

Networked Aquatic Microbial Observing System

Abstract— This paper describes the design and development of a sensor-actuated network for marine monitoring. The network consists of ten static buoy nodes and one mobile robotic boat for real-time in-situ measurements and analysis of chemical, physical and biologically pertinent phenomena governing the abundance of micro-organisms at relevant spatio-temporal scales. The goal of the network is to obtain high-resolution information on the spatial and temporal distribution of plankton assemblages in aquatic environments using the in situ presence afforded by the network, and to make possible network-enabled robotic sampling of hydrographic features of interest. This work constitutes advances in (1) real-time observing in aquatic ecosystems and (2) sensor-actuated sampling for biological analysis.

I. INTRODUCTION

Marine microorganisms (viruses, bacteria, microalgae, protozoa) have a major impact on the ecology of the coastal ocean. For example, blooms of harmful algae (e.g. red, brown and green tides) have increased dramatically on a global scale in recent years. These events result in the loss of human life each year, and economic losses in the billions of dollars due to effects on fisheries and tourism.

A primary scientific goal in marine science is to understand and ultimately predict the environmental conditions under which specific populations of marine microorganisms develop in nature, and/or the sources from which they come at the spatial and temporal scales relevant to the organisms. This level of presence in the ocean is not possible using extant technology and methodological approaches. Sampling the environment with high resolution in real time will constitute a revolutionary step forward in the study of the ecology of marine microbial species. Combined with methodology to rapidly identify aquatic microorganisms, this approach will be extremely valuable for the early detection of organisms of human interest, and the mitigation of their effects on the environment and human population.

Our goals warrant a continuous (sensing) presence in the environment, real-time acquisition and analysis of data related to chemical, physical and biologically pertinent phenomena at relevant spatio-temporal scales and correlating those with the abundance of micro-organisms. At the scales we plan to operate, it becomes quite infeasible to deploy a set of static monitoring stations over the water bodies for continuous monitoring. Deploying a fleet of mobile boats would provide adequate spatial coverage but incomplete temporal coverage. The idea of deploying a network with both static and mobile components to aid each other has been recently introduced [1]. Static buoys provide low-resolution spatial sampling with high temporal resolution while a mobile robotic boat provides high resolution spatial sampling with low temporal resolution. We

developed a small prototype sensor-actuator network consisting of 10 buoy nodes and a robotic boat, equipped with a collection of simple, off-the-shelf sensors (GPS, thermistors, fluorimeters), that can be deployed in-situ to gather and analyze relevant data in an aquatic environment. We describe the system briefly and report on data collected from preliminary field trials.

II. STATIC BUOY NODE DESIGN

The static nodes (buoys) continuously monitor the aquatic environment at the location they are deployed, and communicate the collected sensor information to the robotic boat.

A. Hardware

Each static node consists of a stargate board, an ADC board, a battery, a fluorimeter and an array of 6 thermistors, which are mounted on a wooden chassis and sealed inside a waterproof container (Fig. 1).

The stargate board (Fig. 2 (e)) uses Intel's 400 MHz X-scale processor (PXA255) and an 802.11b wireless card for inter-node communication. It locally logs sensor data received from the ADC board, and transmits such data back to a base station.

The ADC board (Fig. 2 (d)) consists of a basic stamp module (24pin micro-controller BS2sx from Parallax, Fig. 2 (c)) and two ADC chips (16 bit single channel ADS1100 and 12 bit 8 channel ADS7828 from Digi-Key). We use the basic stamp to control the two ADC chips to obtain data from the sensors. The ADC board is connected to the Stargate board through a USB/Serial converter.

We use two type of sensors: fluorimeters and thermistors. A fluorimeter (Fig. 2 (a)) measures the concentration of chlorophyll-a which is indicative of the density of certain photosynthetic micro-organisms in the environment. We use the CYCLOPS-7 submersible fluorimeter from Turner Designs Inc. It has three user settable gain ranges, which provide a wide measurement dynamic range of 0.03 to 500 micrograms/l. The thermistors (Fig. 2 (b)) we used have an accuracy of 0.1 Celsius. They are covered with a custom Titanium coating to make them corrosion resistant. The sensors are suspended from the side of the buoy into the water. The fluorimeter is lowered to a depth of 1m below the water surface while the 5 thermistors are uniformly deployed from 0.5m to 2.5m below the water surface.

Each buoy is powered by a car battery which can be recharged via an external solar panel. Without recharging, a buoy can operate continuously for about a week. Preliminary measurements indicate that connecting the solar panel could potentially increase the lifetime to several weeks.

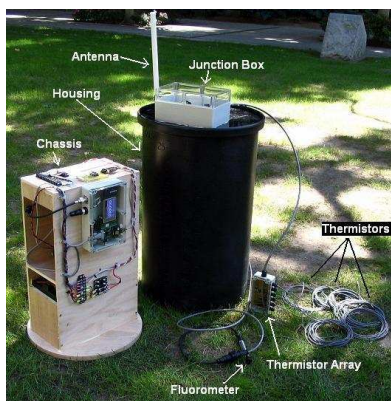


Fig. 1. The configuration of a static buoy node

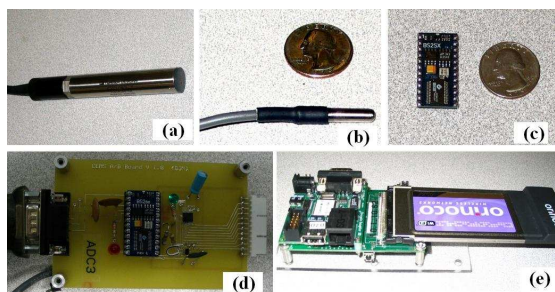


Fig. 2. System Hardware. (a) Fluorometer; (b) Thermistor; (c) Basic Stamp; (d) ADC Board; (e) Stargate Board.

B. Software Components

Our system is built atop EmStar [2], a software system for developing and deploying wireless sensor networks involving Linux-based platforms.

There are three principal components. The first reads, logs, and transmits sensor data. The static nodes are configured to run in ad-hoc mode. Multi-hop protocol is used to create a dynamic routing tree which can reliably route packets through the network. This component is also responsible for time synchronization which is essential for time stamping the gathered sensor data.

The second component is the interface between the sensor network and the users. This component communicates with the first component running on the static nodes and forwards packets between the network and users.

The third component is a toolkit to visualize the sensed data. This toolkit is built with Matlab and Java. This tool provides a graphical interface for the system and can be used to initialize and stop the process of data collection. Finally there is a set of miscellaneous software tools for retrieving and visualizing the data logged on the static nodes.

III. ROBOTIC BOAT DESIGN

To achieve a high degree of spatial sampling, a robotic boat that can sense and collect samples for biological analysis is included in the network. The boat is directed by information collected and processed within the network to identify features

of biological interest [e.g. temperature gradients, peaks in fluorescence (i.e. chlorophyll)] that it then samples. The boat can take measurements and samples at locations where the static entities cannot reach. It can track moving phenomena at greater spatio-temporal resolution than a static network alone. It can also potentially be equipped with expensive one of kind equipment which cannot be replicated for reasons of cost.

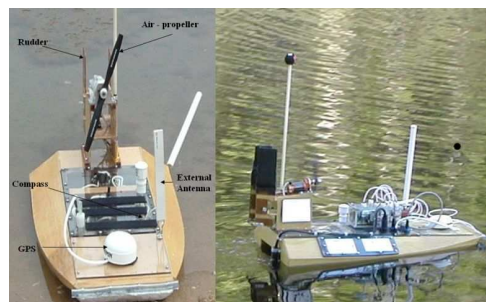


Fig. 3. Robotic boat

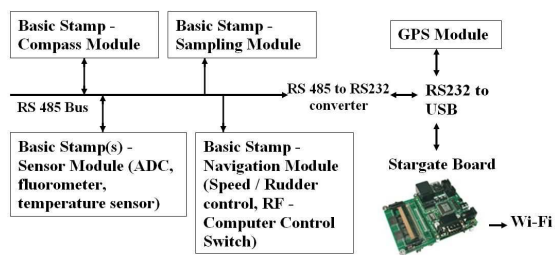


Fig. 4. Robotic boat architecture

A. Design

The prototype boat is a modified RC airboat (Fig. III)(air propeller minimizes disturbance to the water). All modules are connected to the main processor (the stargate board) via the RS-485 bus (Fig. 4). This makes it easy to plug in additional modules without affecting the existing modules. The boat is equipped with a GPS (Fig. 5 (a) Garmin 16A GPS) and compass (Fig. 5 (b) V2XE 2-axis digital compass from PNI Corp.) for navigation. The sensor suite on the boat consists of a thermistor and a fluorometer that are interfaced with the boat via the ADC board similar to the one on the static nodes. Communication with other nodes is based on EmStar over an 802.11b wireless connection. The boat is powered using rechargeable NiMH batteries which give it an approximate lifetime of 4-6 hours of continuous operation.

B. Operation

The stargate receives and processes the inputs from GPS, compass, sensors and the network and makes decisions and sends appropriate navigation commands to the navigation module. The basic stamp in the navigation module converts these into appropriate commands for the motor controllers which are connected to the rudder and the propeller. By

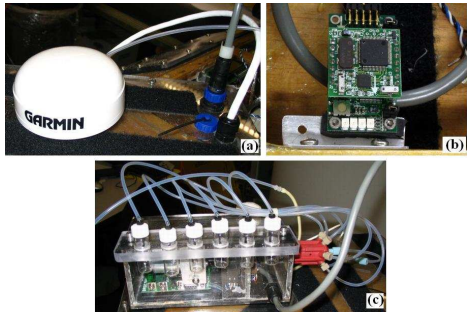


Fig. 5. Boat Components. (a) GPS; (b) Compass; (c) 6-port Water Sampler.

sending appropriate commands, the boat can navigate in both forward and reverse directions.

The robotic boat operates in three modes. In the radio controlled mode, the boat is controlled using RF control from the shore. In the computer controlled mode, appropriate control commands can be sent from the base station to the boat over the ad-hoc network. In the autonomous mode, the boat uses GPS way-point locations (set by a human user or the buoy network) and sensor information to compute control commands. Autonomous navigation over water is non-trivial since the boat is buffeted by wind and water currents. We use a PID controller to compensate for disturbances and to perform waypoint following.

The boat collects position and time stamped measurements of both temperature and fluorometry data, which are transmitted to the network for further analysis. It can also be programmed to collect water samples at designated GPS locations for further lab analysis. Sampling is performed using a custom developed 6-port (Fig. 5 (c)) sampling system controlled by a basic stamp module through a motor controller (a 36-port version is under development).

IV. INITIAL FIELD TESTS

Initial field tests were carried out at Shelter Island, NY to debug an early version of the boat control. We carried out two larger-scale field deployments of five static nodes and the robotic boat in Lake Fulmor, CA in May and July 2005. The static network was deployed for periods of 4 and 2 days respectively during which it continuously monitored and recorded temperature and fluorometry data while simultaneously providing real-time visualization (Fig. 6). The top picture demonstrates the chlorophyll-a distribution in the lake while the bottom picture demonstrates the temperature variation, which is shown in 3D. This information was then used by the boat to direct the sample collection. For a preliminary assessment of the significance of these data see [3].

The robotic boat successfully operated in conjunction with the static network performing autonomous GPS way-point navigation between the nodes collecting sensor data as it moved. Fig. 7 shows a typical path followed by the boat while going from one GPS way-point to another. It also performed autonomous water sample collection for lab analysis at the specified GPS locations.

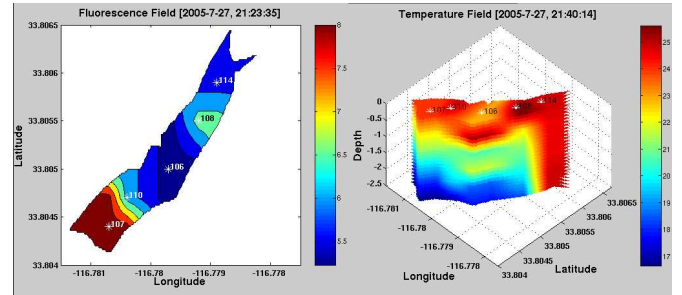


Fig. 6. Fluorometer and temperature data from May, 2005 NAMOS deployment in James Reserve (Node locations shown by *)

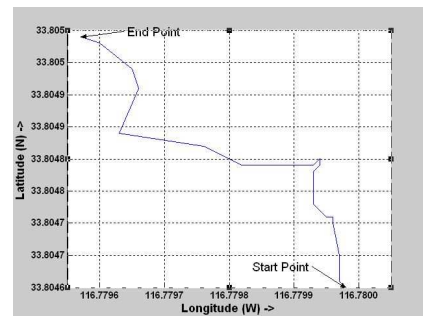


Fig. 7. Boat path - GPS way-point following

V. CONCLUSION

We demonstrated the design and use of a sensor-actuator network for an aquatic observing system. Ultimately such systems will be able to establish patterns in the sensed data, and use their mobility to adapt sample collection, a major step forward in the use of embedded networked sensing in aquatic ecosystems. The field work has demonstrated the basic functionality of the system. The data collected from the deployments revealed interesting spatio-temporal patterns of chlorophyll, and were useful to validate the design of the buoys and the boat. Deployments and experiments have been scheduled for the future, designed to further investigate microbial abundances. Ongoing work includes improving autonomous boat navigation, and improving the stability of the boat to withstand and compensate for stronger air and water currents. A significant portion of our future work is the design and testing of adaptive sampling algorithms allowing the buoys to guide the sampling process.

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