Harmful Algal Bloom Characterization Via the Telesupervised Adaptive Ocean Sensor Fleet

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***Abstract* – We are developing a Sensor Web-relevant system called the Telesupervised Adaptive Ocean Sensor Fleet that uses a group of National Oceanic and Atmospheric Administration extended-deployment autonomous surface vehicles to enable in-situ study of surface and sub-surface characteristics of Harmful Algal Blooms (HAB). The architecture supports adaptive reconfiguration based on environmental sensor inputs ("smart" sensing), and increases data-gathering effectiveness and science return while reducing demands on scientists for tasking, control, and monitoring. It combines and adapts prior related work done at Carnegie Mellon University, NASA Goddard Space Flight Center, Wallops Flight Facility, Emergent Space Technologies, and the Jet Propulsion Laboratory. Initial multi-vessel HAB characterization tests will be performed during summer 2007 with rhodamine dye as a HAB simulant and an airborne sensor validation system. The described architecture is broadly applicable to ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration.**

***Index Terms* — harmful algal blooms, sensor web, ocean sensing, adaptive sampling, telesupervision, multirobot systems.**

I. Introduction

Earth science research must bridge the gap between the atmosphere and the ocean to foster understanding of Earth's climate and ecology. Ocean sensing is typically done with satellites, buoys, and research ships. These sensors are limited in that satellites are often blocked by cloud cover, and buoys and ships have spatial limitations.

The Telesupervised Adaptive Ocean Sensor Fleet (TAOSF) system allows the autonomous repositioning of smart sensors for study of surface and sub-surface characteristics of such ocean phenomena as harmful algal blooms (HAB), coastal pollutants, oil spills, and hurricanes by networking a fleet of autonomous surface vehicles. Telesupervised surface autonomous vehicles are crucial to the sensor web for Earth science.

TAOSF uses Ocean-Atmosphere Sensor Integration System (OASIS) vehicles developed for the National Oceanic and Atmospheric Administration (NOAA) for weather-related ocean monitoring. To enhance the value of these assets, we are developing a telesupervision architecture that supports the following features:

- Adaptive reconfiguration based on environmental sensor inputs ("smart" sensing), which increases data-gathering effectiveness while reducing the effort required for tasking, control, and monitoring of the vehicles;

- Science analysis of the acquired data in order to characterize the extent and nature of Harmful Algal Blooms and other oceanographic features;

- Web-based communications permitting control over long distances and the sharing of data with remote experts;

- Sliding autonomy, allowing an operator to control the vehicles by setting high-level goals, such as specifying an area to monitor, or by taking direct control of the vehicles via teleoperation, or at other levels between these two extremes;

- Hazard and Assistance Detection, permitting identification of events requiring human intervention and scheduling of the human attention resource.

Interest in HAB detection has grown in recent years. The Woods Hole Oceanographic Institution has mapped the distribution of *Alexandrium fundyense* cysts in the sea floor of the Gulf of Maine for both 2005 and 2006 [1]. The Florida Fish and Wildlife Research Institute has recently commissioned statisticians to analyze a historical database of concentrations of the HAB dinoflagellate *Karenia Brevis* in Florida waters [2]. There is also an ongoing effort by the Northwest Fisheries Science Center and collaborators to develop probes for detecting toxins produced by each species of *Pseudo-nitzschia* [3].

There has also been interest in identifying environmental factors that contribute to the occurrence of HABs to incorporate in bloom prediction algorithms. A regional study on the dinoflagellate Karlodinium veneficum has been generating near real-time maps of the HAB in the Chesapeake Bay using a hydrodynamic model and satellite data [4]. The algorithm uses month, salinity, and sea-surface temperature to predict the abundance (low, medium, or high) of the dinoflagellate. The accuracy of these predictions is currently under evaluation.

Cai et al. have developed a system of tracking and predicting the spatiotemporal dynamics of the HAB species *Karenia Brevis* in the Gulf of Mexico area [5]. Cai uses the similarity of target objects in consecutive images to track the target over time. Cai's system predicts the spatiotemporal dynamics with a simulation model based on the growth, shrinkage, and collisions of cellular automata under specific wind conditions. In situations where the similarity between consecutive images falls beneath a particular threshold, Cai's system prompts a human expert to reinitiate the tracking by selecting the object in the current image. This interactive system has been shown to give a 30x speedup over the manual analysis of the image data.

TAOSF will provide the following advantages over existing systems for observing and analyzing HAB:

- Dynamic tasking and adaptation
- Higher resolution and greater insensitivity to cloud-cover in comparison with current satellite systems
- Greater agility in and access to coastal waters than buoys
- Real-time multipoint observation by remote oceanographers.

The TAOSF project is a collaboration among Carnegie Mellon University (CMU), NASA Goddard Space Flight Center (GSFC), NASA Goddard's Wallops Flight Facility (WFF), Emergent Space Technologies, Inc. (EST), and the Jet Propulsion Laboratory (JPL). Each organization has contributed a component technology, and the first eight months of the project have focused on adapting and merging these technologies in preparation for a first-year demonstration of multiple OASIS platforms receiving and executing area coverage commands from human users and detecting the presence of an expanse of rhodamine dye acting as a HAB surrogate. The resultant engineering and science telemetry data are relayed back to the users for display and analysis.

The remainder of this paper describes the following TAOSF system components: software architecture (section II), OASIS platforms and infrastructure (section III), and HAB sensing and characterization (section IV). The final section summarizes results to date and outlines future work.

II. Software Architecture

The TAOSF software architecture (Figure 1) consists of five subsystems provided by the various partners. Development work to date has concentrated on the integration of these existing software systems. We have demonstrated end-to-end integration of SSA, ASF and OASIS in a dry-boat test in May, 2007 and we expect to perform the first in-water test of the integrated system in June, 2007.

The five TAOSF subsystems are:

A. The OASIS Autonomous Surface Vehicle (ASV) System includes the vehicles themselves as well as the land-based control and communications infrastructure which has been developed for them. The OASIS platform software directly controls the hardware of each platform (motors, sensors, etc.) and executes waypoint navigation. This system has been developed by EST working with the team members at WFF, where the platforms are physically built and maintained.

B. The Multi-Platform Simulation Environment has been developed by GSFC as a stand-in for the OASIS ASV system for development and testing of the higher-level software components.

C. The Platform Communicator handles acts as a proxy

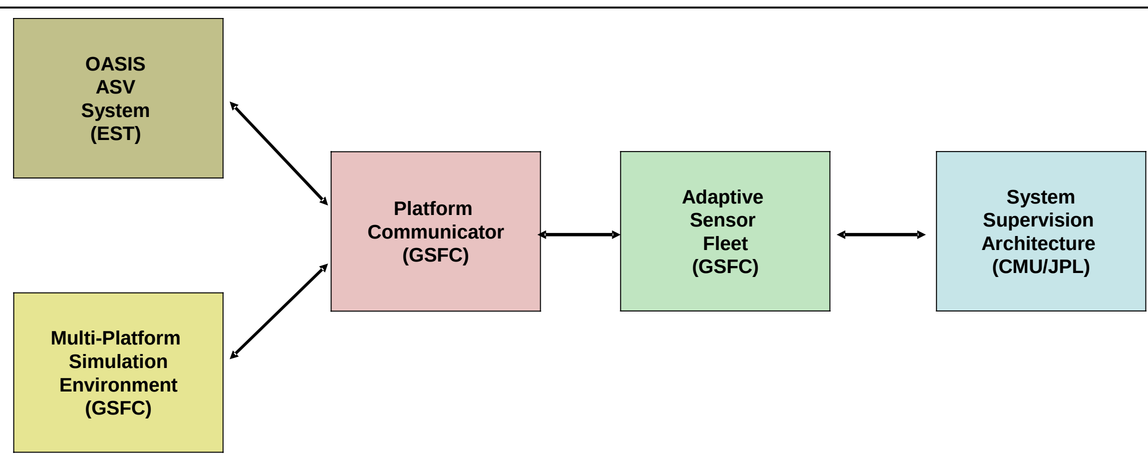

Figure 1. TAOSF High-level Software Architecture

for all physical and simulated platforms. It is responsible for translating platform-independent messages from the higher control systems to the device-dependent communication protocols. This enables the higher-level control systems to interact identically with heterogeneous physical or simulated platforms. This component is developed by GSFC.

D. The Adaptive Sensor Fleet (ASF) provides autonomous platform assignment and path planning for area coverage, as well as monitoring of mission progress. The ASF is developed by GSFC.

E. The System Supervision Architecture (SSA) provides high-level planning, monitoring, and telesupervision, including analysis of science data from both the OASIS platforms and external sources such as satellite imagery and fixed sensors. These data are used by the SSA in the planning of robot paths for data gathering. The SSA also provides an operator interface for those times when a scientist desires direct monitoring and control of individual platforms and their instruments.

The SSA is based on existing software (the Robot Supervision Architecture [6]) which has been developed by CMU and JPL, as well as the Multi-robot Operator Control Unit (see Figure 2) developed by SPAWAR Systems Center San Diego [7].

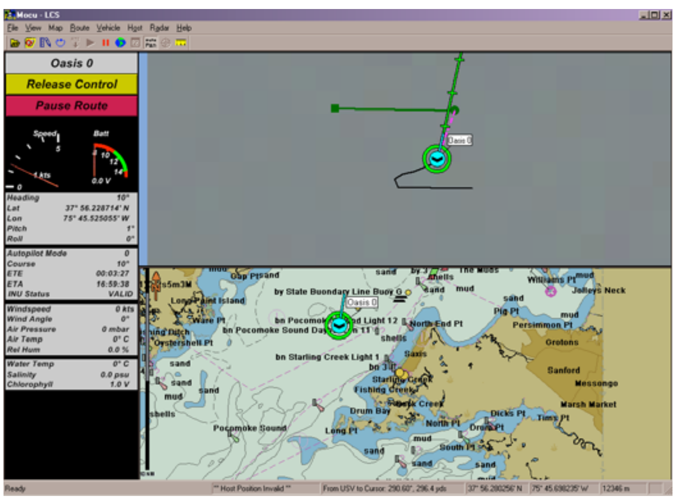

Figure 2. The Multi-robot Operator Control Unit (MOCU). Upper right pane: A path created by MOCU (horizontal green line) and a track of the OASIS platform (black line); Lower right pane: OASIS platform position within a map of the Chesapeake Bay; Left pane: engineering telemetry from the OASIS platform.

III. OASIS PLATFORMS AND INFRASTRUCTURE

The NOAA-funded OASIS Platform Build Team consisting of EG&G, Zinger Enterprises, and Emergent Space Technologies provides for vehicle research and development, payload integration and testing, operations, and maintenance of the OASIS fleet and ground systems. The OASIS platform is a long-duration solar-powered autonomous surface vehicle (ASV), designed for autonomous global open-ocean operations. The platform is approximately 18 feet long and weighs just over 3000 lbs. The vehicle has a payload capacity of 500 lbs., and is designed to be self-righting to ensure survivability in heavy seas. The vehicle supports a wide range of communication links including spread spectrum radio, cellular, and Iridium satellite.

Two platforms are currently undergoing testing at WFF and will support operations for the TAOSF project. Additional platforms are under production and expected to enter the OASIS fleet later this year.

OASIS shakedown operations have been performed since early 2005 in the waters of the DELMARVA region, including the Chincoteague Bay and Pocomoke Sound. The first open-ocean deployment of the OASIS system was performed in November 2006 (Figure 3). During this operation, the OASIS2 platform successfully navigated over 8 nautical miles on a transect line established in the Atlantic Ocean off the coast from WFF. OASIS1 and OASIS2 are currently undergoing upgrades, sensor integration, and testing in preparation for endurance trials and science operations.

Figure 3. First open-ocean deployment, Nov. 2006.

Sensors have been integrated onboard the OASIS2 platform to enable the collection of salinity, conductivity, sea surface temperature, and chlorophyll measurements. A rhodamine fluorometer will be installed in June 2007 to support mapping operations during dye deployment demonstrations.

The forward payload bay (Figure 4) provides space for installation of additional sensors in the future. This bay includes a water flow-through system with manifolds and a de-bubbling system which simplifies installation of new sensors.

The platforms also provide a mast-mounted meteorological station enabling acquisition of atmospheric measurements including barometric pressure, air temperature, relative humidity, wind speed, and wind direction. OASIS2 is also equipped with a forward-looking digital imaging system providing remote scientists with images of atmospheric and sea state conditions.

The off-board infrastructure developed by EST is known as the OASIS Mission Operations Environment (MOE). The MOE resides in the Wallops Coastal Ocean Observation Laboratory (WaCOOL) control room and provides applications and services that enable the WFF engineering and science operations team to perform platform commanding and telemetry monitoring, as well as communication hardware management. The MOE also provides a middleware interface to enable remote observers, such as the TAOSF project, to integrate new systems that further enhance OASIS science operations.

Figure 4. OASIS forward payload bay with salinity and chlorophyll sensors installed.

IV. HAB Sensing and Characterization

Our work in this area has two components. First, we are assembling and analyzing all known HAB-related data from the Chesapeake Bay area. . Second, for initial sensor testing and validation we are developing a means of producing and ground-truthing a surrogate HAB using rhodamine, a fluorescent compound commonly used as a water tracer dye.

A. HAB datasets and analysis

The Maryland Department of Natural Resources (DNR) has provided us with descriptions and HAB species cell-count data from five regions in the Chesapeake and Coastal Bays that have experienced algal blooms. We used a Gaussian process approach to predict the cell counts of the dinoflagellate *Karlodinium micrum* from water quality features (temperature, salinity, and dissolved oxygen). The results (Figure 5) indicate that Gaussian processes using a Gaussian kernel perform just as well as linear regression does for predicting cell counts.

We also investigated an adaptive sampling approach using the Regional Ocean Modeling System (ROMS) model of the Chesapeake Bay using Gaussian processes to select positions for obtaining sensor measurements to optimally characterize the distribution of salinity from known temperature data. The results (Figure 6) show the advantage of the adaptive sampling approach over random selection of sampling positions. The mutual information algorithm achieves low RMS error after selecting only a few points to sample and asymptotically approaches the minimum faster than the random selection algorithm.

The next step in our analysis is to integrate MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data (Chlorophyll A and sea surface temperature) with the DNR cell-count data for HAB prediction.

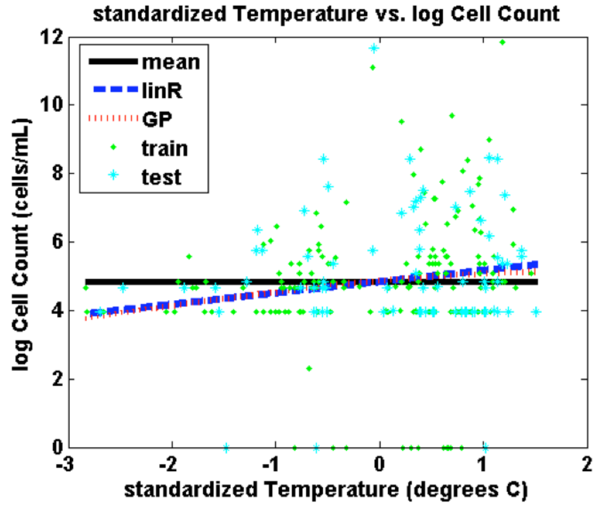

Figure 5. Predicted log cell counts of Karlodinium micrum from temperature using three different algorithms: mean, linear regression (linR), and Gaussian process (GP). The points used for training and testing the algorithms are depicted as green dots and cyan asterisks, respectively.

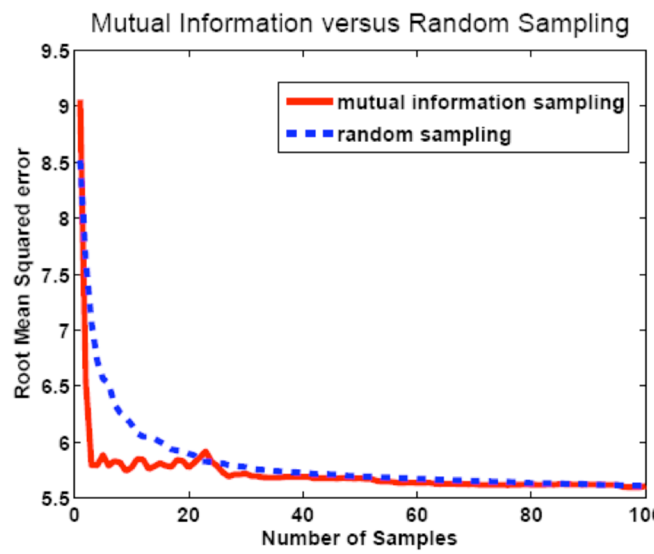

Figure 6. Root Mean Square (RMS) error in selecting points using the Gaussian process-based adaptive sampling approach with the mutual information metric vs. using random selection.

B. Sensor validation

In order to test our ability to map the presence and extent of a phenomenon in the ocean environment, we are using rhodamine WT[1](water-tracing) dye to simulate HABs for Year 1 experiments and tests. To determine the concentration of dye in the water required for visibility by an aerial camera, we conducted tests in a local pond in Pittsburgh.

[1] Technical Data Sheet: http://www.coleparmer.com/catalog/Msds/msdbes002.pdf

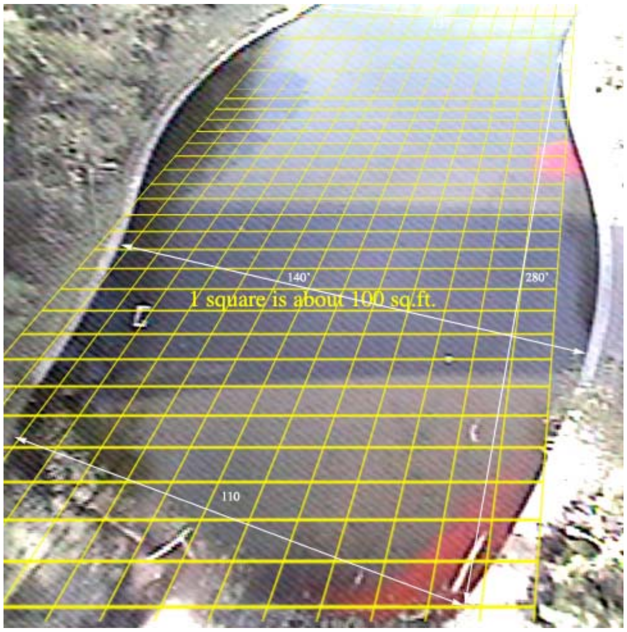

Figure 7. Two dye patches simulating algal blooms, a recent one (upper right), and an earlier one (lower right).

The pond, called Schenley Park Lake (Figure 7), has a surface area of about 9900m^2, and a depth conservatively estimated at 1m. Initial surface concentrations of 5ppm over a 30m^2 area result in the initial dye patch seen at the upper right of Figure 7. An earlier dye patch that dispersed from a similar initial patch over 20 minutes is seen at the lower right of the figure and covers an area of about 65m^2. It is still quite visible from the overhead camera but not nearly as intense.

Surface samples (Figure 8) were taken of each patch at intervals and will be analyzed in a similar fashion to the fluorometers that will be aboard each platform to establish a baseline for correlating camera visibility with in-water concentration measurements.

Figure 8. Surface samples taken of each dye patch.

For validation of OASIS platform position and surface bloom extent, we developed a low-altitude aerial system carrying an avionics package with a recording GPS, barometric altimeter, magnetic compass, serial data link, wide-angle color camera, and transmitter. Figure 9 depicts a typical deployment, showing the OASIS platforms investigating a dye-simulated bloom, and an aerostat carrying the sensor validation avionics package, tethered to a human-piloted boat.

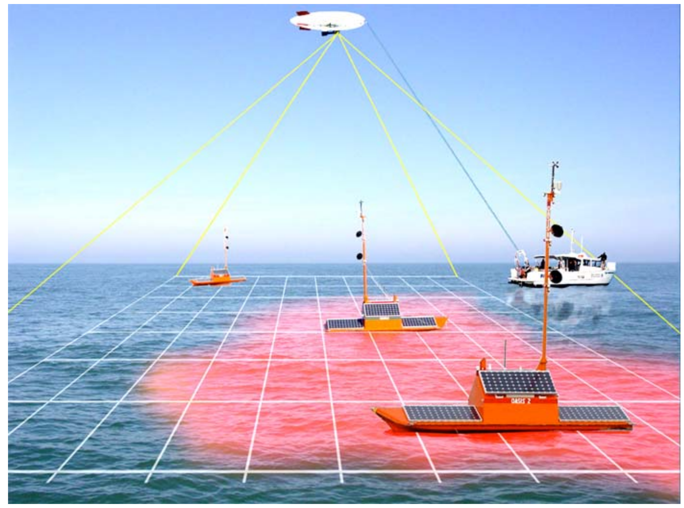

Figure 9 – Concept for sensor validation system: overhead aerostat with camera view tethered to a manned operations boat, three OASIS platforms, and a patch of rhodamine dye.

CMU and JPL conducted a series of tests to validate the ground-truthing capability of the sensor validation package by flying tethered over parking areas. The camera images were easily aligned to satellite photos from Google Earth. The GPS data were used to recover an aerial image of the test site from Google Earth, and the obtained camera image was then overlaid on the Google Earth image in order to check correspondence and heading uncertainty.

An example is shown in Figure 10, where the yellow triangle indicates heading uncertainty, the base of the arrow marks the position believed by the ground-truthing system to correspond to the indicated lat/long position, and the blue quadripartite square marks Google Earth's record of this position. In this case, there is a 2 m error in position and a 30-degree error in heading. We expect to improve the heading error through the use of a more stable aerostat in future tests.

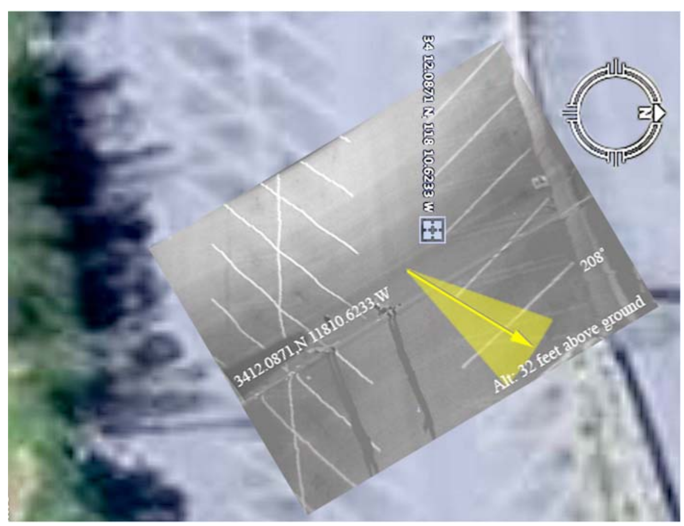

Figure 10 – Initial aerial sensor validation system results showing heading (yellow triangle) and position (blue square) error.

V. Conclusions and Future Work

This paper describes a telesupervision architecture for multiple autonomous platforms and its application to the particular problem of the detection of harmful algal blooms. Initial work has concentrated on the integration of subsystems developed by the collaborating organizations in preparation for a summer 2007 end-to-end test in which multiple OASIS platforms map a rhodamine-dye HAB surrogate under human telesupervision in a calm aquatic environment. In the project's second year, we intend to increase the number of platforms, develop and deploy adaptive sensing algorithms, and deploy to the Chesapeake Bay estuary. In year three, we intend to deploy and control as many as twelve OASIS platforms in a dynamic environment with significant water movement.

Because of their spatial reach and resolution and their adaptivity, telesupervised autonomous surface vehicles are crucial to the sensor web for Earth science. The telesupervision architecture underlying TAOSF is broadly applicable to a wide variety of domains beyond HAB, to include ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration.

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