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The Telesupervised Adaptive Ocean Sensor Fleet

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ABSTRACT

We are developing a multi-robot science exploration architecture and system called the Telesupervised Adaptive Ocean Sensor Fleet (TAOSF). TAOSF uses a group of robotic boats (the OASIS platforms) to enable in-situ study of ocean surface and sub-surface phenomena. The OASIS boats are extended-deployment autonomous ocean surface vehicles, whose development is funded separately by the National Oceanic and Atmospheric Administration (NOAA). The TAOSF architecture provides an integrated approach to multi-vehicle coordination and sliding human-vehicle autonomy. It allows multiple mobile sensing assets to function in a cooperative fashion, and the operating mode of the vessels to range from autonomous control to teleoperated control. In this manner, TAOSF increases data-gathering effectiveness and science return while reducing demands on scientists for tasking, control, and monitoring. It combines and extends prior related work done by the authors and their institutions. The TAOSF architecture is applicable to other areas where multiple sensing assets are needed, including ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration. The first field application chosen for TAOSF is the characterization of Harmful Algal Blooms (HABs). Several components of the TAOSF system have been tested, including the OASIS boats, the communications and control interfaces between the various hardware and software subsystems, and an airborne sensor validation system. Field tests in support of future HAB characterization were performed under controlled conditions, using rhodamine dye as a HAB simulant that was dispersed in a pond. In this paper, we describe the overall TAOSF architecture and its components, discuss the initial tests conducted and outline the next steps.

Keywords: telesupervision, multirobot systems, sensor web, adaptive sampling, harmful algal blooms, ocean sensing.

1. INTRODUCTION

Earth science research requires information obtained from space, the atmosphere and the ocean to foster understanding of the Earth and its natural processes. Developing a better understanding of ocean processes, in particular, is crucial for global warming, meteorological and ecological studies. Ocean sensing is typically done with satellites, buoys, airborne assets and research vessels. Satellites and airplanes are limited by cloud cover and temporal/geographical coverage and resolution; while research vessels are expensive to deploy, and buoys cannot be self-deployed to specific areas of interest.

The National Oceanic and Atmospheric Administration (NOAA) is addressing some of these constraints through the development of robotic ocean vessels for weather-related ocean monitoring. The OASIS (Ocean-Atmosphere Sensor Integration System) vessels are long-duration solar-powered autonomous surface vehicles (ASVs), designed for global open-ocean operations (Fig. 1). In this paper, we present a software architecture developed to enhance the science value of multiple robotic sensing assets by coordinating their operation, adapting their activities in response to sensor observations, and allowing a human operator to oversee multiple assets.

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Figure 1. Artist's concept of the OASIS robot vessels investigating the nature and extent of a Harmful Algal Bloom (HAB).

The Telesupervised Adaptive Ocean Sensor Fleet (TAOSF) architecture provides an integrated approach to multi-vehicle coordination and sliding human-vehicle autonomy. It allows multiple mobile sensing assets to function in a cooperative fashion, and the operating mode of different vessels to vary from autonomous control to teleoperated control.

The TAOSF architecture supports the following features:

- **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 autonomy levels in between.
- **Adaptive replanning** of the activities of the OASIS vessels based on sensor inputs ("smart" sensing) and sensorial **coordination between multiple assets**, thereby increasing data-gathering effectiveness while reducing the effort required for tasking, control, and monitoring of the vehicles.
- **Web-based communications** permitting control and communications over long distances and the sharing of data with remote experts;
- **Autonomous hazard and assistance detection**, allowing automatic identification of hazards that require human intervention to ensure the safety and integrity of the robotic vehicles, or of science data that require human interpretation and response.
- **Science analysis** of the acquired data in order to perform an initial onboard assessment of the presence of specific science signatures of immediate interest.

The Telesupervised Adaptive Ocean Sensor Fleet system allows the networking of a fleet of autonomous ocean vehicles to study the surface and sub-surface characteristics and the dynamics of such ocean phenomena as coastal pollutants, oil spills, hurricanes or harmful algal blooms (HABs).

2. HARMFUL ALGAL BLOOMS

To provide an initial field application for the TAOSF system we have chosen the characterization of Harmful Algal Blooms (HABs).

Interest in HAB detection has grown in recent years, for scientific, commercial and public health reasons. The Woods Hole Oceanographic Institute (WHOI) 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].

Additionally, there has been interest in identifying environmental factors that contribute to the occurrence of HABs, so that these may be incorporated in bloom prediction algorithms. A regional study on the dinoflagellate *Karlodinium veneficum* has been generating near real-time maps of HABs in the Chesapeake Bay using a hydrodynamic model and satellite data [4]. The methodology 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.

Another group has developed a system of tracking and predicting the spatiotemporal dynamics of the HAB species *Karenia Brevis* in the Gulf of Mexico [5]. The similarity of target objects in consecutive images is used to track the target over time. The system predicts the spatiotemporal dynamics of a bloom using a cellular automata model to simulate the growth, shrinkage, and collisions under specific wind conditions. If automatic tracking of the target fails, a human expert reinitiates the track by selecting the object of interest 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 HABs:

- Dynamic tasking and adaptation
- Higher resolution and greater insensitivity to cloud-cover in comparison with current satellite systems
- Access to and greater agility in coastal waters than what is available through buoys
- Real-time multipoint science data observation by associated interpretation by remotely-located oceanographers.

The remainder of this paper describes the TAOSF system architecture (section 3), the OASIS platforms and infrastructure (section 4), HAB sensing and characterization (section 5) and the initial tests performed and results obtained (Section 6). Section 7 provides conclusions and outlines future work.

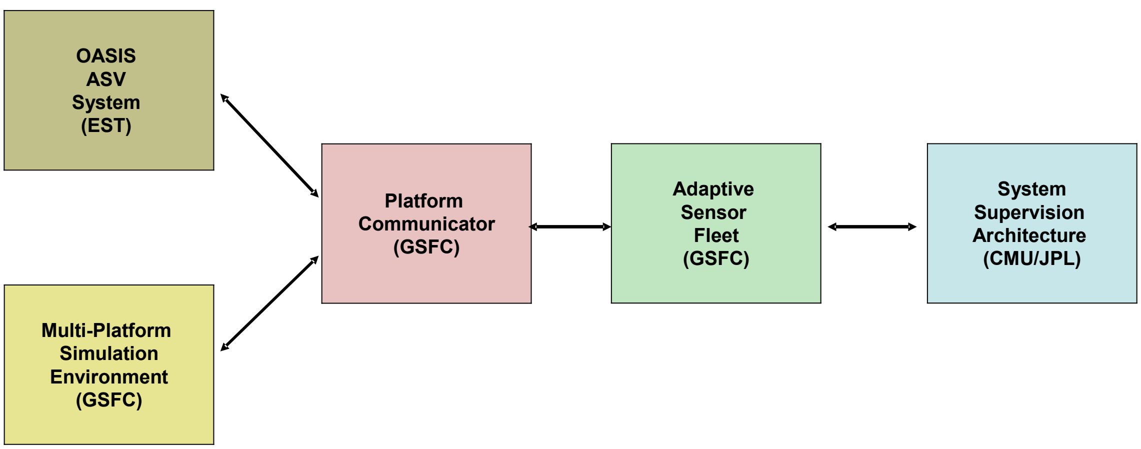

Figure 2. TAOSF High-level software architecture.

3. SOFTWARE ARCHITECTURE

The TAOSF software architecture (Fig. 2) integrates and extends five subsystems developed by the participating institutions. The five TAOSF subsystems are:

A. The **OASIS Autonomous Surface Vehicle (ASV) System** includes the vessels 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 (sensors, actuators, etc.), and also provides a low-level waypoint navigation capability. This system has been developed by Emergent Space Technologies (EST) working with the team members at the NASA Wallops Flight Facility (WFF), where the platforms are physically built and maintained.

B. The **Multi-Platform Simulation Environment** has been developed by NASA Goddard Space Flight Facility (GSFC) as a surrogate for the OASIS ASV system, allowing independent development and testing of the higher-level software components.

C. The **Platform Communicator** acts as a proxy for both actual and simulated platforms. It translates platform-independent messages from the higher control systems to the device-dependent communication protocols. This component, developed by GSFC, enables the higher-level control systems to interact identically with heterogeneous actual or simulated platforms.

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, as well as 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 planning of vessel navigational trajectories for data gathering. The SSA also provides an operator interface for those ocasions when a scientist desires to exert direct monitoring and control of individual platforms and their instruments. The SSA is based on the Robot Supervision Architecture [6] developed by CMU and JPL, as well as the Multi-Robot Operator Control Unit (Fig. 3) developed by SPAWAR Systems Center San Diego [7].

Our initial development effort has concentrated on the integration of these subsystems. We have demonstrated end-to-end integration of SSA, ASF and OASIS in a dry-boat test in May of 2007, and expect to perform the first in-water test of the integrated system in the next few months.

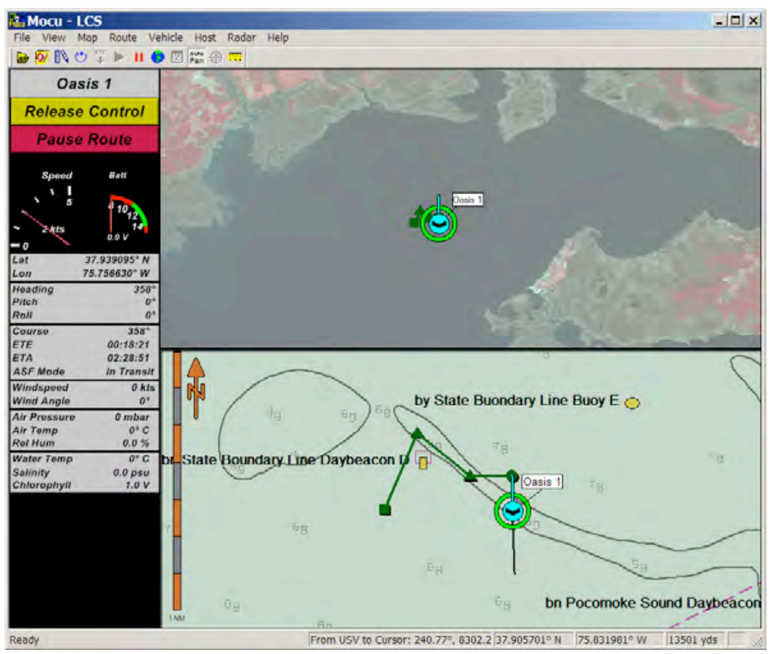

Figure 3. The Multi-robot Operator Control Unit (MOCU). Lower right pane: OASIS platform position overlaid on a nautical chart of the operating area, with a user-drawn path shown in green. Upper right pane: The robot position and path overlaid on a satellite image of the operating area. Left pane: engineering and science telemetry from the platform.

4. OASIS PLATFORMS AND INFRASTRUCTURE

The NOAA-funded OASIS Platform Build Team, which consists of EG&G, Zinger Enterprises, and Emergent Space Technologies, provides vehicle research and development, payload integration and testing, operations, and maintenance of the OASIS fleet and ground systems. The OASIS platform itself 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 (named OASIS1 and OASIS2) are currently undergoing testing at WFF and will support operations for the TAOSF project. Additional platforms are under production.

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 (Fig. 4). 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 4. First open-ocean deployment of an OASIS platform, November 2006.

Sensors have been integrated onboard the OASIS2 platform to enable the collection of water salinity and conductivity, sea surface temperature, and chlorophyll measurements. A rhodamine fluorometer will support mapping operations during dye deployment demonstrations. The forward payload bay (Fig. 5) 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.

Figure 5. OASIS forward payload bay with salinity and chlorophyll sensors installed.

The OASIS boats have a mast-mounted meteorological station for 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 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.

5. 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.

5.1 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 (Fig. 6) 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 (Fig. 7) 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 will be to integrate MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data (Chlorophyll A and sea surface temperature) with the DNR cell-count data for HAB prediction.

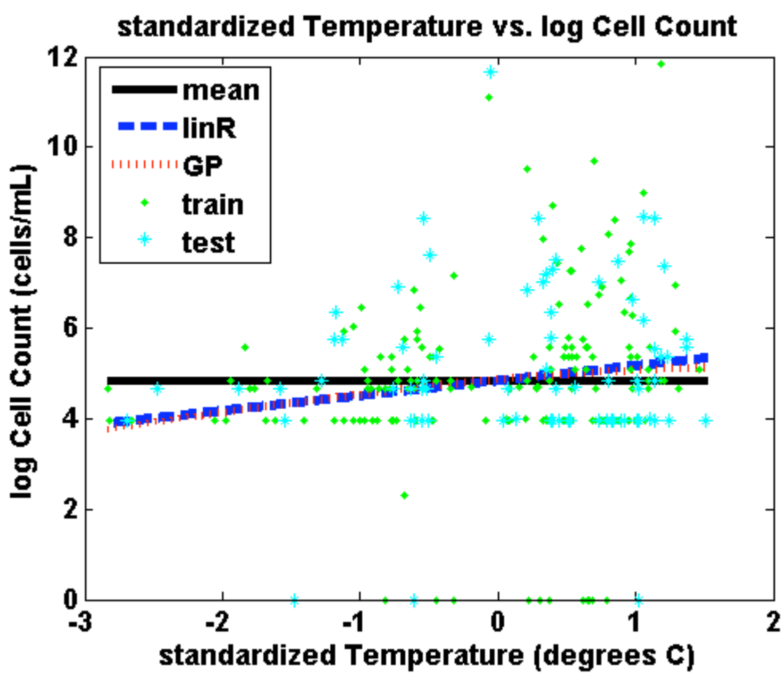

Figure 6. Predicted log cell counts of *Karlodinium micrum* from temperature using three different algorithms: mean, linear regression (linR), and Gaussian process (GP). The points used for training and testing the algorithms are depicted as green dots and cyan asterisks, respectively.

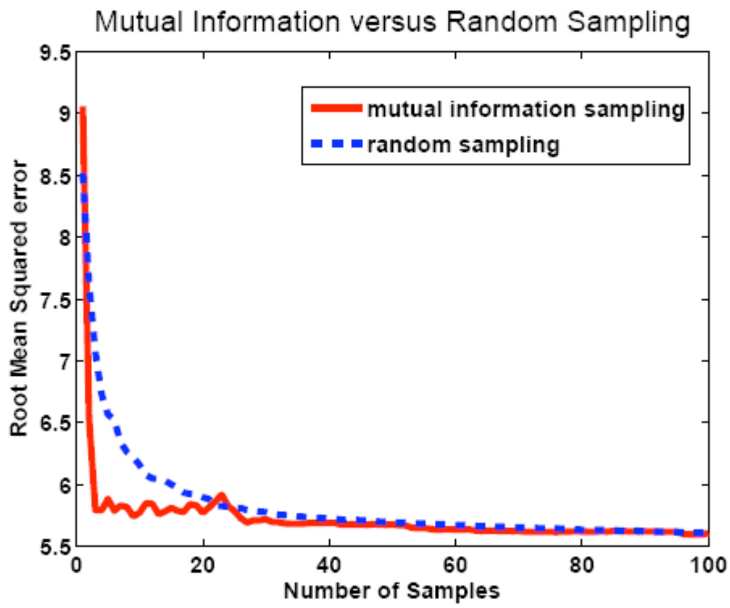

Figure 7. Root Mean Square (RMS) error in selecting points using the Gaussian process-based adaptive sampling approach with the mutual information metric vs. using random selection.

5.2 Sensor validation

To test our ability to map the presence and extent of a phenomenon in the ocean environment, we are using rhodamine WT (water-tracing) dye [8] to simulate HABs for initial 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.

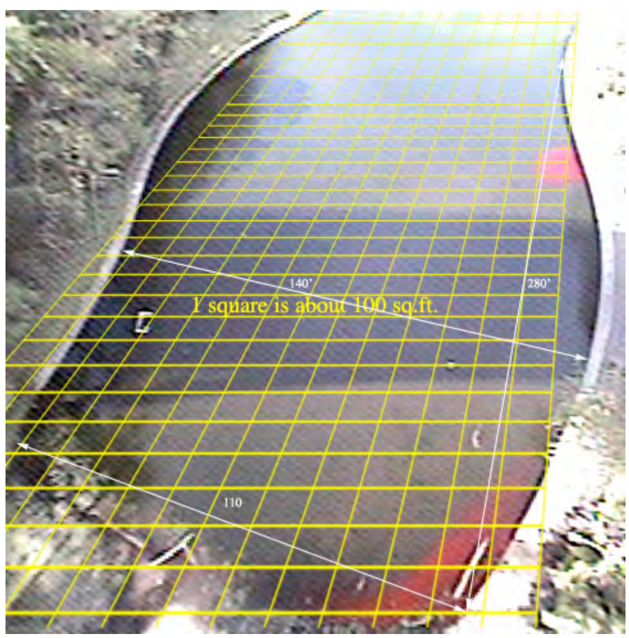

Figure 8. Two dye patches simulating algal blooms. The first (earlier) patch is shown on the lower right, while the second (subsequent) patch is on the upper right. The test was conducted at the Schenley Park Lake in Pittsburgh.

The pond, called Schenley Park Lake (Fig. 8), has a surface area of about 9900m^2, and a depth conservatively estimated at 1m. The first dye patch, with a concentration of 5ppm, was dispersed from a location at the lower right of the pond, and is shown after 20 minutes of dispersion, when it covered an area of approximately 65m^2. At this point in time, the patch is still quite visible from an overhead camera but not nearly as intense as the second patch. The latter patch, also with an initial dye surface concentrations of 5ppm, is shown dispersed over a 30m^2 area. Surface water samples (Fig. 9) were taken of each patch at measured time intervals and will be analyzed using the same fluorometers that will be aboard each OASIS platform. This will allow us to establish a baseline for correlating camera visibility with in-water concentration measurements.

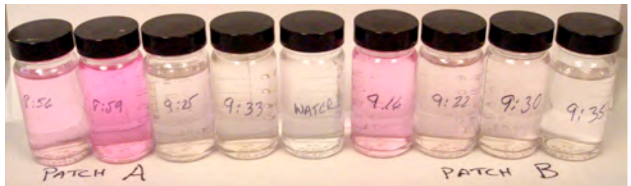

Figure 9. Surface water samples taken of the dye patches shown in Fig. 8.

5.3 Automated Dye Patch Mapping

In the TAOSF system, we will use the Inference Grid (IG) model to represent multiple spatially- and temporally-varying properties. The Inference Grid is a probabilistic multi-property spatial lattice model (a Markov Random Lattice) [9], where sensor information is stored in spatially and temporally registered form, and which is used for both scientific inferences and for vehicle mission planning. The information in Inference Grid cells is represented as a stochastic vector, and metric such as entropy are used to measure the uncertainty in the IG.

As part of the HAB sensing and characterization effort, we have developed an initial automated dye patch mapping system using the IG model. Overhead imagery of the pond was processed to perform automated cluster identification using an unsupervised clustering algorithm. Using a reference dye spectral signature, the dye dispersion patch was identified and segmented in the image, and a probabilistic metric was associated with the distance to the reference signature in the spectral space. The results for a single pond image is shown in Fig. 10, and for a sequence of images in Fig. 11.

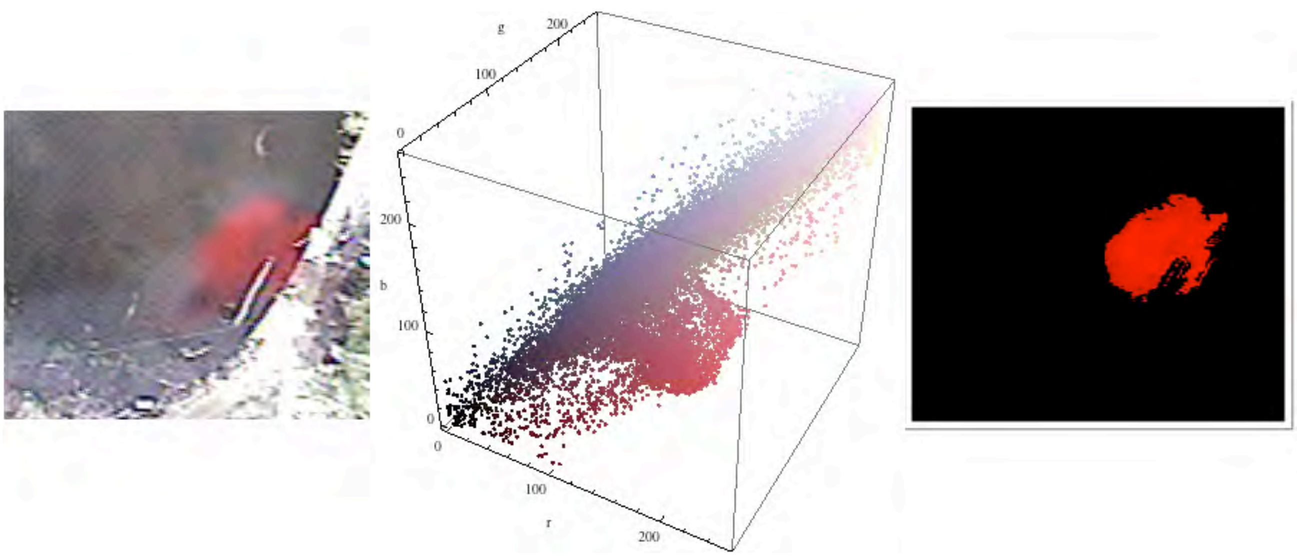

Figure 10. The left image shows the first patch in Fig. 8, after several minutes of dye dispersion. The center plot shows the RGB intensity distributions of the left image; automated image segmentation is done using an unsupervised clustering algorithm. The map on the right shows an Inference Grid with the spatially distributed probabilities of dye being present in the water.

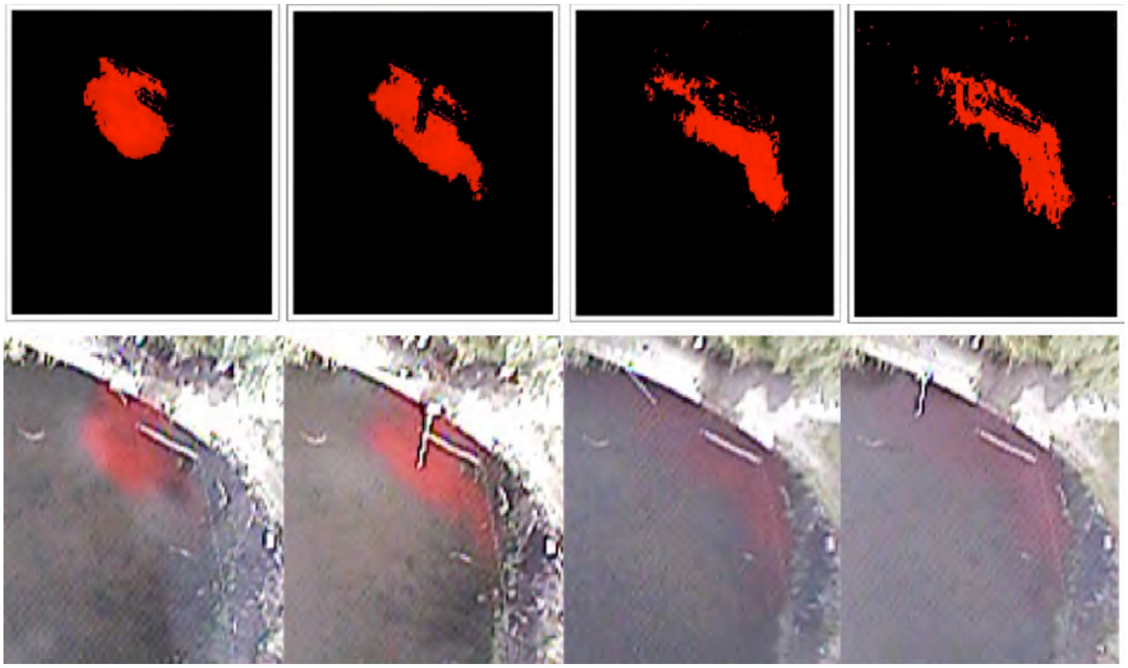

Figure 11. Automated dye patch extent mapping and characterization using the Inference Grid model. The images in the bottom row show the first patch in Fig. 8 dispersing over time. The corresponding Inference Grids are shown in the upper row, where the spatially and temporally varying dye presence probabilities are shown. The images and maps are rotated counterclockwise (relative to Figs. 8 and 10) for presentation convenience.

6. SYSTEM TESTING AND VALIDATION

One important component in the field testing and validation process of the overall TAOSF system is the ability to have a "bird's eye" view of how an algal bloom (or a dye patch) is moving and dispersing in the water, and how the OASIS boats are responding to this process. To address this need, 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 12 depicts what a typical deployment and testing configuration would look like, showing the OASIS platforms investigating a dye-simulated bloom, and an aerostat carrying the sensor validation avionics package tethered to a human-piloted chase boat.

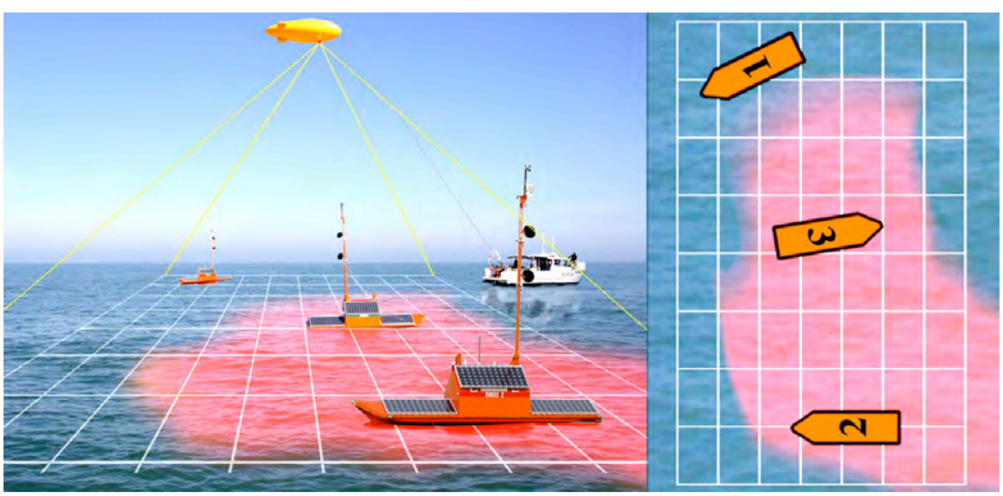

Figure 12. Concept of the TAOSF field validation system: an overhead aerostat (an unmanned blimp tethered to a manned field operations vessel) provides a global camera overview of three OASIS platforms and a patch of rhodamine dye. The overhead map is shown on the right.

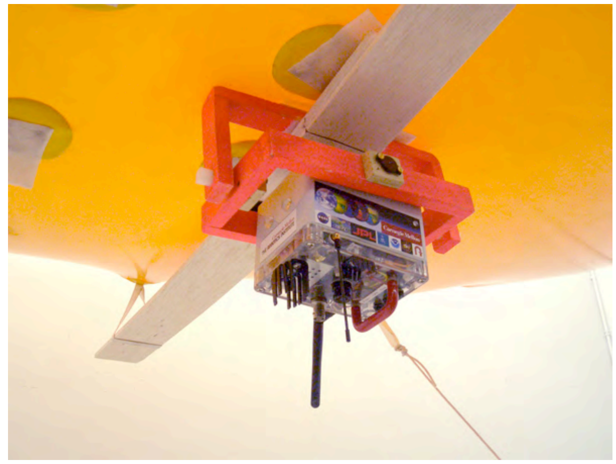

Figure 13. The TAOSF aerostat observation platform. The photo on the left shows the aerostat, which is an unmanned, lighter-than-air (LTA) unpowered blimp on a tether. Helium is used for buoyancy. The gimballed TAOSF observation platform avionics package is shown on the right. It includes a GPS, a barometric altimeter, a magnetic compass, a serial wireless data link, a wide-angle color camera, and a video transmitter.

The TAOSF aerial observation platform is a 6m long, 2m diameter aerostat (Fig. 13). The aerostat is an unmanned, helium-filled, lighter-than-air (LTA) blimp on a tether. In its current configuration the system is flown unpowered. The onboard avionics package is gimballed, and includes a GPS, a barometric altimeter, a magnetic compass, a serial wireless data link, a wide-angle color camera, and a video transmitter. The avionics package weighs 700g.

We conducted a series of tests to validate the ground-truthing capability of the TAOSF aerostat observation platform. These tests were conducted over land, at JPL. The camera imagery was registered a posteriori to satellite imagery from Google Earth using the GPS data. Satellite/aerial image registration allowed estimation of the observational uncertainties associated with the aerostat/avionics platform, including heading uncertainty (Fig. 14).

Figure 14. Initial results from the TAOSF aerostat observation platform. Tests of the ground truthing system were conducted. By registering aerial imagery to satellite imagery, the overall uncertainty in the ground position estimates derived from the aerostat platform were estimated. The camera image (in grey) was taken when the aerostat was 30 m above ground.

7. 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 the development of HAB and dye observation systems, and in building an aerial platform to allow observation of the TAOSF system and the OASIS boats from the air. One of our key next steps is an end-to-end test in which multiple OASIS platforms map a rhodamine-dye HAB surrogate under human telesupervision in a calm aquatic environment. Over the next year we plan to increase the number of platforms, develop and deploy adaptive sensing algorithms, and deploy the TAOSF system in the Chesapeake Bay estuary.

Because of their in-situ observation capabilities and resolution, as well as 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, including ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration.

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