

Autonomous Adaptive Environmental Assessment and Feature Tracking via Autonomous Underwater Vehicles

Stephanie Petillo, Arjuna Balasuriya, and Henrik Schmidt
Laboratory for Autonomous Marine Sensing Systems
Department of Mechanical & Ocean Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
Email: spetillo@mit.edu

Abstract—In the underwater environment, spatiotemporally dynamic environmental conditions pose challenges to the detection and tracking of hydrographic features. A useful tool in combating these challenges is Autonomous Adaptive Environmental Assessment (AAEA) employed on board Autonomous Underwater Vehicles (AUVs). AAEA is a process by which an AUV autonomously assesses the hydrographic environment it is swimming through in real-time, effectively detecting hydrographic features in the area. This feature detection process leads naturally to the subsequent active/adaptive tracking of a selected feature. Due to certain restrictions in operating AUVs this detection-tracking feedback loop setup with AAEA can only rely on having an AUV's self-collected hydrographic data (e.g., temperature, conductivity, and/or pressure readings) available. With a basic quantitative definition of an underwater feature of interest, an algorithm can be developed (with which a data set is evaluated) to detect said feature. One example of feature tracking with AAEA explored in this paper is tracking the marine thermocline. The AAEA process for thermocline tracking is outlined here from quantitatively defining the thermocline region and calculating thermal gradients, all the way through simulation and implementation of the process on AUVs. Adaptation to varying feature properties, scales, and other challenges in bringing the concept of feature tracking with AAEA into implementation in field experiments is addressed, and results from two recent field experiments are presented.

I. INTRODUCTION

Underwater environments are highly dynamic and varied in space and time, posing significant challenges to the detection and tracking of hydrographic features. Often, oceanographers want to collect data for a given feature, and to do so, need to have knowledge of when and where it may occur. However, the data collected may be sparse or fail to capture the feature if it is highly dynamic. This is where Autonomous Underwater Vehicles (AUVs) are becoming more and more valuable. AUVs are frequently used to sample the ocean across a much larger depth range than possible with satellites and much more coverage than instrument casts from a ship, providing four-dimensional coverage in an underwater data set. With the aid of the rapid development of underwater acoustic communications, along with sophisticated AUV instrumentation, autonomy and control software, it is now feasible for an AUV

to autonomously adapt its motions to more intelligently and efficiently sample the environment through which it swims.

Autonomous Adaptive Environmental Assessment (AAEA) is a process by which an AUV autonomously assesses the hydrographic environment it is swimming through in real-time. This assessment is essentially the detection of hydrographic features of interest and leads naturally to the subsequent active/adaptive tracking of a selected feature. The detection-tracking feedback loop setup with AAEA currently aims to use solely an AUV's self-collected hydrographic data (e.g., temperature, conductivity, and/or pressure readings), along with a basic quantitative definition of an underwater feature of interest, to detect and track the feature. Feature tracking must be both autonomous in the sense that the AUV operator is not involved in guiding the vehicle outside of commanding it to "track feature X," and adaptive in the sense that, as a dynamic feature evolves over space and time, the AUV will recognize any changes and alter course accordingly to retain data coverage of the feature.

II. BACKGROUND & IMPORTANCE

Two main fields of research are directly benefited by the implementation of AAEA on AUVs: engineering technology and oceanographic science. Currently, in the field of engineering, many engineers who implement software on and deploy AUVs often do not have the knowledge base of an oceanographer to determine where to fly the AUV to capture a desired hydrographic feature. Alternatively, oceanographers only have an educated guess (often based on models, theory, and past observations) as to where and when a feature is present in the water. The use of AAEA in conjunction with an autonomous control system on board an AUV gives the AUV a method of calculating the boundaries of the feature of interest and using that information to alter its course and more fully capture the feature's properties in its data.

A. Science/Oceanography

At-sea data collection is typically a very expensive and planning-intensive exercise for oceanographers, often limiting

their ship time to a week or so every few years. They must conduct rigorous experiments during these times and hope that their predictions of when and where the features of interest may occur are sufficiently accurate. More accessible data sources frequently used by oceanographers include satellites, ship casts, floating profilers, buoys, and moored arrays. This restricts them to studying mostly what can be observed from these uncontrollable sources. The advantage to AUVs programmed with AAEA for feature tracking is that oceanographers using these vehicles have a higher likelihood of collecting a relevant data set with the information they need for furthering research, making their precious time at sea even more productive.

B. Technology/Engineering

Looking at the ocean from the perspective of an ocean engineer running, designing, or writing software for AUVs, we see limitations that the ocean imposes on our vehicles and operations. We can run the vehicles in a variety of locations and send them on complex missions, yet many of the engineers do not have a solid oceanographic background and do not understand how all of the puzzle pieces of the oceanographic environment interact to create a bigger picture. In this way, many engineers are unable to send their AUVs on missions to sufficiently capture data sets characteristic of many environmental features (e.g., eddies, thermoclines, fronts, etc.).

Combining the knowledge of scientists with the tools of engineers is a significant benefit to the spread of knowledge and technology throughout both fields.

III. AAEA & FEATURE TRACKING: A NOVEL APPROACH

In collecting data with AUVs, we have an AUV moving through the water in space and time and we want to know: where (or when) is feature X? Up until recently, AUVs have not had the ability to react to environmental variations in real-time. Many AUVs are used for environmental monitoring, but the data is not processed on board the vehicle. Most data processing occurs post-mission on powerful, speedy computers in a lab, whereas processing on board AUVs must take a much more conservative, controlled approach. The motivation behind AAEA is to be able send the AUV on a mission to “track feature X”, and the vehicle will make all proceeding decisions. To accomplish this, the AUV must use AAEA to process environmental data (from CTDs, ADCPs, fluorometers, etc.) on board the vehicle. This processing will determine where feature X occurs, allowing the AUV to autonomously react to its surroundings and track the feature.

Due to the restrictions of working with AUVs, which will be mentioned later, we are limited to determining the boundaries of feature X based on just the environmental information the AUV collects and processes on board. This must be done completely autonomously (with no human actively in the loop), allowing the AUV to make decisions of its own based on the environment it is swimming through.

Before the AUV begins AAEA, however, we must determine what feature it is that we want to detect and track, and

TABLE I
FEATURES, THEIR MEASURABLE VARIABLES, AND ASSOCIATED INSTRUMENTATION

Features/Observations	Measurable Variables	Instruments
Thermocline, halocline, pycnocline, sound speed	Temperature, conductivity, pressure	CTD [1]
O_2 concentration	Partial pressure of O_2 in water (via temperature & conductivity)	Dissolved Oxygen sensor [2]
Phytoplankton biomass & chl concentration	Chlorophyll-a fluorescence	Fluorometer [3]
Light attenuation	Photosynthetically Active Radiation (PAR) of 400-700nm wavelength	PAR sensor [4]
Currents	Doppler (frequency) shift of sound waves	ADCP [5]
Fronts	Temperature, conductivity, pressure, Doppler shift	CTD, ADCP

what measurable environmental state variables describe that feature.

A. Oceanographic Features

Almost every feature in the ocean environment is of interest to some scientist somewhere. Just a small subset of these features is given in Table I. Many of these features are delineated by gradients of measurable environmental variables, e.g., temperature gradients define the vertical location of the thermocline.

B. Defining a Feature Based on Data

Before we can detect a feature in the ocean (by running a feature-detecting algorithm on a set of data), we must be able to define the feature. Hence, a robust quantitative definition must be developed for each feature and implemented in the form of an algorithm. This algorithm must also account for the temporal and spatial scales characteristic of an ocean feature, since many of these features are highly dynamic. Determining the physical spatial and temporal boundaries of a feature requires either research into the underlying processes that form the feature (not discussed in this paper), or qualitative observations of the feature in plotted data, along with some general knowledge of the properties of the ocean environment.

C. AAEA Process

Once a feature-detecting algorithm has been created, it must be converted into a piece of code that can interface with the autonomy software of the AUV. This will be addressed briefly in Section IV-C. The AUV will then have the ability to perform AAEA by processing its self-collected data using the algorithm code. This action determines the spatial and/or temporal boundaries of the feature in question.

D. Tracking

Knowing the boundaries of a feature, an interface is made with the on board autonomy control to reposition the AUV. This repositioning, or path adjustment, is used to track a feature, i.e., collect a more complete data set describing the feature. Feature tracking is done by the AUV actively (yet autonomously) keeping itself within or around the feature's physical boundaries.

IV. IMPLEMENTATION ON AUVs

A. Oceanography & Computer Programming

The first step in the implementation of AAFA and feature tracking on AUVs requires the implementing engineer to study oceanography (or at least the feature of interest) thoroughly enough to quantitatively define the feature. Then he/she must employ a knowledge of computer programming in order to implement that definition as an algorithm that will determine (from a data set) the presence and/or location of the feature.

B. Physical Limitations of AUVs

When implementing any autonomy processes, such as AAFA and feature tracking, on board AUVs, it is vital to the success of the mission (and life of the vehicle) to account for the physical limitations of the AUV. A number of these constraints are described below.

- Dive limit
 - All AUVs have a depth rating. These range from about 200m for a coastal AUV to about 2000m for a deep-rated AUV. This ultimately restricts how deep an AUV can dive.
- Surface obstacles
 - AUVs on or just below the surface are not easily visible to surface craft such as ships and boats, making AUVs vulnerable to collisions at shallow depths.
- Daytime operations
 - Since it is both difficult and dangerous to operate AUVs and deployment/retrieval equipment in the dark, we are restricted to operating AUVs during the daylight hours. Also, a typical (actively propelled) AUV only has a battery life of about 5 to 8 hours, which must be charged or replaced overnight.
- Ocean acoustics restrict the AUV to accessing only data collected on board
 - The ocean environment attenuates high-frequency sound waves over a much shorter distance than low-frequency sound waves. This restricts any acoustic communications between the AUV and ship to lower frequencies to increase transmission range at the cost of bandwidth. Thus, only a minimal amount of data may be transmitted to and from the AUVs through the water. Sending higher bandwidths of data a reasonable distance ($O(500m)$) through the water (which is trivial in air with RF or wireless internet connections) requires a significant amount more

power underwater than in air, making it infeasible to power such an acoustic source.

- Memory and processing time
 - Each AUV must store logs of all the missions of a given day (or experiment) on board, consuming a few gigabytes of memory at a time. These small quantities add up over time, so to avoid accidentally filling a hard drive it is important not to store more data than necessary for on board computations. This means that we cannot store satellite data or large ocean models on board the vehicle. In addition, since most data processing occurs on board the AUV in near-real time, it is important that no one piece of code, algorithm, or process takes more than fractions of a second at a time.

C. Acoustic Communications & MOOS-IvP Autonomy

Acoustic communications (acomms) are the primary form of communications between the ship and the AUVs. The ship receives status and data updates from the vehicle every couple of minutes through acomms while the vehicle is under water. This allows for near-real time monitoring of the AUV throughout a mission.

The autonomy system used on board the AUVs is the Mission Oriented Operating Suite (MOOS) [6]. MOOS employs a publish-subscribe architecture where Parameter:Value pairs are published to (and read from) the MOOS 'database' by any autonomy process. MOOS-IvP (short for Interval Programming) [6] interfaces with MOOS, acting as a virtual (autonomous) 'backseat-driver' on board the AUV. This backseat-driver paradigm adds behavior optimization to the autonomy system. The design of MOOS-IvP autonomy also allows AUV operators to write plug-and-play code (processes and behaviors), significantly easing implementation.

V. RECENT DEVELOPMENTS: TRACKING THE MARINE THERMOCLINE

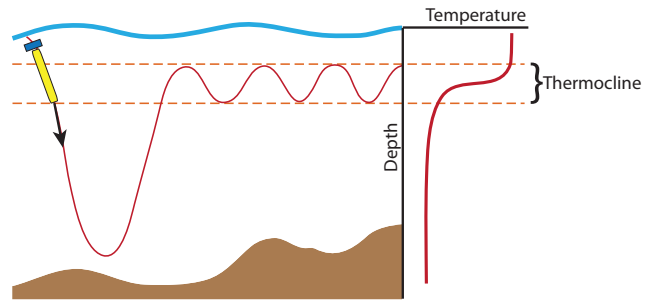


Fig. 1. A conceptual sketch of thermocline tracking using an AUV, which collects and processes all necessary temperature data on board.

The first and most recent developments using AAFA for feature tracking have been applied to autonomously tracking the marine thermocline. The thermocline tracking procedure has been built up from concept (sketched in Figure 1) to

implementation, and finally tested in field experiments. This section will outline this procedure, following the guidelines for AAEA and feature tracking from Section III.

The thermocline was chosen as a simple, well-defined example of an oceanographic feature that is present in most large bodies of water (e.g., large lakes, seas, oceans). Hence, thermocline tracking is used as a proof-of-concept for AAEA and feature tracking. Another reason to begin with thermocline tracking is that most AUVs are equipped with a CT (conductivity-temperature) or CTD (conductivity-temperature-depth) sensor, which collects the temperature (and depth) data necessary to detect the thermocline.

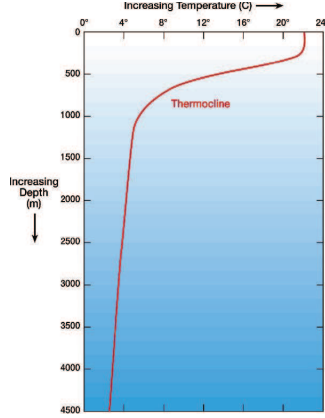


Fig. 2. A typical mid-latitude oceanic Temperature vs. Depth profile. The thermocline region (that of most rapid decrease in temperature over depth) in this profile is apparent between about 300 meters and 1000 meters depth. The strength of this thermal stratification is often highly variable, depending on location and over time. Image courtesy of Windows to the Universe [7].

By definition, the thermocline is “the region in a thermally stratified body of water which separates warmer surface water from cold deep water and in which temperature decreases rapidly with depth” [8]. Such a feature is shown in Figure 2. From this (qualitative) definition, we can quantitatively define the thermocline as the depth range over which the vertical derivative of temperature, $\partial T / \partial z$, exceeds some threshold value, as depicted in Figure 3.

A. Algorithm

Constructing an algorithm from this definition is rather straightforward. We will assume an ideal temperature profile similar to that in Figure 2 as an approximation to a profile obtained from CTD data (Figure 3). Let us define variables T for temperature in $^{\circ}\text{C}$, z for depth in meters (positive up from the free surface), and H for water depth in meters.

- 1) Calculate the slope of the temperature curve at each point in depth, z' .

$$\left. \frac{\partial T}{\partial z} \right|_{z'}$$

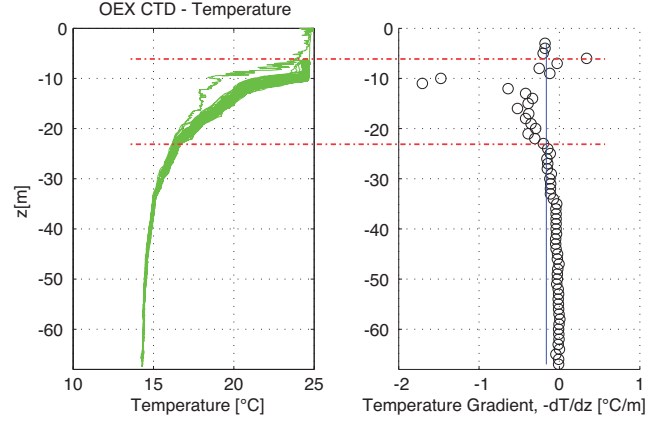


Fig. 3. Temperature data through the water column (left) collected during GLINT '09 by the CTD aboard the NURC OEX AUV. On-board data processing was done to calculate the average temperature gradients at 1-meter depth levels (circles, right) and through the entire water column (solid vertical line, right). The dashed lines indicate the upper and lower bounds of the detected thermocline region, calculated by *pEnvtGrad* (described in Section V-B).

- 2) Average the vertical derivatives over the span of the water column. This yields the threshold value.

$$\left(\frac{\partial T}{\partial z} \right)_{tot_avg} = \frac{1}{H} \int_{z'=0}^{-H} \left. \frac{\partial T}{\partial z} \right|_{z'} dz'$$

- 3) Determine the upper and lower depth limits of the thermocline region.

$$\text{If : } \left| \left. \frac{\partial T}{\partial z} \right|_{z'} \right| \geq \left| \left(\frac{\partial T}{\partial z} \right)_{tot_avg} \right|$$

Then : z' within thermocline ($z_{in_thermocline}$)

$upper_thermocline_depth \equiv -\max(z_{in_thermocline})$

$lower_thermocline_depth \equiv -\min(z_{in_thermocline})$,

where $depth$ is the distance, positive down, from the free surface.

An analogous determination can be done for the region of maximum sound speed variation over depth, which we will call the ‘acousticline’, or the halocline or pycnocline.

B. Algorithm Implementation: pEnvtGrad

The algorithm described above is implemented on the AUV as a piece of code called *pEnvtGrad*, which stands for ‘process: Environmental Gradient.’ This code calculates the vertical temperature and sound speed gradients and quantitatively defines and detects both the thermocline and acousticline. [Note: It is up to the AUV operator to determine which of these features to track. Here we will continue with tracking the thermocline, since sound speed variations are dominated by temperature variations in coastal and surface-ocean waters.] This process then interfaces with the MOOS-IvP autonomy to guide the AUV in a vertical yo-yo pattern (see Figure 1) between

the upper and lower thermocline depth limits, continuously adapting the limits to the variations in thermocline range over space and time. A more detailed description of the steps taken within *pEnvtGrad* are given below.

1) Initial yo-yo:

At the start of the mission the AUV dives from the surface to as deep as is allowable to get as complete a data set as possible over the water column.

2) Create depth “bins”:

The water temperature data is split up into vertical depth levels, or “bins.” This gives us discrete depth levels to work with.

3) Average T in each bin:

The temperature values within each depth bin are averaged to eliminate sub-scale variations in temperature. It is memory-consuming and not useful to determine thermocline bounds on the sub-1-meter scale when the bounds of the thermocline itself are not absolutely defined. A brief scales analysis of depth bin size and thermocline depth range is given in Table II.

4) Vertical derivative, $\Delta T/\Delta z$, over adjacent bins:

The discrete vertical derivative over each pair of adjacent bins is computed.

$$\left. \frac{\partial T}{\partial z} \right|_{z'} \approx \left. \frac{\Delta T}{\Delta z} \right|_{bin_i, bin_i(i+1)} = \frac{T_{i+1} - T_i}{z_{i+1} - z_i}$$

5) Threshold:

Average $\Delta T/\Delta z$ over the sampled water column.

$$\left(\frac{\Delta T}{\Delta z} \right)_{tot_avg} = \frac{1}{n-1} \sum_{i=1}^{n-1} \left. \frac{\Delta T}{\Delta z} \right|_{bin_i, bin_i(i+1)},$$

where n is the total number of depth bins in the water column.

6) Determine the thermocline depth range, $\max|\Delta T/\Delta z|$:

$$\text{If : } \left| \left. \frac{\Delta T}{\Delta z} \right|_{z'} \right| \geq \left| \left(\frac{\Delta T}{\Delta z} \right)_{tot_avg} \right|$$

Then : z' within thermocline ($z_{in_thermocline}$),

where z' is the depth bordering between bin_i and $bin_i(i+1)$. Thus,

$$upper_thermocline_depth \equiv -\max(z_{in_thermocline})$$

$$lower_thermocline_depth \equiv -\min(z_{in_thermocline}).$$

7) Track the thermocline:

Adjust yo-yo depth limits continuously (and autonomously) by keeping a running average of the temperature data collected for each bin. In this way, the thermocline tracking process is adaptive to its dynamic environment.

8) Periodic reset:

After a fixed amount of time, t_R , reset the gradient determination process by ‘forgetting’ all previous data, and start over from the initial yo-yo. Ideally t_R is no

TABLE II
SCALING OF DEPTH BINS WITH WATER DEPTH

	Water Depth	Thermocline Dange	Depth Bin Range
Shallow water/coastal system	O(100m)	O(10m)	$\sim 1m$
Open ocean	O(1000m)	O(100m)	$\sim 10m^a$

^a Here it is natural to scale all values up by one order of magnitude from shallow water to the open ocean, however the open ocean may also have a second, transient near-surface thermocline (O(10m) range) that would require a depth bin range of $\sim 1m$ to adequately capture.

longer than half the length of the characteristic time scale, t_0 , over which there is a significant change in the feature. That is,

$$t_R \leq \frac{t_0}{2}.$$

Essentially, this is a reset at the Nyquist frequency of the feature’s variations. In tracking a coastal thermocline over the course of a day, there may be significant changes in thermocline depth as the surface warms from the sun and begins to mix due to winds in the morning, and then cools again in the evening. In such cases, we may see variations in thermocline depth over the course of a couple hours ($t_R \approx 0.5 - 1hr$), whereas calmer, cloudier days may see variations on the scale of 3-6 hours ($t_R \approx 1.5 - 3hr$) or longer, depending on location and season.

C. Simulation & Testing

The final steps of the implementation process involve simulation and testing of *pEnvtGrad* before an AUV can be deployed on a thermocline tracking mission. Using a MOOS-IvP interface to a dynamic ocean model (stored as a NetCDF file), we can simulate an AUV flying through a dynamic ocean and autonomously tracking the thermocline as if it were actually in the water. The results of this testing are plotted in Figure 4. The MOOS-IvP simulation interface is nearly identical to the runtime interface (used during an actual mission), making the transition from simulation to runtime virtually seamless.

VI. FIELD EXPERIMENTS

With the implementation and testing complete, we are ready to conduct field experiments to track the thermocline (or acousticline). Here it is useful to first become familiar with the ‘topside’ setup used by MIT on board the ship to deploy and monitor the AUVs underwater.

A. MIT Topside Setup

On board a research vessel, the lab is set up with laptops from which we command the AUVs. The ship has a GPS link for positioning, which is decoded on the topside laptop, allowing us to see where the ship is relative to the AUV. The AUV itself has acoms with the ship (and topside computer) via ship- and AUV-mounted acoustic modems, so we can send status messages, commands, and minimal amounts of

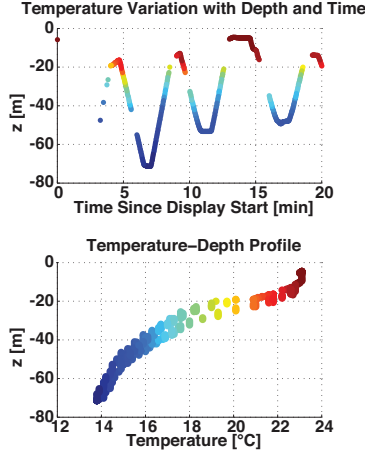


Fig. 4. These plotted mission data are from a simulation run using *pEnvtGrad* to track the surface thermocline in the Middle Atlantic Bight region. This region was modeled by the MIT MSEAS group [9] in early 2008 from data collected in that region during the Shallow Water '06 experiment in late August, 2006 [10]. These plots show (top) the AUV depth over time and (bottom) the temperature-depth profile. Coloring corresponds to the temperature indicated by the bottom plot. In the upper plot, the initial (deep) yo-yo is seen, followed by a few shallow yo-yos between the depths of 12 and 52m, indicative of tracking the thermocline when compared to the thermocline depth range of the lower plot (about 10-50m).



Fig. 5. The Google Earth interface for Ocean Vehicles (GEOV) [11] real-time topside situation display in Google Earth [12] showing two AUVs swimming in sync (trailed by purple and green lines) past an acoustic communications buoy (yellow circle) and a field of objects on the sea floor (pink arrows).

data between the two platforms. The command and control station setup on the topside computer includes *iCommander* (a command line GUI that functions as a rapidly reconfigurable mission commander) that allows us to command the AUV to, e.g., track the thermocline for 1km heading 45°, and it will deploy itself on that mission. The topside situation display includes a display of the incoming CTD data in near-real time (similar to that shown in Figure 4), as well as the Google Earth interface for Ocean Vehicles (GEOV) [11]. GEOV, as shown in Figure 5, is a very useful real-time display of the positions of the research vessel, AUV(s), and their recent paths, in Google Earth [12]. It is an integral piece in the planning and

monitoring of AUV missions.

B. GLINT '09

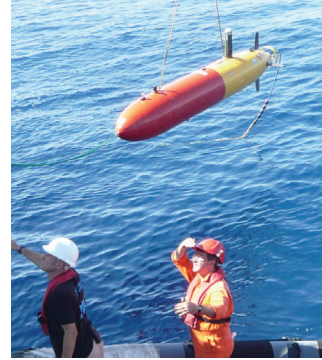


Fig. 6. The NURC OEX AUV used during GLINT '09. This AUV communicates with the ship via acomms (underwater). It also carries a GPS for positioning.

The GLINT '09 experiment took place in the Tyrrhenian Sea near Porto Santo Stefano, Italy. Adaptive feature tracking missions were run 13-14 July, 2009, with the coordinated efforts of MIT and the NATO Undersea Research Centre (NURC, based in La Spezia, Italy). The NURC OEX AUV (shown in Figure 6) running the MOOS-IvP autonomy system was deployed from the R/V Alliance for adaptive feature tracking missions.

During this cruise, *pEnvtGrad* underwent development, testing, and simulation before its first sea trial. The mission during these days was to track the acousticline. The AUV was deployed into a north-south racetrack pattern of 1km x 200m and performed an adaptive-depth yo-yo pattern based on the acousticline depth determined by *pEnvtGrad*.

C. GLINT '09 Results

Figure 7 shows the actual depth of the OEX AUV over the course of approximately 2 hours. The initial yo-yo is visible as the deep dive from 7 to 70m and back, and then the OEX began tracking the acousticline between 9 and 28m depth (smaller amplitude undulations). The depth bins were chosen to be 1m deep (due to a water depth of about 105m) and the periodic reset was set to 30 minutes.

Post-processing of the sound speed and temperature data from the entire 2+ hour mission (see Figure 8) shows the similarities in the shape of the sound speed and temperature profiles in this region. This is due to the fact that sounds speed is dominated by temperature in shallow waters such as these and in the upper layer of the ocean, and by pressure deep in the ocean. The formula used here to calculate sound speed is the MacKenzie Sound Speed Equation (1981) [13]. The calculated average acousticline depth range was 3-28m with a threshold total average gradient ($(\Delta c / \Delta z)_{tot_avg}$, where c is the sound speed through the water in m/s) of 0.427(m/s)/m,

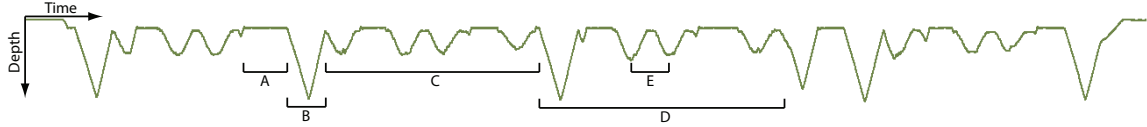


Fig. 7. Depth history of the OEX AUV during an adaptive acousticline tracking mission. (A) is the default shallow turning and transiting depth (7m). (B) is the initial yo-yo (7-70 meters) performed by the AUV to ensure sampling of the entire water column down to the vehicle's maximum dive depth. (C) is the adapted yo-yo tracking the acousticline between 9 and 28 meters depth. (D) is a 30-minute tracking period after which the AUV re-initializes the yo-yo through the full water column to account for acousticline depth variation over space and time. (E) is the 400-meter period (length) of a single yo-yo.

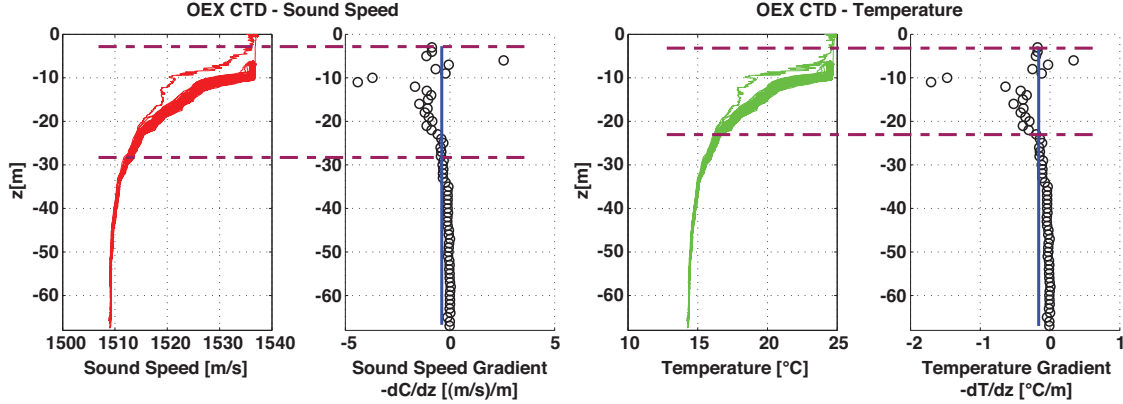


Fig. 8. The leftmost plot of each pair gives the sound speed-depth (left) and temperature-depth (right) profile, respectively, over the entire mission (multiple dives). The rightmost plot of each pair shows the vertical sound speed (left) and temperature (right) gradients averaged over 1-meter depth bins. The solid vertical blue lines (on the gradient plots) represent the threshold values (average gradient over all sampled depths). A gradient greater in magnitude than the threshold magnitude is determined to be within the depth range of the acousticline or thermocline, respectively. The acousticline and thermocline regions are bounded by the dashed lines shown.

while the calculated average thermocline depth range was 3-23m with a threshold total average gradient ($(\Delta T / \Delta z)_{tot_avg}$) of $0.162^\circ\text{C}/\text{m}$.

The primary difference between the 9-28m acousticline range tracked by the AUV and the 3-28m range calculated in post-processing is that the post-processing range also included some near-surface sound speed data collected during deployment and surfacing for getting GPS position locks. On board, the acousticline determination is limited to the data collected within the initial yo-yo range (7-70m in this case), slightly increasing the threshold value and setting a deeper upper acousticline boundary (at 9m) than that calculated in post-processing.

D. Champlain '09

The Champlain '09 experiment took place in Lake Champlain, VT, USA (a freshwater lake). Adaptive feature tracking missions were run 03-05 October, 2009, with the coordinated efforts of MIT and the Naval Undersea Warfare Center (NUWC, based in Newport, RI, USA). The NUWC Iver AUV (shown in Figure 9) running the MOOS-IvP autonomy system was deployed from a small motor boat for adaptive feature tracking missions.

During this experiment, *pEnvtGrad* underwent further testing and its second sea trial. The mission during these days was to track the thermocline of the lake. The AUV was

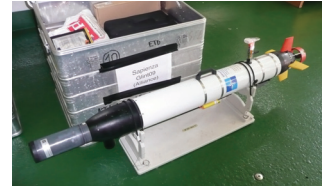


Fig. 9. The NUWC 'Hammerhead' Iver AUV used during Champlain '09. This AUV carries a complete environmental package in its nose and communicates with the ship via RF (on the surface) and acommms (underwater). It also carries a GPS and Doppler Velocity Logger (DVL) for positioning.

deployed into a northwest-southeast straight line pattern 1km long and performed an adaptive-depth yo-yo pattern based on the thermocline depth determined by *pEnvtGrad*.

E. Champlain '09 Results

Figure 10 (left, colored data points) shows the actual depth of the Iver AUV over the course of approximately 2 hours, about 1.5 hours of which it is deployed on the thermocline tracking mission. The initial yo-yo is visible as the first dive from 3 to 30m, and then the Iver begins tracking the thermocline between about 14 and 29m depth (smaller amplitude undulations). The depth bins were chosen to be 1m deep (due to a water depth on the order of 100m) and the periodic reset was set to 30 minutes. This plot also displays the thermocline

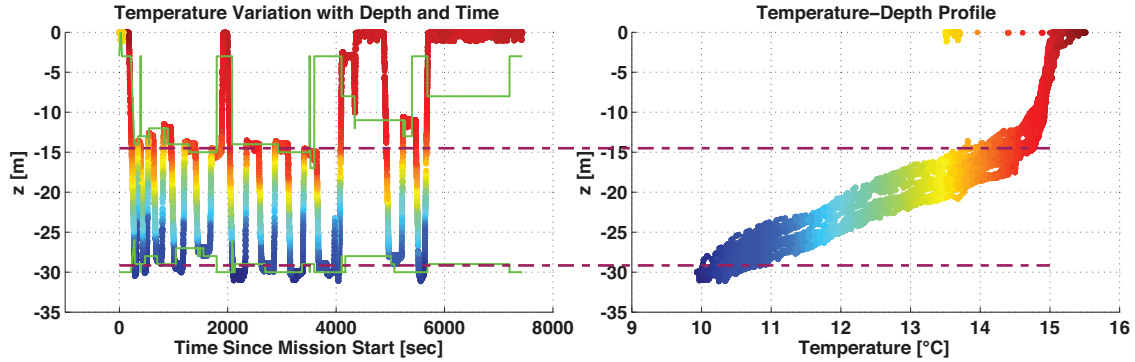


Fig. 10. These data were taken from the real-time topside CTD display showing temperature variations over depth and time. The colors of the data on the left plot correspond to the temperature color coded by the right plot. The squared-off green lines across the plot on the left give the exact values of the thermocline boundaries as determined by *pEnvtGrad* throughout the mission. The dashed red lines approximate (by inspection) the average thermocline bounds as determined by *pEnvtGrad*.

depth bounds (left, green lines) calculated by *pEnvtGrad*, which, when plotted with the data of the AUV's actual depth over time (left, colored data points) shows that the AUV is able to actively and autonomously track the thermocline, adjusting to a change in thermocline depth of even a meter over a couple dives.

Post-processing of the temperature data from the entire mission (see Figure 11) results in an average thermocline depth range of about 16-29m with a threshold total average gradient ($(\Delta T / \Delta z)_{tot_avg}$) of $0.168^{\circ}\text{C}/\text{m}$. This average thermocline range is very close to that determined by inspection of the AUV's actions and calculations in Figure 10 (left).

Relating back to the generally qualitative definition of a thermocline and its algorithm developed earlier in this paper, it is essential to keep in mind that all of the calculated thermocline (and acousticline) bounds are relative to the threshold value, which is relative to the depth of the water column that can be sampled by an AUV. In some cases such as this, the AUV could not risk diving much deeper than 35m (due to a very muddy lake bottom) and only captured part of the thermocline. However, this also shows that *pEnvtGrad* as a thermocline detecting algorithm is robust enough to still detect the majority of the thermocline range even without full water column coverage.

VII. FUTURE OF AAEA & FEATURE TRACKING

Thus far, the AAEA and Feature Tracking process have been implemented on one vehicle at a time, each tracking a thermocline or acousticline feature. The natural continuation of this is to expand this process across multiple AUVs swimming in an area and interacting (via acommms) to paint a clearer picture of the ocean environment on small and large scales. Essentially, this will result in better data coverage over time and space. Tracking more complex oceanographic features over two or more dimensions (rather than just one, i.e., depth), such as eddies, oceanographic fronts, and bathymetry contours, is a useful development that will require multi-AUV data exchange and feature determination techniques to be adapted

to capture the motion of highly dynamic (and larger-scale) features autonomously. Once multiple AUVs identify the bounds of a single feature, the challenge is then to re-deploy each one on a different path such that they will (collectively) track the feature, continuously and autonomously adapting to the feature's motions.

VIII. CONCLUSION

By implementing AAEA on board AUVs with acommms ability and MOOS-IvP autonomy, we have developed a means of autonomously detecting and actively tracking oceanographic features *in situ*, in near-real time, on board an AUV. The thermocline tracking example is a successful proof-of-concept for autonomous detection and tracking of hydrographic gradients using AAEA. This is especially important because most hydrographic features are characterized or delineated by gradients of some environmental variable(s).

In this paper we have described the step-by-step process of developing AAEA and feature tracking from concepts through testing in field experiments. The thermocline and acousticline detection algorithm implemented in the *pEnvtGrad* code was tested successfully in conjunction with MOOS-IvP autonomy on AUVs during the GLINT '09 and Champlain '09 field experiments. This demonstrates that *pEnvtGrad* is robust enough to handle thermocline/acousticline tracking in both freshwater and saline environments and is seamlessly adaptable to use on very different AUVs running the same (MOOS-IvP) autonomy system. At this point, the stage is set to begin development of techniques for tracking more complex features in single- or multiple-AUV missions.

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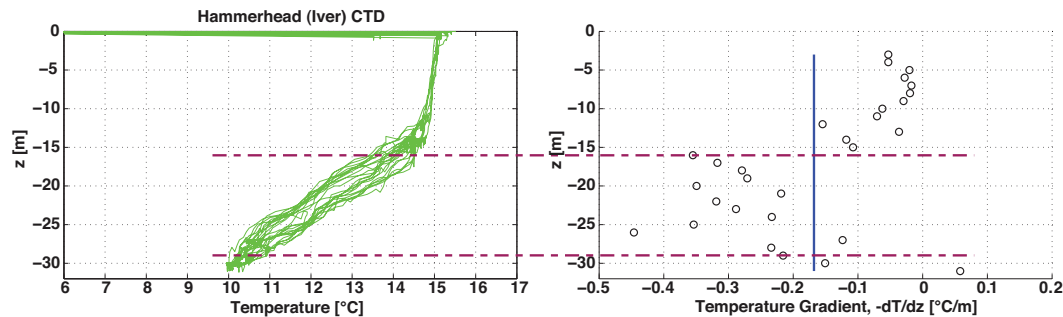


Fig. 11. The plot on the left gives the temperature-depth profile over the entire mission (multiple dives). The plot on the right shows the vertical temperature gradients averaged over 1-meter depth bins. The solid vertical blue line (right) represents the threshold value (average gradient over all sampled depths). A gradient greater in magnitude than this average value's magnitude is determined to be within the depth range of the thermocline, the region bounded by the dashed lines.

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REFERENCES

- [1] "Ocean instruments: Conductivity, Temperature, Depth (CTD) sensors." [Online]. Available: <http://www.whoi.edu/instruments/viewInstrument.do?id=1003>
- [2] "Sensorex: Dissolved oxygen technical education." [Online]. Available: http://www.sensorex.com/support/education/DO_education.html
- [3] "WET Labs: ECO fluorometer." [Online]. Available: <http://www.wetlabs.com/products/eflcombo/fl.htm>
- [4] "Satlantic: PAR sensor series." [Online]. Available: http://www.satlantic.com/Radiometers_PAR_Sensors/Radiometers_PAR_Sensors.asp
- [5] "Ocean instruments: Acoustic Doppler Current Profiler (ADCP)." [Online]. Available: <http://www.whoi.edu/instruments/viewInstrument.do?id=819>
- [6] M. R. Benjamin, J. J. Leonard, H. Schmidt, and P. M. Newman, "An overview of MOOS-IvP and a brief users guide to the IvP Helm autonomy software," MIT, Tech. Rep. MIT-CSAIL-TR-2009-028, 2009. [Online]. Available: <http://hdl.handle.net/1721.1/45569>
- [7] "Windows to the universe." [Online]. Available: http://www.windows.ucar.edu/tour/link=earth/Water/images/temperature_depth_jpg_image.html
- [8] "Merriam-Webster online." [Online]. Available: <http://www.merriam-webster.com/dictionary/thermocline>
- [9] "Multidisciplinary Simulation, Estimation, and Assimilation Systems (MSEAS)." [Online]. Available: <http://mseas.mit.edu/>
- [10] "MSEAS re-analyses for the AWACS-SW06 exercise in the Middle Atlantic Bight region." [Online]. Available: http://mseas.mit.edu/Research/AWACS/Model_Output/
- [11] T. Schneider, "Google Earth interface for Ocean Vehicles (GEOV)." [Online]. Available: <http://aubergine.whoi.edu/geov/index.php>
- [12] "Google Earth." [Online]. Available: <http://earth.google.com/ocean/>
- [13] K. V. MacKenzie, "Nine-term equation for the sound speed in the oceans," *The Journal of the Acoustical Society of America*, vol. 70, no. 3, pp. 807–812, September 1981.