can detect. Because the upwelling process brings up cold water from depth, surface temperature in an upwelling region is considerably lower than that in stratified water. A Wave Glider can detect the upwelling front based on the horizontal gradient of the near-surface temperature. We have tested the algorithm by using previous AUV data (only using near-surface temperature measurements) and Wave Glider data. We plan to run field experiments in the summer of 2016 and report the results in the presentation.**

***Index Terms*—Wave Glider, upwelling front, detection, tracking.**

I. INTRODUCTION

Coastal upwelling is a wind-driven ocean process that brings cooler, saltier, and nutrient-rich deep water upward to the surface. The boundary between the upwelling water and the normally stratified water is called the "upwelling front" [1]. Upwelling fronts support enriched phytoplankton and zooplankton populations [2]–[7], thus having great influences on ocean ecosystems. Traditional ship-based methods for detecting and sampling ocean fronts are often laborious and very difficult, and long-term tracking of such dynamic features is practically impossible.

In our prior work, we developed a method of using an autonomous underwater vehicle (AUV) to autonomously detect and track an upwelling front [8]–[10]. In [10], each time the AUV crosses and detects the front, the vehicle makes a turn at an oblique angle to re-cross the front, thus zigzagging through the front to map the frontal zone. In 2013, the *Tethys* long-range AUV ran the algorithm to map and track an upwelling front in Monterey Bay, CA, over five and one-half days [10].

A Wave Glider is a wave-propelled autonomous surface vehicle [11], as shown in Figure 1. It comprises a surface float and a submerged "glider", connected by a 4-m tether. The vehicle's propulsion is by the conversion of ocean wave energy into forward thrust [11], [12]. The solar panels on the surface float charge the batteries that supply power to the vehicles navigation, control, communications, and payload systems. The vehicle uses a GPS receiver for positioning and a rudder on the submerged glider for steering. Wave Gliders make long-range near-surface oceanographic and atmospheric surveys using a suite of sensors that can be mounted on the float and the submerged glider. Wave Gliders' persistence and cost-effectiveness make them ideal platforms for tracking ocean features with sea-surface expressions. Because the upwelling process brings up cold water from depth to surface, sea-surface temperature in an upwelling region is considerably lower than that in the adjacent stratified water. The upwelling front (i.e., the boundary between the two distinct water columns) is delineated by a strong horizontal gradient of sea-surface temperature. In this paper, we present a method for a Wave Glider to autonomously detect and track an upwelling front based on its surface thermal gradient.

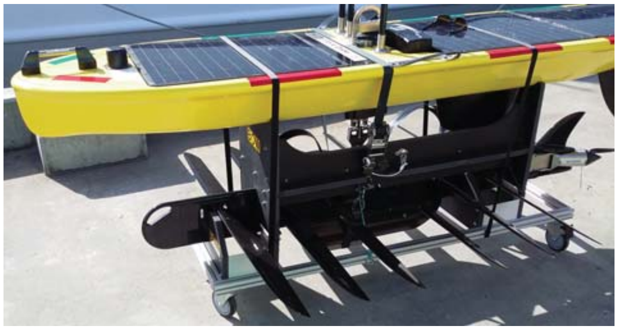

Fig. 1. The *Sparky* Wave Glider operated by the Monterey Bay Aquarium Research Institute (MBARI). Two sets of Sea-Bird GPCTD sensors are mounted on the float and the lower body (4-m depth when submerged)

II. WAVE GLIDER FRONT TRACKING ALGORITHM

Based on our prior work of AUV front tracking, we have developed a method for a Wave Glider to autonomously detect and track an upwelling front. Unlike an AUV which runs on a yo-yo trajectory to measure vertical profiles of water properties, a Wave Glider's measurements are confined to the surface (from the "float") and a fixed depth of only several meters (from the submerged "glider"). Because the upwelling process brings up cold water from depth, surface temperature in an upwelling region is considerably lower than that in stratified water. When a Wave Glider crosses the frontal zone from warm stratified water to cold upwelling water, the near-surface temperature it measures will decrease steeply and persistently; if the Wave Glider crosses the frontal zone in the reverse direction, the near-surface temperature

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will increase steeply. Thus the Wave Glider can detect the upwelling front based on the horizontal gradient of the near-surface temperature: when the gradient is continuously high over some distance, the front is detected.

Gradient calculation is carried out by differentiation which tends to amplify noise. To suppress noise and small-scale variations, the raw temperature is low-pass filtered before calculating the horizontal temperature gradient. The front-tracking algorithm comprises the following steps:

1) The raw temperature measurement is low-pass filtered by a sliding distance window. The distance span of the window is set based on the typical width of an upwelling frontal zone. A Wave Glider's speed is variant depending on the sea state. To guarantee a constant low-pass filtering distance, we use a distance window rather than a time window. In real-time processing, distance is constantly calculated (using GPS latitude and longitude of each temperature data point) to determine how many data points to include in the window. Low-pass filtering using a 1-km sliding window is illustrated in the upper panel of Figure 2. The low-pass filtered temperature $Temp_{LP}$ is shown in the middle panel.

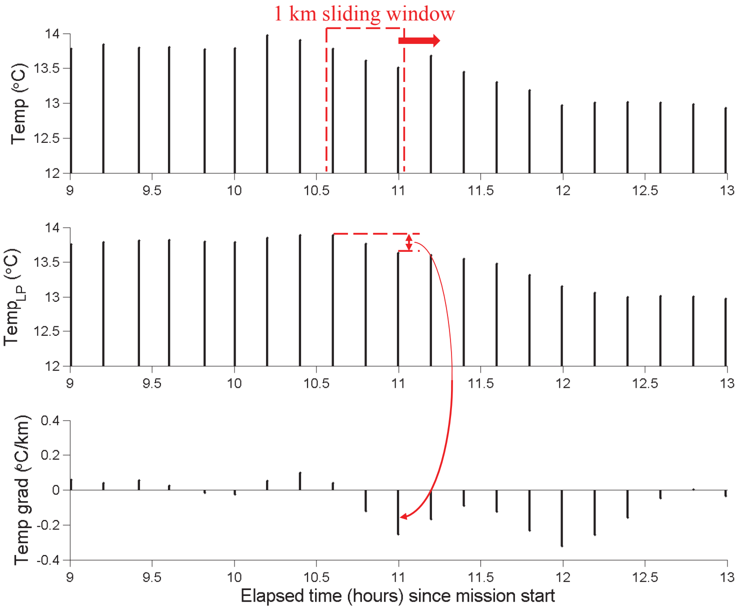

Fig. 2. Temperature low-pass filtering and gradient calculation, using the *Sparky* Wave Glider data from Mission 20160523. The temperature sensor is mounted on the submerged glider at 4-m depth. Upper panel: raw temperature measurement. Middle panel: low-pass filtered temperature using a 1-km sliding window. Lower panel: horizontal temperature gradient.

2) The horizontal gradient is calculated as the difference between the $Temp_{LP}$ values at the two ends of the sliding distance window, as illustrated in the middle and lower panels of Figure 2.
3) Suppose the Wave Glider runs from upwelling water (where temperature is low) to stratified water (where temperature is high), when the horizontal temperature gradient is higher than a preset gradient threshold, a distance accumulator starts to accumulate. If the gradient subsequently falls below the threshold, the accumulator will reset to zero. The gradient threshold is set based on previous AUV front-tracking experimental data (see Section III).
4) When the high-gradient distance accumulator exceeds a distance threshold, the Wave Glider determines that it has passed a consistently high gradient zone, i.e., the front. The following steps for tracking the front are adopted from the AUV front-tracking method [10].
5) The Wave Glider continues the flight in the stratified water for some distance to sufficiently cover the frontal zone, and then turns an oblique angle to go back to the upwelling water, as illustrated in Figure 3. On the way back to the upwelling water, when the absolute value of the horizontal temperature gradient is greater than the gradient threshold, the distance accumulator starts to accumulate (note the gradient is negative). When the high-gradient distance accumulator exceeds the distance threshold, the Wave Glider determines that it has detected the front again. It continues the flight in the upwelling water for some distance, and then turns an oblique angle to go back to the stratified water.
6) The Wave Glider repeats the above cycle, thus zigzagging through the frontal zone. The zigzag tracks alternate in northward and southward sweeps, so as to track the front as it moves over time. The front-tracking mission terminates once the prescribed mission duration has elapsed.

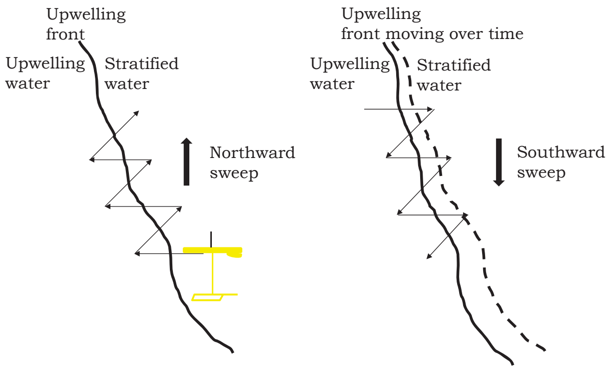

Fig. 3. Illustration of a Wave Glider's front tracking on zigzag tracks.

III. POST-PROCESSING TESTS USING AUV AND WAVE GLIDER DATA

A. Algorithm Parameter Setting Using Previous AUV Front-Detection Mission Data

To appropriately set the low-pass filter window distance and the gradient threshold, we utilize a previous AUV front-detection mission dataset. In a June 2011 experiment in Monterey Bay, the Dorado AUV autonomously detected an upwelling front and triggered water sampling in the front [9]. The AUV's flight was on a yo-yo trajectory in the vertical dimension. We extract the AUV's temperature measurement at 4-m depth to simulate the Wave Glider's measurement.

The width of the front was a few kilometers. Hence we set the low-pass filter window width to 1 km. By setting the gradient threshold to $0.3°C$ and the high-gradient distance threshold to 2 km, the Wave Glider front-detection algorithm detects the front that matches the AUV's front-detection output. The simulation performance on one transect across the front (from stratified water to upwelling water) is shown in Figure 4. The raw temperature (at 4 m depth) is low-pass filtered by a 1 km sliding distance window, which is then used to calculate the horizontal gradient. When the high-gradient distance accumulates above 2 km, front detection is declared. This simulation confirms the feasibility of using a Wave Glider to detect the surface signature of an upwelling front.

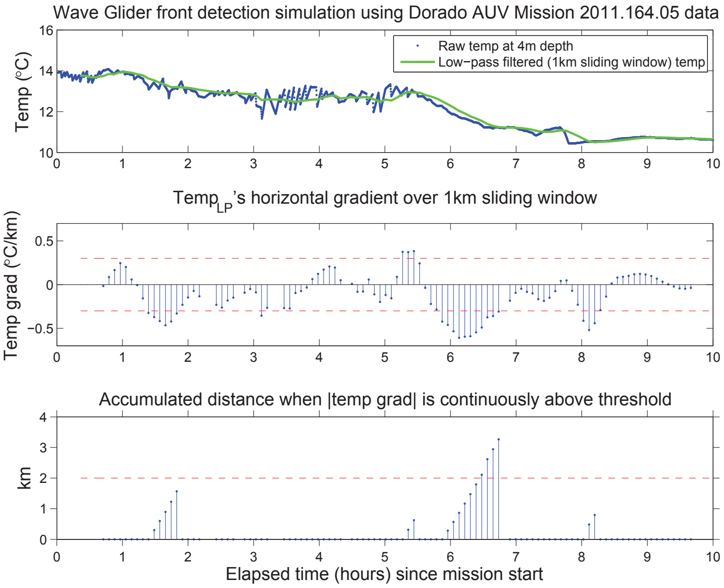

Fig. 4. Simulation of Wave Glider front detection on one transect across the front (from stratified water to upwelling water), using a previous AUV mission dataset. First panel: raw temperature (at 4 m depth) and low-pass filtered temperature (using a 1 km sliding distance window). Second panel: horizontal temperature gradient over 1 km distance. The gradient threshold is set to $0.3°C$. Third panel: accumulated distance when the horizontal temperature gradient is continuously above the gradient threshold. When the accumulated distance exceeds 2 km, front detection is declared.

B. Test Using Wave Glider Data

The MBARI-operated Wave Glider *Sparky* has two sets of Sea-Bird GPCTD sensors mounted on the float and the submerged glider (at 4-m depth). We ran the front-detection algorithm to post-process the 4-m temperature data from one westward transect in Monterey Bay in May 2016. The vehicle speed was about 0.7 m/s. The temperature measurement came in "bursts" at 12-minute intervals. Each burst contained 8 data points at 10-second intervals.

To cut down on unnecessary computations, the algorithm ignores data points too close to each other. For this temperature data stream, it only takes the first data point in each burst and passes it through the low-pass filter. However, the 12-minute interval between bursts appears to be too coarse, because the 1-km window only contains three data points (see Figure 2), rendering the low-pass filtering likely insufficient. The test result is shown in Figure 5. No front was detected. In upcoming field experiments, we will modify the temperature sampling interval settings.

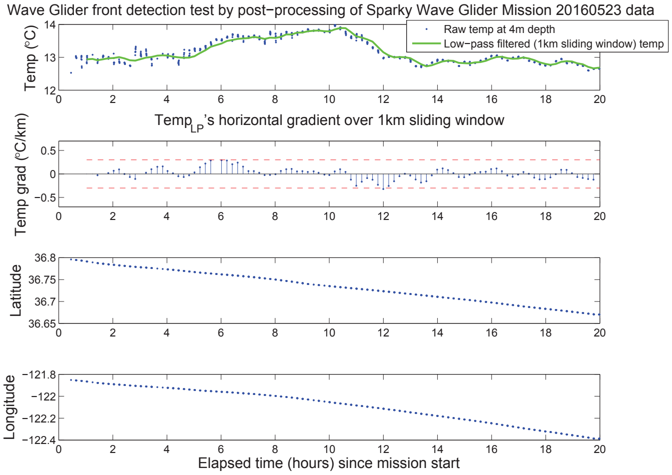

Fig. 5. Post-processing test using the *Sparky* Wave Glider mission data. First panel: raw temperature and 1-km low-pass filtered temperature. Second panel: the horizontal gradient of temperature. Third and Fourth panels: latitude and longitude of the temperature measurements.

IV. NEXT-STEP WORK

We have coded the algorithm in Python which is the Wave Glider's programming language. We are preparing for field tests in Monterey Bay.

ACKNOWLEDGMENT

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