Compact Ocean Models Enable Onboard AUV Autonomy and Decentralized Adaptive Sampling

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LONG-TERM GOALS

Improve synoptic observations and enhance ocean prediction through development of new capabilities for persistent underwater ocean surveillance.

OBJECTIVES

Multi-platform ocean observing systems are typically centrally controlled from shore, limiting their ability to adapt to new observations which would inform more effective sampling strategies. Our objectives are:

1. Enhance the ability of mobile agents to respond adaptively by providing them with a synoptic realization of the environment in the form of compact models of the observed ocean, similar to [Frolov et al., 2009; van der Merwe et al., 2007a].
2. Develop compact representation of the ocean models that can be economically computed or transmitted onboard an AUV.
3. Develop algorithms for adaptive planning of AUV surveys.
4. Demonstrate use of compact ocean models onboard a long-range AUV during a field deployment.

APPROACH

To enhance the ability of mobile agents to respond to dynamic events in the ocean, we used the following approach:

1. To enhance the on-board decision making capabilities, we developed compact ocean models that can bring synoptic information on-board a mobile platform.
2. To benefit from additional information provided by synoptic models, we developed a combination of path-planning and data assimilation techniques that can be used either on-shore or on-board the vehicle.
3. To test the newly developed technology in practice, we developed a set of use-cases.

WORK COMPLETED

1. Compact models of synoptic circulation:
    a. Developed a statistical model for surface currents in Monterey Bay [Frolov et.al., 2012a].
    b. Studied feasibility of porting HF-Radar prediction capabilities to a new location, off the coast of South Carolina (summer intern, 2012) and off the Basque region in Spain (collaboration with Jeff Paduan at NPS).
    c. Ported model emulator code on-board the long-range AUV.
    d. Automated process to calculate new expansion coefficients and send them to long-range AUVs via Iriduim for use as inputs to the onboard model emulator.
    e. Completed many deployments running the on-board emulator code in the field in the background when long-range AUVs were tasked on other missions. These deployments helped us debug and refine the onboard implementation.
    f. Expanded and refined existing long-range AUV software architecture to better support compact model debugging and development. This specifically includes improved multdimensional array support.
    g. Developed and demonstrated an efficient time-space interpolation technique based on the EOF decomposition, and implemented it in the onboard long-range AUV software for use in the field.
2. Data assimilation system:
    a. Published results on data assimilation system for assimilating bio-optical data into a coupled physical-biogeochemical model of Monterey Bay [Shulman et.al. 2013].
    b. Developed and tested (using twin data) a data assimilation system for on-board assimilation of AUV-measured surface currents into an on-board model of surface currents [Frolov et.al. 2012b].
3. Use cases:
    a. Synoptic sampling of algal blooms off the U.S. West Coast [Frolov et.al. 2012c, Frolov et.al. 2011a].
    b. Tracking of biological processes in Lagrangian Coherent Structures using AUVs [Frolov et. al 2011b].

c. Persistent monitoring of algal blooms using a Wave Glider platform [Frolov et. al 2011c].
d. Implemented a parallel navigation module onboard the long-range AUV to use surface currents from the compact models to aid in dead reckoning while the vehicle performs shallow transits.
e. Implemented path planner using surface currents from onboard compact model to find the fastest path from the vehicle location to its destination, assuming constant speed through water.
f. Designed and demonstrated a new long-range AUV mission in which the vehicle intercepts and then circles a virtual surface drifter that moves freely in the surface currents predicted by the onboard compact model.

RESULTS

Originally, we proposed to develop compact models based on 3D circulation models for Monterey Bay. However, our evaluation of existing circulation models showed that their accuracy and resolution was insufficient for planning of advanced sampling strategies. Instead, we decided to develop compact models based on surface current data available from the HF-radar system in Monterey Bay.

Last year, we conducted two field trials with the onboard emulator running on a Tethys-class long-range AUV and estimating the surface current at the location of the LRAUV. These trials included automating shore-side tools to pull the most recent HF radar observations, project the data into the EOF subspace that the emulator runs in, and send the projected data to the vehicle periodically via Iridium satellite communication. These trials proved useful in testing and debugging the onboard implementation of the compact ocean models code, and provided useful data for the push toward integrating estimated surface currents into the vehicle navigation code.

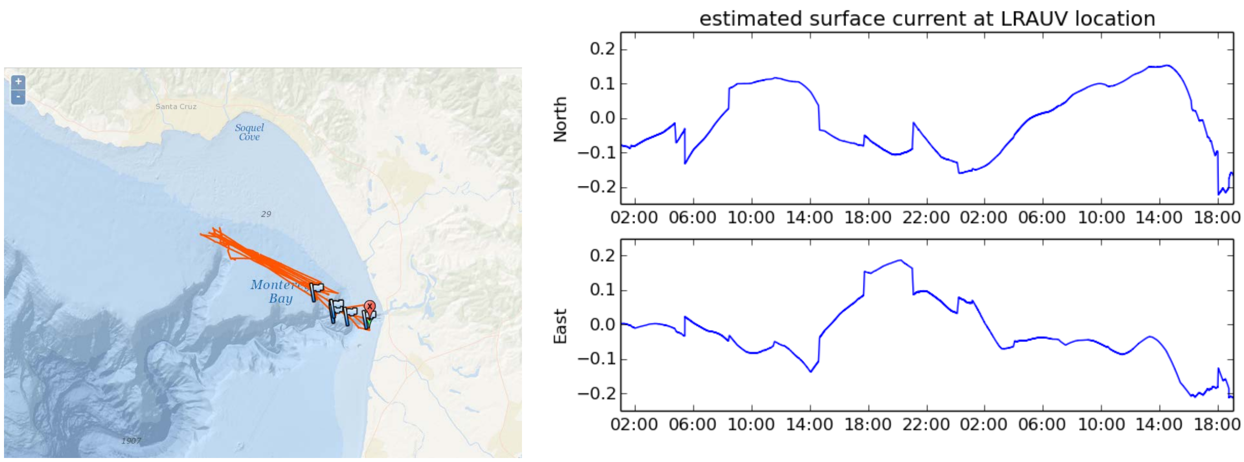

Figure 1: Field trial using onboard emulator to estimate surface current at LRAUV location. Left panel shows vehicle track and right panel shows estimated surface currents over time.

This year, we conducted two more field deployments, testing compact-model aided dead reckoning, a shortest time path planning algorithm, and circling a virtual drifter as it advected through the forecast surface currents (Figure 2). The onboard model code ran well during these deployments, but the HF radar stations on shore covering Monterey Bay often experienced technical problems. This meant that there were large, unknown errors in the expansion coefficients sent as inputs to the onboard model. Effectively, the onboard model was running open-loop for long periods, so its outputs did not reflect reality. It is encouraging that the outputs were still reasonable, and did not put the vehicles at risk at any point. We are looking forward to an opportunity this fall for another field deployment where the long-range AUVs and the shore-based HF radar stations will all be working together at the same time.

Figure 2: Path taken by LRAUV Daphne as she circled a virtual surface drifter in Monterey Bay. The drifter track was calculated from surface currents predicted hourly by the onboard compact model, interpolated in time and space using the method mentioned in work completed point 1.g.

USE CASES: **Compact model aided dead reckoning, path planning, and virtual drifters.**
We implemented onboard code for each of these use cases, and demonstrated the code in two field deployments. Unfortunately, as mentioned previously, we experienced technical problem with the shore-based HF radar stations during both of these deployments. While the onboard code performed well, the lack of sufficient HF radar coverage during the deployments calls into question any comparison between compact model forecast and true ocean conditions. By extension, for these deployments, any vehicle actions taking the forecast into account cannot be expected to reflect true conditions. We are looking forward to an opportunity this fall for another field deployment where the long-range AUVs and the shore-based HF radar stations will all be working together at the same time.

IMPACT/APPLICATIONS

- This project has developed the first implementation of a circulation model that can be run on small AUVs in real time, providing a foundation for model-driven adaptive sampling in situ.
- Developed compact models for prediction of surface currents. These are under consideration to be used operationally as a part of IOOS surface current datasets. A draft implementation was used in the Fall 2013 MBARI CANON field experiment.

- This project inspired the time-space interpolation technique presented in the ASLO Ocean Sciences poster (Stanway 2014), which may prove useful in other applications and could be a fruitful direction for future research.
- Developed data assimilation tools for bio-optical data assimilation that are currently in use by researchers from the U.S. Naval Research Laboratory.
- Analysis of AUV and LCS data forms a foundation for future field programs at MBARI that will focus on better understanding of ecosystem processes in front-like features.
- Published analysis of sampling strategies for algal blooms that are likely to affect future designs for operations and research on harmful algal blooms.

TRANSITIONS

The current prediction code developed in this project has been provided to the Naval Postgraduate School to be used as the basis of a new prediction product for their HF radar facility.

RELATED PROJECTS

MBARI internal project CANON: Field testing of the optimal survey design methods is supported with MBARI internal project CANON. CANON aims at developing new Lagrangian observing systems that can study the dynamics of marine ecosystems by following their evolution in time and space. In recent years, the fall CANON field program has focused on following emergence, growth, and decay of phytoplankton bloom patches in Monterey Bay.

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HONORS/AWARDS/PRIZES

Frolov, et. al. (2013) refereed article in *Harmful Algae* was the second most-downloaded article that was published in 2013.