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Networked Architecture for Robotic Environmental Ocean Science Sensors

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Abstract:

This paper describes an architecture for environmental science sensors deployed on a fleet of networked unmanned extended-deployment autonomous ocean surface vessels. This architecture allows one land-based human scientist to effectively supervise data gathering through a web of widely-dispersed mobile sensors supported by multiple robotic assets to enable in situ study of phenomena at the interface between the ocean and the atmosphere. In addition to meteorological and ocean surface data, the system supports characterization of Harmful Algal Blooms (HABs).

Keywords: Telesupervision; Sensor Web; Harmful Algal Blooms; Inference Grids.

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1. Introduction

Gathering and disseminating data on ocean processes is crucial for meteorological and ecological studies. This paper describes a multi-robot science exploration architecture and system called the Telesupervised Adaptive Ocean Sensor Fleet (TAOSF). TAOSF is based on the Multilevel Autonomy Robot Telesupervision Architecture (MARTA) [1, 2, 3]. TAOSF supervises and coordinates a fleet of robotic sensor boats, to enable in situ study of phenomena at the ocean/atmosphere interface, as well as on the ocean surface and sub-surface.

The TAOSF system is applicable to the study of dynamic processes such as coastal pollutants, oil spills, hurricanes or harmful algal blooms. More generally, it can be used in a variety of areas where multiple sensing assets are needed, including ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration.

Environmental ocean sensing is typically supported by satellites, aircraft, buoys, and crewed research vessels. Satellites and aircraft are limited by cloud cover, temporal/geographical coverage, and resolution; while manned research vessels are expensive to deploy, and buoys cannot be repositioned to specific areas of interest.

The National Oceanic and Atmospheric Administration (NOAA) has been addressing some of these constraints through the development of robotic senor boats called OASIS (Ocean-Atmosphere Sensor Integration System) which are long-duration solar-powered autonomous surface vehicles (ASVs), designed for global open-ocean operations. One of the key objectives of our research is to enhance the science value of multiple robotic sensing assets, such as the OASIS vessels, by coordinating their operation, adapting their activities in response to sensor observations, and allowing a human teleoperator to supervise these multiple assets efficiently. This approach integrates well into the "Sensor Web" concept, that is, providing within a single information system a geographically and temporally wide array of sensor data. This is useful by providing simultaneous physical phenomena measurements that can otherwise only be achieved by laborious data collection and collation.

The first field application chosen for TAOSF is the characterization of Harmful Algal Blooms (HABs). In the following sections, we will discuss the TAOSF architecture, describe field tests of the system conducted under controlled conditions, and present a result from these tests.

2. Telesupervised Adaptive Ocean Sensor Fleet

2.1 TAOSF Architecture

The TAOSF system architecture (Figure 1) provides an integrated approach to multi-robot coordination and multi-level robot-human autonomy. It allows multiple robotic sensing assets (both mobile and fixed) to function in a cooperative fashion, and the operating mode of different robots to vary from full autonomy to teleoperated control.

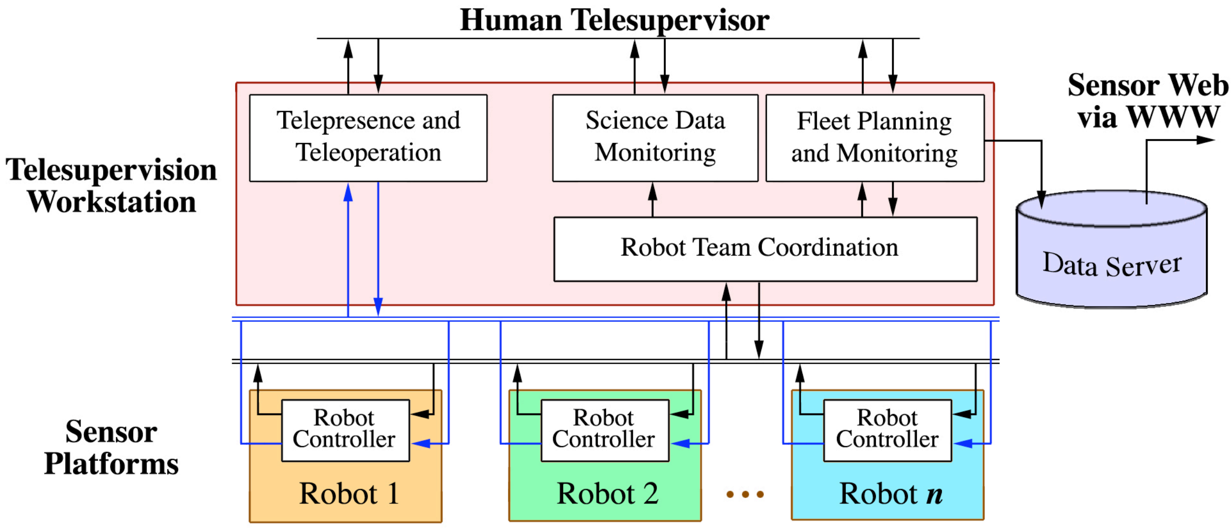

Figure 1. TAOSF Telesupervision Architecture.

High-level planning and monitoring allows a human telesupervisor to assign to a fleet of robotic assets high-level goals, such as specifying an area of ocean to investigate, which are then automatically subdivided and operational commands sent to each robot by the Robot Team Coordinator. As the robots execute these plans their operation is monitored both by the Robot Team Coordinator module and by the human telesupervisor. Adaptive replanning of the robot assignments is based on sensor inputs (dynamic sensing) and coordination between multiple assets, thereby increasing data-gathering effectiveness while reducing the human effort required for tasking, control, and monitoring of the vehicles.

Multi-level autonomy includes low-level autonomy on each independently-operating robot; autonomous monitoring of the fleet; adaptive replanning; and when necessary, intervention by the human telesupervisor either with manual replanning, or by taking direct control of a robot via teleoperation.

Algorithms for science analysis of the acquired data can perform an initial assessment of the presence of specific science signatures of immediate interest both onboard each robot, and at the telesupervisor's workstation. Web-based communications support both control and communications over long distances of the robotic fleet, and the sharing of currently-sensed and historical data with remote experts.

2.1 OASIS Platforms and Infrastructure

The NOAA-funded OASIS Platform is a long-duration solar-powered autonomous surface vehicle (ASV), designed for autonomous global open-ocean operations (Figure 2). The self-righting platform is approximately 18 feet long and weighs just over 3000 lbs. As a sensor-web-connected platform, each OASIS communicates via spread-spectrum radio, cellular data phone, or an Iridium satellite link.

Multiple platforms have supported development of higher-level system functions through real-world testing in Chincoteague Bay and Pocomoke Sound in southern Maryland. Environmental sensors onboard each platform enable the collection of data on concentrations of chlorophyll-a (for algal concentration measurements), as well as water surface salinity and temperature data. Mast-mounted meteorological sensors allow acquisition of atmospheric measurements, including wind speed, wind direction, air temperature, barometric pressure, and relative humidity. A digital imaging system provides remotely-located scientists with images of atmospheric and sea conditions. The platforms have been augmented with fluorometers for measuring concentrations of rhodamine water-tracing dye. Dye is deployed in patches to simulate HABs thus allowing reliable development and testing of navigation and mapping algorithms.

In the current deployment configuration, both engineering telemetry (GPS position, roll, pitch, yaw, battery voltage, &c.) and science sensor data are communicated between each robotic platform and NASA's Goddard Space Flight Center via the Internet. It is from this point that NOAA weather researchers would receive data on ocean/atmosphere interface sensor data.

For investigating an algal bloom, researchers at Carnegie-Mellon University take control of the platforms and provide the high-level planning and monitoring. The weather-related data is not interrupted, but the additional sensing for investigating the algal bloom is brought online to map the extent of a bloom, chlorophyll concentrations, and with additional sensors, eventually allow a land-based biologist the ability to determine the species of the algae to assess whether it is harmful. If it is, local authorities can be notified at aquaculture businesses, fisheries, and beaches.

The data collected is archived on a data server where both immediate and historical data can be accessed by researchers via the World Wide Web.

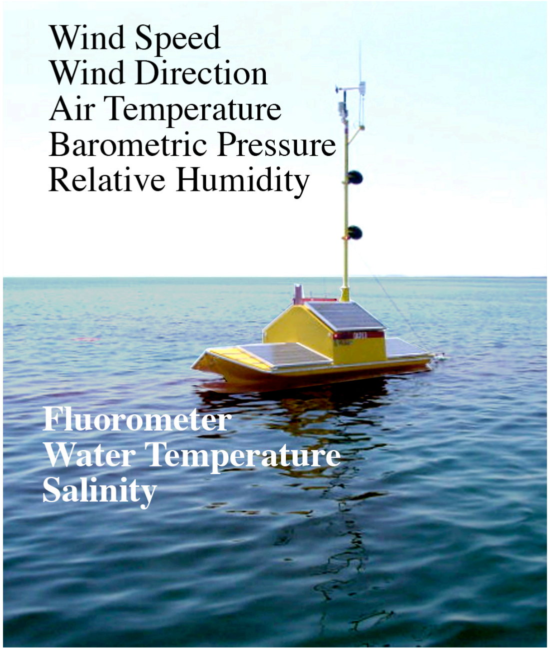

Figure 2. *OASIS Platform with atmospheric and sea water sensors identified.*

3. Experimental Results and Discussion

Figure 3. *OASIS-2 and OASIS-mapping a patch of rhodamine water-tracing dye.*

For controlled experiments such as mapping while compensating for drift currents, geometric patches of rhodamine water-tracing dye are laid; here as two parallel stripes (Figures 3 and 4). An aerostat, tethered to a manned tender boat, carries an instrument package aloft including GPS, altimeter, compass, and video camera to provide validation images of data gathered by OASIS platforms that are mapping with fluorometers.

For analysis of science sensor data, we employ an implementation of Inference Grids [4] for bloom measurement

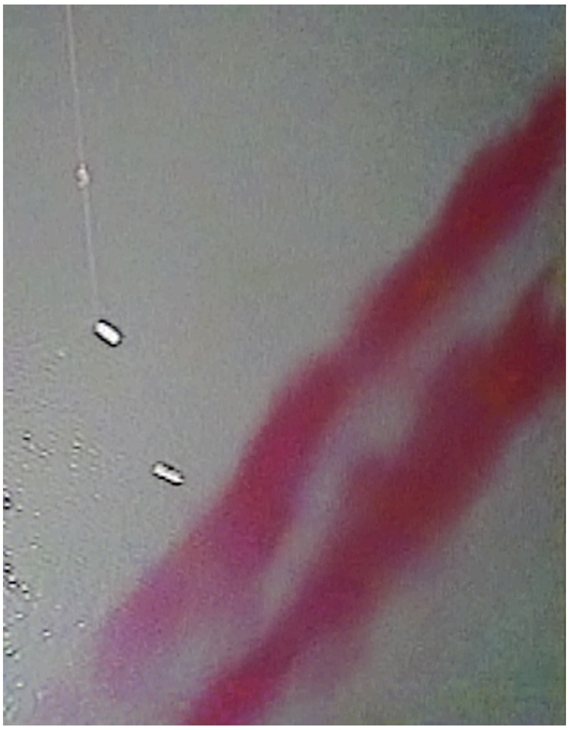

Figure 4. *Aerial view of dye patch, aerostat tender boat and OASIS platform.*

and mapping. The rhodamine dye concentration measurements taken by the OASIS platforms during field tests were used as input to the Inference Grid mapping process. The fluorometer measurements were used to compute the presence, *or absence* of dye for each cell in the area traversed by each OASIS boat. The probabilistic sensor model was derived from information on the sensitivity and performance of the. The Inference Grid map of rhodamine dye for an initial mapping experiment is shown in Figure 5.

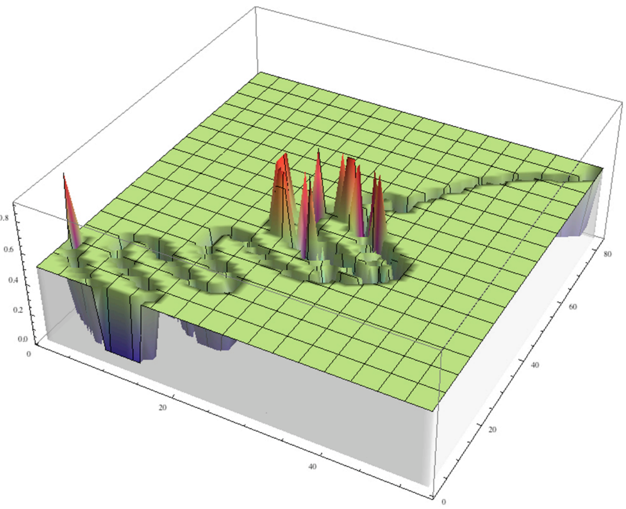

Figure 5. *Inference Grid probabilistic mapping of presence or absence of dye.*

4. Conclusions

The MARTA-based TOASF multi-level autonomy control architecture provides many advantages over existing systems for observing and analyzing HABs including: dynamic tasking and adaptation; higher in situ resolution and greater insensitivity to cloud cover (as compared with satellite systems); access to and greater agility in coastal waters than that available through buoys; real-time multipoint science data observations and generation of associated interpretations by remotely located oceanographers.

Using the TOASF architecture, increases data-gathering effectiveness and science return while reducing demands on scientists for robotic asset tasking, control, and monitoring. The data are also made available to other scientists via the world-wide-web both as they are collected, and from an historical data archive server.

Acknowledgements

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References and Notes

1. Podnar, G.; Dolan, J.M.; Elfes, A. “Operation of Robotic Science Boats Using the Telesupervised Adaptive Ocean Sensor Fleet System”, *Proceedings of the 2008 IEEE International Conference on Robotics and Automation (ICRA '08)*, May 2008.
2. Podnar, G.; Dolan, J.M.; Elfes, A.; and Bergerman, M. “Human Telesupervision of Very Heterogeneous Planetary Robot Teams”. *Proceedings of the AIAA Space 2007 Conference*. Septenber 2007.
3. Podnar, G.; Dolan, J.M.; Elfes, A.; Bergerman, M.; Brown, H.B.; and Guisewite, A.D. "Human Telesupervision of a Fleet of Autonomous Robots for Safe and Efficient Space Exploration". *Proceedings of the 1st Annual Conference on Human-Robot Interaction (HRI-2006)*. March 2006.
4. Elfes, A. “Robot Navigation: Integrating Perception, Environment Constraints and Task Execution Within a Probabilistic Framework”. *Reasoning with Uncertainty in Robotics*, Springer-Verlag, Berlin, Germany, 1996.