MAS 01 Trajectory design for Mobile Sensor Platforms based on Ocean Model Predictions

MAS 01.1 People

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MAS 01.2 Overview

Trajectory design for Autonomous Underwater Vehicles (AUVs) is of great importance to the oceanographic research community. Intelligent planning is required to maneuver a vehicle to selected locations to collect data with scientific merit. This planning not only determines how to get from one point to another, but also determines which locations should be visited to best understand the feature(s) under investigation. We consider the use of ocean model predictions to determine the locations to be visited by mobile sensor platforms. The platforms, in turn, provide near-real time, in situ measurements back to the model to increase the skill of future predictions. A simple planning strategy and algorithm have been developed which determine relevant points of interest for a chosen oceanographic feature. This strategy represents a first approach of an end-to-end autonomous prediction and tasking system for aquatic, mobile sensor networks.

MAS 01.3 Approach

The goal of this research is to develop an innovative ocean sampling trajectory planner that utilizes model predictions, mobile sensing platforms and sensor networks together to collect data which can increase model skill and is scientifically relevant to ocean research. The motivation for this study is to track and collect daily information about an ocean process or feature that has a lifespan on the order of a week. The basic idea is to use an ocean model to predict the behavior of an interesting artifact over a small time period, e.g., one day. This prediction is then used as an input to an algorithm that determines a sampling plan for the mobile sensing platforms. The sensors are consequently deployed for the one-day mission. At the end of this mission, the collected data is assimilated into the ocean model and a new prediction is computed for the following day. A new sampling plan is created and the process is repeated until the artifact has disseminated, is out of range or is no longer of interest. An ocean-embedded sensor network is utilized for handling all data transfers between the systems.

The work presented here serves as a proof of concept for the utilization of ocean model forecasts as input to determine the trajectories that define sampling missions for mobile sensor platforms to follow an ocean feature and collect important scientific data.

To implement this research, we have chosen to track a fresh water plume in the ocean. Such an event may occur at a river mouth after a significant rain event. Due to the low salinity and density, this type of feature will propagate through the ocean, mainly driven by the ocean's surface currents. A plume may dissipate rapidly, but can stay cohesive and detectable for up to weeks. Here, we assume the later case. It is of interest to track these plumes to
test for concentrations of certain phytoplankton known to produce toxins harmful to aquatic creatures and humans, for specifics, see Schnetzer et al. (2004) or Anderson (2008). In addition to tracking the plume over the course of its life cycle, it is also important to accurately predict where a plume will go on a daily basis; in the interest of public safety, beach closures may be necessary.

For an ocean model, we use the Regional Ocean Modeling System (ROMS), which is described in the following section. The ROMS prediction capabilities for a plume are good, but the model skill can significantly increase from a continuous data stream of in situ measurements collected from an AUV tracking the feature. Enhancing ROMS skill in the local area will produce more accurate predictions on subsequent model runs.

The chosen mobile sensor platform is the Webb Slocum glider AUV. This is a platform that we currently have access to, and can readily deploy into the field. Since the glider is designed for endurance missions and is very energy efficient, it cannot travel at high velocities, thus, we currently restrict ourselves to consider obtaining samples at (visiting) two locations for each hour of sampling. To this end, we first choose to track the centroid of the plume extent; similar to the ‘eye of the storm.’ Optimally, we would also like to gather a sample on the boundary of the plume. However, the glider may not be able to reach the plume centroid and a point on the boundary in a given hour. We resolve this by choosing a second sampling point as far from the centroid as possible that still allows the vehicle to reach the next computed centroid. We remark here that this algorithm is implemented onto gliders, but there is nothing specific about its design that limits the application exclusively to gliders. We can consider any other mobile sensor platform for trajectory design utilizing this proposed system.

**MAS 01. 4 System(s) Description and/or Experiments**

ROMS is a split-explicit, free-surface, topography-following-coordinate oceanic model that is described in detail in Shchepetkin and McWilliams (2005). The reason for using ROMS is twofold. First, it is an open source ocean model that is widely accepted and supported throughout the oceanographic and modeling communities. Secondly, the model was initially developed to study ocean processes along the western U.S. coast that is our primary area of study.

Research is currently ongoing to update and improve the ROMS model for the southern California bight in an effort to characterize and understand the complex upwelling and current structure that exist and drive our local climate. The Jet Propulsion Laboratory (JPL), California Institute of Technology, in Pasadena, CA, provides nowcasts and hourly forecasts (up to 48 hours) for Monterey Bay, the southern California bight and Prince William Sound. This ROMS model assimilates HF radar surface current measurements, data from moorings monitored by the Monterey Bay Aquatic Research Institute (MBARI), satellite data for sea surface temperature and sea surface height as well as any data available from AUVs that are deployed in the area.

Additionally available from the JPL ROMS is the ability to insert Lagrangian drifters into the model and predict their location over a given time period. Initially, these drifters will be used as the proxy to define a fresh water plume and its movement in simulation. For field experiments, we plan to deploy actual oceanic drifters for model and algorithm comparison and validation, respectively.

As mentioned above, the mobile sensor platform used in this study is a Webb Slocum autonomous underwater glider, as seen in Fig. 1; a detailed description of this type of AUV can be found at Webb Research Corporation (2008).
 Modifications have been performed on our gliders to upgrade the communication capabilities and include the glider as a node in a large-scale sensor network. Details on these modifications can be found in a forthcoming article, Heidarsson et al. (2009).

The Slocum glider is a type of AUV designed for long-term ocean sampling and monitoring. These gliders fly through the water by altering the position of their center of mass and changing their buoyancy by use of battery powered motors and pumps, respectively. Due to this method of locomotion, gliders are not fast moving AUVs, and generally have operational velocities on the same order of magnitude as oceanic currents. The endurance and velocity characteristics of the glider make it an ideal vehicle to track ocean features that have movements that are determined by currents, and that have a residence time on the order of weeks.

The primary communication method for the gliders is the Iridium satellite phone network. While this utility is globally accessible, it is cost prohibitive for glider operations involving multiple gliders and/or multiple communications as are typical with coastal observations. To this end, we have begun equipping pre-existing networked CODAR-sites and other elevated locations with Freewave radio modems. This effort will result in a robust, cost-effective network capable of servicing multiple gliders and multiple communication links. One main advantage is that the Freewave radio network has significantly higher bandwidths as compared to Iridium. This feature allows us to transfer more data from the gliders while spending less time at the surface. This results in a faster and cheaper capability to re-task gliders during extended deployments as well as transfer larger data files. This system additionally includes a complete glider-control system that automatically updates glider-information when the glider surfaces, and allows file uploads/downloads to be handled via the Freewave radio-modem network. The implementation of this system is part of ongoing and future CENS related activities.

**MAS 01. 5 Accomplishments**

A primary accomplishment of this research to date is the successful verification of the technology chain connecting an ocean model prediction, a trajectory design algorithm, mobile sensor platforms and data assimilation back into the model. Much effort has been put into the collaborative effort of closing this large-scale loop while concurrently working on each component separately. Our collaborators at JPL run ROMS and have developed a web portal for the upload of initial conditions to track a plume event and the download of the resultant ocean prediction computed. Currently, the trajectory design algorithm is run off line at USC and waypoints can be uploaded to the glider via Iridium or the Freewave network. The data collected by the glider during a mission is loaded to an ftp site that is periodically checked by ROMS for assimilation into the next prediction.

Additionally, the development of the plume tracking trajectory design algorithm is the other main result of this research. This algorithm is based on following the centroid of a fresh water plume. Either from an expert oceanographer or from remote sensing data, the 2-D plume area on the ocean surface is defined. A set of points, referred to as drifters, is selected which bounds the plume region. These drifter locations are the initial input to ROMS. An hourly prediction of the location of these drifters is output by ROMS for a given duration of time. Each hour, the convex hull of the drifters and its centroid are computed. These centroids are the primary sample locations for the glider to visit. As mentioned before, this is analogous to tracking the eye of the storm. Note that the glider has one hour to traverse from one centroid to the next. The algorithm then considers the distance between two consecutive centroids to determine if the glider can visit an additional point and make the second centroid within one hour. If so, another waypoint is added to the trajectory. This process continues iteratively for the determined time span of the mission. These sampling sites are then exported to a formatted file that is readable by the glider and uploaded to the network for retrieval by the glider upon its next surfacing.

Simulation experiments have been conducted to verify the operation of the technology chain as well as the trajectory design algorithm. The collaborative effort is functioning well, and the trajectories produced by the algorithm are implementable missions for which theoretical predictions matched well with the presented realistic scenario. In particular, Fig. 2 shows a satellite image taken on February 10, 2009 from Oceansat-1 of chlorophyll, with units given in mg/m3. Here, the red area indicates a region of high chlorophyll content that is consistent with a fresh water plume produced by a rain event earlier in the week. This region was depicted by use of 15 points that
were used as the initialization locations for the ROMS prediction. Figure 3 presents the predicted paths of the 15 drifters over a period of 24 hours. From this prediction, we generated a trajectory for the glider to follow the predicted plume location for the 24-hour period. In Fig. 4, we present an overview of the San Pedro Channel and the area of interest for our study. Here, the yellow and red lines depict the 20 m and 30 m isobaths, respectively. The black line represents the initial plume boundary and the dark blue line is the computed plume-tracking trajectory. If we zoom in on the area designated by the initial plume boundary, as seen in Fig. 5, we see the computed trajectory for the first six hours of this period. Here, the yellow pins represent the sampling locations to be visited by the glider. The pin labeled “Start” is the centroid of the initially chosen points defining the plume boundary; this is the starting location for the mission. During the first hour, the glider visits points 1a and 1b, during the second hour it visits points 2a and 2b, etc. We remark here that the ROMS prediction, and thus the designed trajectory moved north and west along the coast while also moving onshore. From remote sensing data, we can confirm that this was also the general path of the detected plume.
From the above simulation, we have provided a proof of concept and are moving forward to implementation in a field experiment. Since rain events are common for the southern California area in late February to early March, we are planning a full-scale plume tracking experiment for this time period. The glider will be operating in the San Pedro shelf area performing a predetermined transect survey. In the event that a fresh water plume develops as a result of a rainfall event, we will employ the aforementioned sequence of events and re-task the glider to follow the plume.

Figure 4: Overview of the San Pedro Channel region of interest. The black line defines the initial plume boundary and the dark blue line is the computed plume-tracking trajectory. Figure created by use of Google Earth.

Figure 5: Magnification of the plume region shown Fig. 4. The black line defines the initial plume boundary, the dark blue line is the computed plume-tracking trajectory and the yellow pins represent sampling locations for the glider. Figure created by use of Google Earth.
**MAS 01. 6 Future Directions**

Designing effective sampling strategies to study ocean phenomena is a challenging task and an area of active research from many different angles. Here, we present a method to exploit multiple facets of technology to achieve the goal of designing a fresh-water plume following trajectory. Utilizing a complex ocean model, AUVs and an embedded sensor network, we were able to construct a technology chain that will design a trajectory for the AUV to effectively follow a plume centroid in the ocean for an extended period of time. From the information presented, it is clear that the algorithm and technology chain give a theoretical prediction that matches well with actual observations from remote sensors. It is now a task to successfully implement and improve upon this proof of concept model. After the successful completion of our field test, one obvious extension is to include multiple mobile sensor platforms. This would allow for different features of the plume to be tracked, i.e., a boundary following trajectory as well as a centroid tracker. We plan to use two gliders to demonstrate this capability, but remark that we are not limited to gliders as the primary sensor platform. At this stage, the trajectory design is computed only in two dimensions; it is an ocean surface problem. One step to expand this research is to extend this into a 3-D trajectory design algorithm. Along with this step comes the incorporation of 3-D ocean currents as well as an accurate model of the glider kinematics and dynamics to effective design an implementable trajectory. With this structure in place, we can then begin to consider optimization within the trajectory design. For example, time minimization trajectories that utilize the predicted ocean currents to reach a chosen sampling location. Finally, it is a long-term goal to implement autonomy to this entire system in particular; the human is only in the control loop as a fail-safe. In this case, we assume that there are mobile sensor platforms in the ocean. An event would be detected via remote sensing or a human trigger. An initialization is determined, a prediction is run and a sampling mission is uploaded to the platforms. As data is collected and assimilated into ROMS, the platforms are able to autonomously adapt and effectively as well as optimally track the ocean feature of interest.

**MAS 01. 7 External Research Partnerships**

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**MAS 01. 8 Literature Cited**


