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# Feature based adaptive energy management of sensors on autonomous underwater vehicles

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) are an indispensable tool for studying the world's oceans. They can be equipped with sophisticated sensors and are capable of collecting scientific data under difficult and harsh conditions. Most AUVs rely on batteries to operate, making energy a critical resource. This paper evaluates the benefits of adaptive sampling strategies that allow AUVs to change sensing behaviors by modeling and tracking underwater features. For many AUVs, particularly gliders, these strategies can effectively extend mission duration. Often, necessary or likely preconditions of environmental features can be detected with simple, low energy cost sensors in combination with modeling software. Once precursors have been identified, more sophisticated and energy-hungry sensors can be utilized, collecting scientific data of higher quality. The use of both hardware and software trigger chains can reduce the energy consumption of sensors without sacrificing the collection of relevant data. We used thermocline detection software together with a lower powered sensor to trigger more expensive fluorescence and backscatter sensors on the Slocum Glider. The use of several different thermocline detection algorithms enabled us to compare their precision and power/energy savings. We show energy savings of up to 82% in simulations, and 50% and 63% through two at-sea experiments.


## 1. Introduction

Autonomous Underwater Vehicles (AUVs) are an integral part of studying the world's oceans. Not only can they provide a long term presence in the water, but they also gather orders of magnitude of data for a fraction of the cost of research vessels. AUVs are also able to operate in historically inaccessible or dangerous environments, such as in severe storms or under ice.

Increasingly complex sets of sensor payloads that are integrated into today's AUVs place significant demands on a vehicle's energy resources, which are typically provided by onboard batteries. Effective management of the limited battery energy has become a critical challenge since not all sensors can be active at all times during a mission. As a result, sensors are typically managed manually by remotely switching them on or off, and fixing a data sampling policy *a priori* for each dive segment while the AUV is at the ocean's surface and able to communicate *via* a satellite link with researchers. Once submerged, communication between the AUV and the control center is not possible. The availability of energy-efficient computing platforms with significant computing capabilities enable *in situ* data processing and decision making, allowing sensors to be activated in flight when the likelihood of collecting scientifically relevant data is above particular thresholds.

In many ocean science applications, energy expensive sensors may be triggered based on observed or predicted features in the surrounding environment. Such features may include a particular depth or lighting condition, the presence or the absence of a chemical (*e.g.* oxygen or salinity levels, pollutants, or tracer chemicals), or the presence or the absence of life forms (*e.g.* krill or algae). Onboard computing systems allow an AUV to change its flight pattern and sensor readings depending on such features, making feature based or adaptive ocean sampling a reality (Schofield et al., 2007).

An example of adaptive sampling that has gained recent attention is thermocline tracking (Wang et al., 2009; Woithe and Kremer, 2009; Petillo et al., 2010; Zhang et al., 2012; Cruz and Matos, 2010a). A thermocline is a layer in the water column where temperatures change drastically with depth, separating the warmer mixed layer from the deep water layer. Fig. 1 shows the temperatures of a water column measured using a Sea-Bird Conductivity, Temperature, and Depth (CTD) profiling sensor lowered from a research vessel off the coast of New Jersey. The thermocline becomes apparent by the sudden change in temperature of the water column starting at a depth of 7 m and ending near 20 m.

The study of thermoclines has both military and scientific interests. They can influence the propagation of sound, *i.e.* sonar, which is important in submarine warfare (Haeger, 1995).

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Additionally, phytoplankton, which are responsible for much of the oxygen in the atmosphere and are an important link in the ocean's food chains, can reside near or within a thermocline (Gessner, 1948).

Current thermocline tracking algorithms influence the AUV's vertical flight profile in the water column to remain within the boundaries of the thermocline. This enables larger and more fine-grained spatiotemporal data sets to be collected by the vehicle in the target area. However, this approach may be accompanied by a significant increase in energy consumption, especially for buoyancy driven AUVs such as the Slocum Glider. The features of the Slocum Glider will be discussed in Section 2.2.

*Importance of energy management*: Energy is a crucial resource on a battery-operated AUV. The portion of the energy budget dedicated to vehicle operation versus sensing can be significantly different for AUVs designed for short term missions (hours to a few days) and AUVs designed for a long term, sustained the presence in the ocean (weeks to months). Propeller-driven vehicles are limited to short-term missions because the motors, which consume the most energy, run during the entire mission. In contrast, buoyancy-driven gliders are designed for long term missions, with the buoyancy engine running only for tens of seconds at inflection points, with significant engine idle times between inflection points. The work presented in this paper optimizes the use of sensors and therefore targets AUVs where a significant amount of the energy budget is dedicated to sensor operations rather than vehicle operations. Using a reasoning similar to Amdahl's (1967) law for performance and the fact that our optimizations target the energy consumption of the sensing component, the effectiveness of our approach is limited by the portion of the overall energy budget dedicated to vehicular operation. For example, if 90% of the energy budget is consumed by the motors, even a “perfect” energy optimization of the sensor payload can at best result in 10% overall energy savings. However, if 10% of the overall energy is dedicated to motors, the potential energy savings through effective sensor management may reach 90% of the overall budget.

*Glider deployment*: Gliders often operate in unpredictable environments due to shifting underwater currents and weather conditions. Adverse conditions, resulting in unplanned changes to the vehicle's route, may affect the overall energy consumption of a mission. Getting a glider back home safely, *i.e.* back to shore or to a recovery vessel, is mission critical. Therefore, energy budgets contain mission-specific energy reserves and as a result, only a limited percentage of the overall energy budget is available for the sensor payload. Managing energy is therefore critical for the overall scientific effectiveness of a mission. Fig. 2(a) shows a glider deployment off the coast of New Jersey in 2009. A Slocum Glider was equipped with WET Labs' Environmental Characterization Optics (ECO) puck sensors, the BBFL2S and BB3SLO, which measure fluorescence and backscatter. The glider was tasked to fly to the continental shelf and back to shore. During the deployment, a storm caused the vehicle to drift south while it continued to progress towards the shelf. Eventually, with the glider not making enough progress towards the commanded waypoint, it was retasked to fly back to shore. On the ninth day of the deployment it was determined that the glider's overall battery voltage, shown in Fig. 2(b) and an indicator of an alkaline battery's remaining life, was becoming low considering the length and conditions of the journey home. Thus, non-critical sensors, including the ECO-Pucks, were turned off to conserve energy for the flight (as observed by the increase in voltage in Fig. 2(b)). Potentially significant data collection had to be stopped in order to allow the safe return of the vehicle. In Section 3, we will use this deployment to investigate the benefits of feature based, adaptive sampling for sensor energy savings, and the impact it could have had for the scientific value of the overall mission.

Finally, it is important to appreciate the fact that many types of ocean phenomena are transient and opportunities for observation are limited. In addition, although the cost of deploying a glider is at least an order of magnitude lower than collecting data through surface vessels, it can still be costly, ranging in the thousands to tens of thousands of dollars. These costs cover personnel for mission preparation, flight control, boat rental and crew, equipment insurance, and satellite communications. Maximizing the scientific value of a mission is therefore still a crucial goal and is directly correlated with the effective use of the AUV's energy.

*Summary of contributions*: For many AUVs, particularly buoyancy-driven vehicles, a substantial part of the overall energy budget is dedicated to sensing and data acquisition. Typically, a

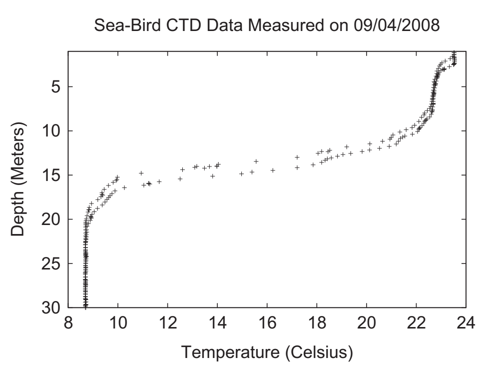


**Fig. 1.** Vertical temperature profile measured by a Sea-Bird Conductivity, Temperature, and Depth (CTD) sensor. The thermocline is present between 7 and 20 m.

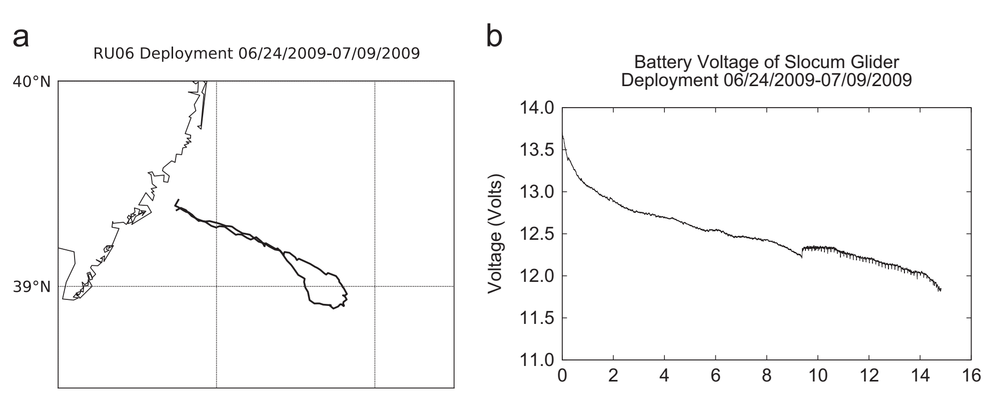


**Fig. 2.** (a) A glider deployment off the coast of New Jersey (June 24 through July 9, 2009) and (b) its measured alkaline battery voltage. The increase in voltage on day nine corresponds to the shutdown of the ECO-Puck sensors.