The Design and Development of a Wireless Robotic Networked Aquatic Microbial Observing System

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Abstract

This paper describes the design and development of a sensor-actuated network for aquatic monitoring. The network consists of ten stationary buoys and one mobile robotic boat for real-time, in-situ measurements and analysis of chemical and physical factors governing the abundances and dynamics of microorganisms at biologically-relevant spatiotemporal scales. The goal of the network is to obtain high-resolution information on the spatial and temporal distributions of plankton assemblages and concomitant environmental parameters 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.

Keywords: sensor-actuator network, aquatic microbial observing system, robotic sensor network

Introduction

Aquatic microorganisms (viruses, archaea, bacteria, microalgae, protozoa) play fundamental roles in the ecology and biogeochemistry of marine and freshwater ecosystems. Planktonic cyanobacteria and eukaryotic microalgae produce much of the organic matter that constitutes the base of the food webs in these ecosystems (Falkowski, 1994), while archaea, bacteria and heterotrophic protists (protozoa) consume or degrade much of this primary production via trophic interactions and decompositional processes (Cole et al., 1988; Sherr and Sherr, 2002). Collectively, microbial assemblages and their processes dominate the biogeochemical cycles of our planet (Karl, 2002, 2003).

On the other hand, microorganisms can cause ecological damage and present significant risks to human health. For example, blooms of harmful algae (e.g. red, brown and green tides) appear to be on the rise globally (Smayda, 1989), and presently result in the loss of $10Ms annually in the U.S. (Anderson et al., 2000). Similarly, contamination of drinking water supplies, beaches and other recreational waters with sewage and/or urban runoff causes economic loss and represents an increasing threat to human health (Pruss, 1998). Detection and characterization of these events is improving, but the time scales for responding to impending or emerging problems are still too long to avoid unfavorable and costly outcomes (Corso et al., 2003).

A primary scientific goal in aquatic science is to understand, predict and ultimately ameliorate the environmental conditions under which specific populations of aquatic microorganisms develop in nature, or identify the sources from which they originate (e.g. in the case of sewage entering aquatic ecosystems). In order to be useful, these measurements must be performed at fine spatial and temporal scales that are relevant to the organisms, their ecologies and the environmental setting. They must also be carried out in conjunction with approaches that can collect samples for later analyses of microbial presence and/or activity (or, ultimately, for on-board analyses). This level of presence in the ocean has not been possible using extant technology and methodological approaches. Only recently have large-scale networks been designed and implemented (Glenn et al. 2000). While these scales of measurement are appropriate for some addressing questions, these systems do not provide sufficient spatiotemporal coverage that will facilitate improvements in our fundamental knowledge of the factors controlling the distributions of planktonic microbes.

Sampling the environment with high resolution in real time using embedded sensor networks constitutes a revolutionary step forward in the study of the ecology of aquatic microbial species (Glasgow et al. 2004; Porter et al. 2005). Combined with a new generation of techniques to rapidly identify aquatic microorganisms (UMCES, 2005), such networks provide an extremely valuable tool for the early detection of organisms of human interest, and the mitigation of their effects on the environment and human population.

The goal of developing a predictive understanding of aquatic microorganismal distributions warrants a continuous (sensing) presence in the environment to enable real-time acquisition and analysis of chemical and physical data collected at relevant spatiotemporal scales, and correlated with measurements of specific microorganisms. However, at the scales required to attain this goal, it is infeasible to deploy a set of stationary monitoring stations that will provide sufficient spatial density and continuous monitoring. Conversely, deploying a fleet of mobile autonomous vehicles might provide adequate spatial coverage but insufficient temporal coverage. The concept of deploying a high-density, wireless network consisting of both stationary and mobile components to aid each other has been recently introduced (Batalin et al. 2005). Stationary buoys provide low-resolution spatial sampling with high temporal resolution while a mobile robotic boat provides high-resolution spatial sampling with relatively low temporal resolution. Collectively, we believe this network provides unprecedented coverage and thus unique insights into microbial plankton distributions and dynamics. Here we describe our prototype sensor-actuator network consisting of 10 buoys and a robotic boat, equipped with a collection of simple, off-the-shelf sensors (GPS, thermistors, fluorometers) that can be deployed in-situ to gather and analyze relevant data in an aquatic environment. We describe the design of the system and report on data collected from preliminary field trials.

System Description

The stationary nodes (buoys) continuously monitor the aquatic environment at the location at which they are deployed, and communicate the collected sensor information to the robotic boat, which is capable of autonomous navigation and sampling. We begin by giving an overview of the hardware constituents of the system.

A. Hardware

Each stationary node consists of a stargate board, an ADC board, a battery, a fluorometer 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 XScale 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. The present node configuration uses two types of sensors: fluorometers and thermistors. A fluorometer (Fig. 2 (a)) estimates the concentration of chlorophyll-*a*, which is indicative of the density of photosynthetic microorganisms in the environment. We use the CYCLOPS-7 submersible fluorometer for chlorophyll *a* 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)) have an accuracy of 0.1 degree Celsius. They are covered with a custom Titanium coating for corrosion resistance. The sensors are suspended from the buoy into the water. The fluorometer is lowered to a specified depth while the 6 thermistors are uniformly deployed from 0.15m to 2.65m 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 approximately a week. Preliminary measurements indicate that connecting the solar panel could potentially increase the lifetime to several weeks.

The robotic boat is a modified RC airboat (Fig. 3). An air propeller provides propulsion and minimizes disturbance to the water. All processing modules are connected to the main processor (the stargate board) via the RS-485 bus (Fig. 4). This allows integration of 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 stationary nodes. Communication with other nodes takes place via an 802.11b wireless connection. The boat is powered using rechargeable NiMH batteries, which at present give it an approximate lifetime of 4-6 hours of continuous operation.

B. Software Components and Algorithms

Our software system is built atop EmStar (Girod et al. 2004), 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 stationary nodes are configured to run in ad-hoc mode. A 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 that 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 stationary 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, 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 stationary nodes.

The boat is directed by information collected and processed within the network to identify features of biological interest. The stargate board on the boat receives and processes the inputs from GPS, compass, sensors and the network, 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 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 waypoint 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 wind and water currents affect the boat's heading and speed. Limited GPS availability and inaccuracies in sensor information (both GPS and compass) introduce further problem and are an area of ongoing research. We use a PID controller to compensate for disturbances and sensor errors while performing waypoint following. Based on the accuracy of the GPS, the system dynamically adjusts its error tolerances for waypoints resulting in reliable waypoint following in varying conditions. Figure 6 gives a high-level pseudocode description of the way-point navigation and control algorithms.

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 (3 ml) is performed using a custom-built 6-port sampling system (Fig. 5 (c)) controlled by a basic stamp module through a motor controller (a 36-port version is under development).

Experiments and Results

Initial field tests of the robotic boat were carried out at Shelter Island, NY during May 2004, and subsequently in Echo Park, Los Angeles, CA and Lake Fulmor, San Jacinto Mountains, CA. Three larger-scale field deployments of five or more stationary nodes and the boat were carried out in Lake Fulmor in May (4 days), July (2 days), and October (4 days) 2005. The stationary network continuously monitored and recorded temperature and fluorometric data while simultaneously providing real-time visualization of chlorophyll *a* and temperature across the surface of the lake (Fig. 7). The top sub-picture in each visualization depicts the chlorophyll-*a* distribution in the lake while the bottom picture shows the vertical and horizontal patterns of temperature. The latter are shown in 3D. The pattern of chlorophyll distribution was synthesized within the network, then transferred to the boat to direct sample collection.

In each of the Lake Fulmor deployments, relative chlorophyll concentrations varied spatially along the surface and temporally on daily cycles, apparently indicating a phytoplankton population that was actively migrating in the water column. For a preliminary assessment of the significance of these data see (Stauffer et al. 2005). The diel pattern in chlorophyll *a* observed at individual buoys was supported by temporal changes in the pattern of chlorophyll *a* across the lake (Fig. 7). A broad maximum in chlorophyll *a* concentration near the middle of the lake was present at 09:00 in May, 2005. The spatial extent of this peak in chlorophyll *a* concentration decreased in size by 12:00 although peak concentrations remained high at the center of the feature. Chlorophyll concentrations near the surface throughout the lake were greatly reduced by 15:00 and remained low at the 18:00. Chlorophyll concentrations during that time interval decreased by approximately an order of magnitude.

The daily pattern in water temperature in Lake Fulmor during May 2005 was featureless in the morning (09:00) both horizontally and vertically (Fig. 6(a), lower picture). The temperature at that time was relatively constant throughout the lake at approximately 12-14˚C. This pattern changed dramatically by 12:00, with substantial heating of water at the northeast end of the lake, but little change in the lower two-thirds of the lake. Maximum temperature at the northern edge of the lake approached 25˚C. Water enters the lake at the northeast end and passes through an adjacent marsh area before reaching the lake proper. Temperatures at 15:00 and 18:00 indicated a uniform warming of surface waters (approximate range of 14-16˚C) horizontally across the lake, possibly due to wind-driven spreading of warm waters from the northeast section of the lake. Water temperatures at the northeast end of the lake were substantially less than temperatures observed at 09:00.

The robotic boat successfully operated in conjunction with the stationary network performing autonomous GPS way-point navigation between the nodes collecting sensor data as it moved. Fig. 8 shows a typical path followed by the boat while moving from one GPS waypoint to another. The navigational capabilities of the robotic boat, coupled to the chlorophyll information collected from the network of stationary nodes, enabled the collection of water samples at pertinent biological features (e.g. chlorophyll maxima) for lab analysis.

Discussion

Deployments of the NAMOS system in Lake Fulmor, California, afforded a constant, in-situ presence which yielded information from several locations in the lake throughout the two- to four-day deployments. This level of observations enabled a ‘whole system’ approach to understand physical/chemical processes taking place in the lake, and thus useful information for developing hypotheses regarding ecosystem-level processes and an excellent setting for future experimental tests of those hypotheses. Although our network employed relatively simple ‘off the shelf’ sensor technology, the incorporation of more sophisticated or more specialized sensors will provide a rich data environment for detecting and characterizing features and processes of interest.

Equally important, the presence of the wireless network allowed the utilization of spatial information collected and synthesized from the stationary nodes to guide the boat to locations which best optimized sampling effort. The ability to collect samples from aquatic ecosystems presently surpasses the capacity to process samples for most biologically meaningful parameters. Therefore, use of the sensor network to optimize the sampling effort of a mobile sampling robot constitutes a significant improvement in cost efficiency and labor allocation to identify and sample features of biological interest.

The addition of solar panels to recharge batteries should increase the duration of deployments to several weeks, thereby producing longer-term data on the temporal distribution of phytoplankton in the lake. In addition, the cooperative function of the autonomous boat with the stationary network allows for more specific interrogations of the environment and the collection of samples which are essential to the characterization of phytoplankton populations. In the three Lake Fulmor deployments described in this paper, for example, different species were found to be dominant in samples collected by the autonomous boat. A mixed microalgal assemblage was wide-spread in May, while samples collected in July were heavily dominated by the cyanobacterium *Spirulina sp.*, and a diverse cyanobacterial community was present in October.

Summary

We describe herein the design and use of a sensor-actuator network for an aquatic observing system. We have designed a network to establish patterns in sensed data, and use that information to guide a mobile boat and recover samples at features of interest (as determined by the pattern generated by the network. Our fieldwork demonstrates the basic functionality of the system, which constitutes a major step forward in the use of embedded networked sensing in aquatic ecosystems. The data collected from the deployments revealed interesting spatio-temporal patterns of chlorophyll and temperature, 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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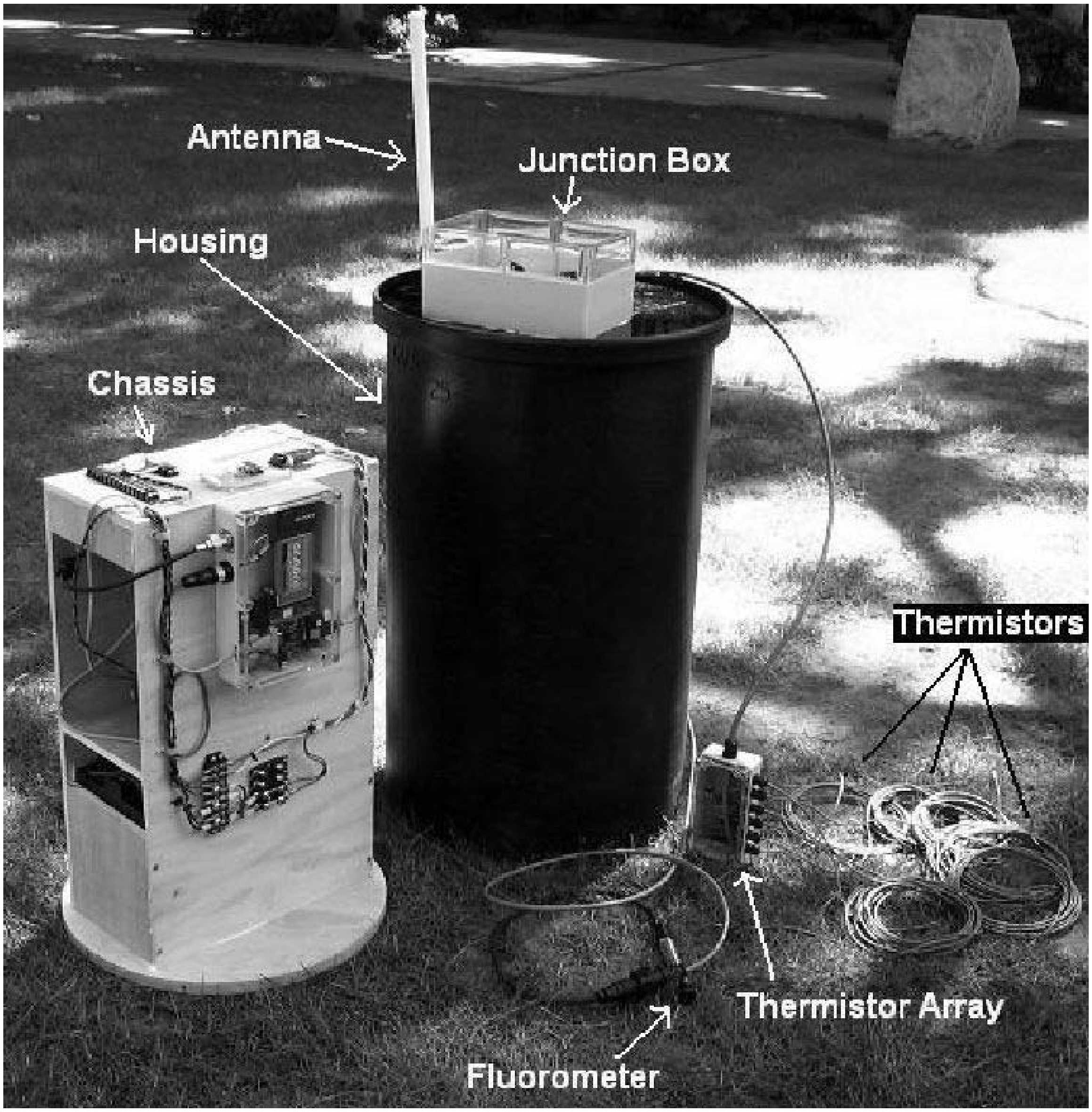


Fig. 1: The hardware configuration of a stationary buoy node. A wooden chassis holds the computer and interface boards, and is mounted within a waterproof housing.

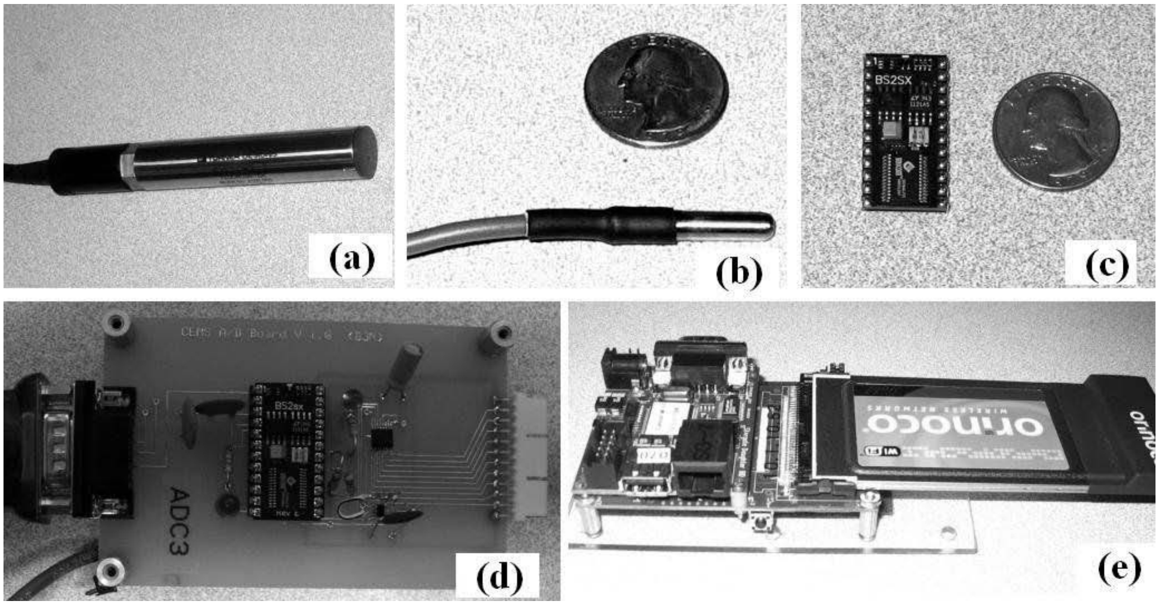


Fig. 2: Sensing, communication, and processing hardware on each buoy and the robotic boat. (a) Fluorometer; (b) Thermistor; (c) Basic Stamp; (d) ADC Board; (e) Stargate Board.

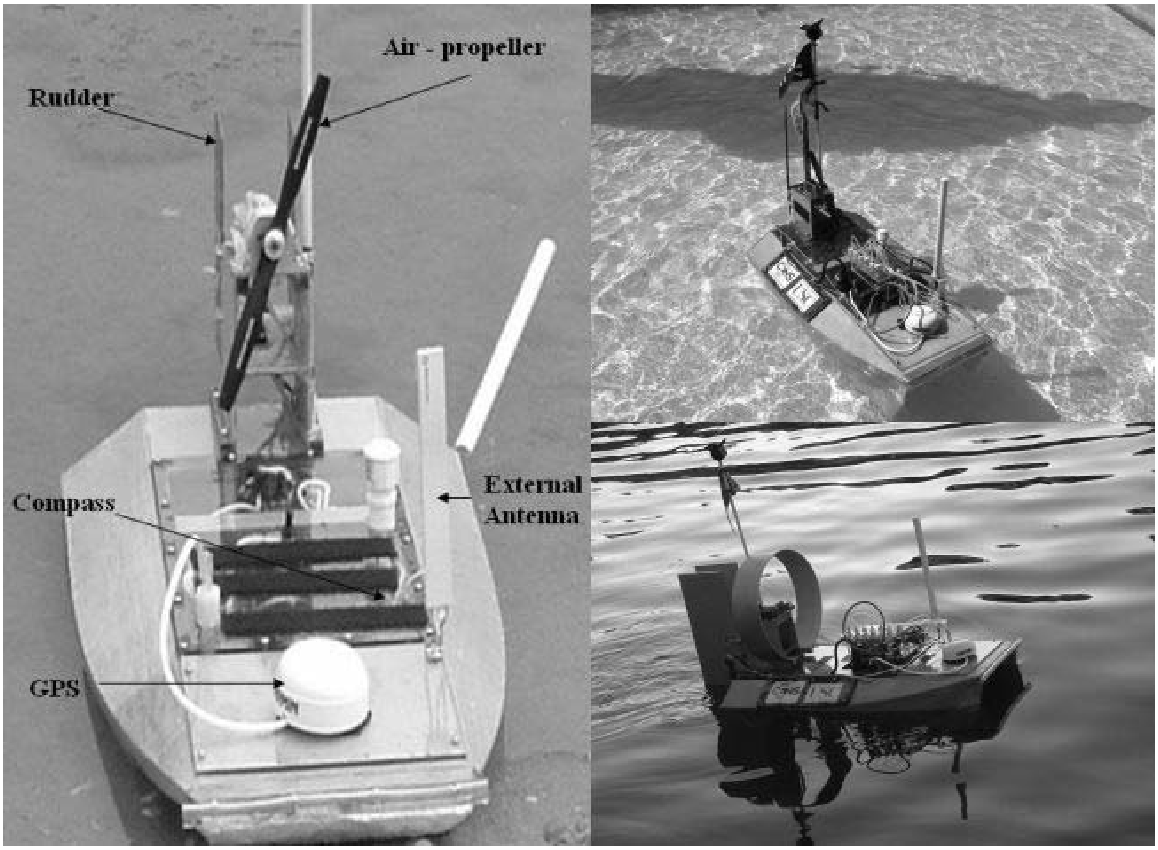


Fig. 3: External views of the robotic boat.

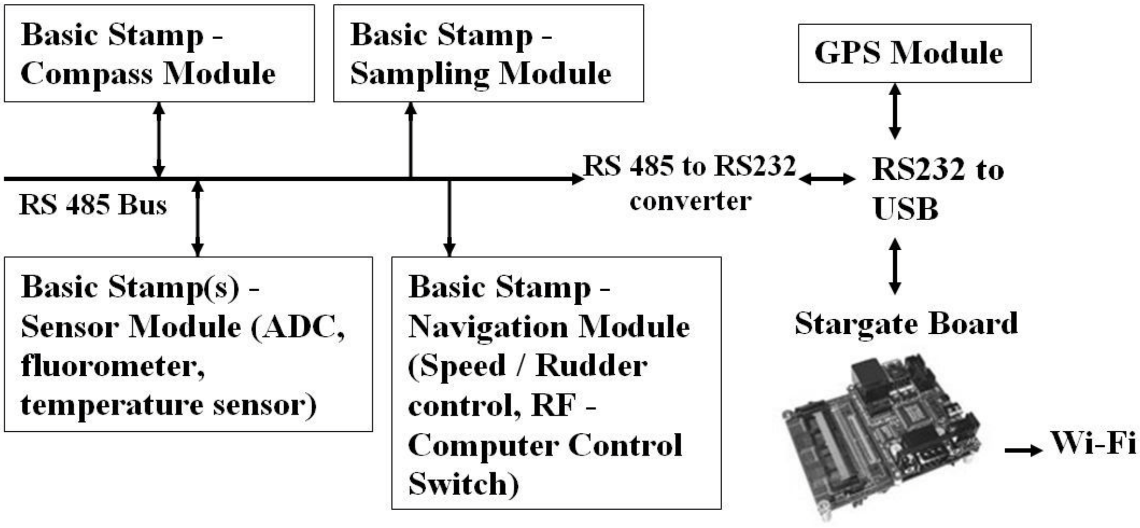


Fig. 4: Overall system architecture of the robotic boat.

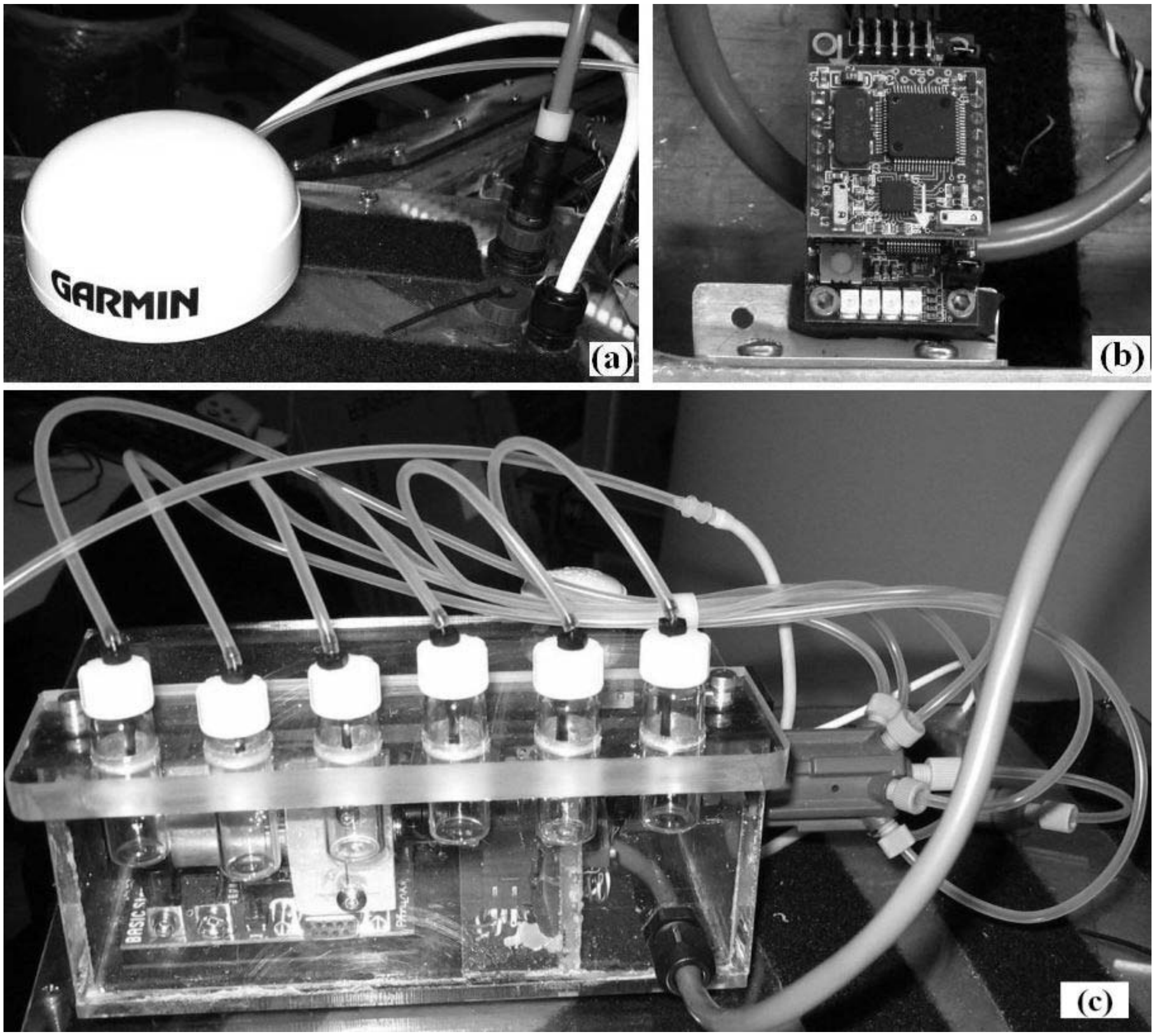
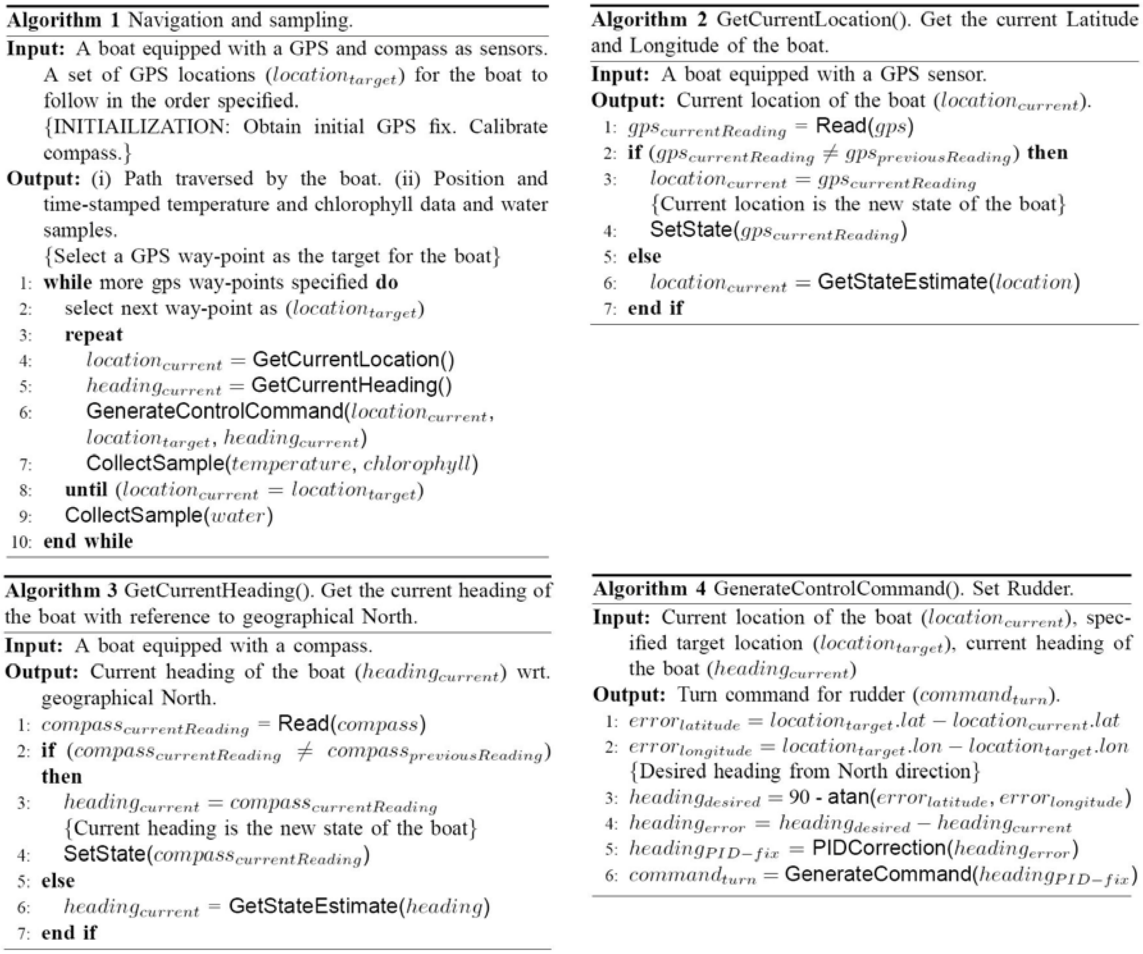


Fig. 5: Sensing and sampling on the boat. (a) GPS; (b) Compass; (c) 6-Port custom water sampler.



Algorithm 1 Navigation and sampling.

```
Input: A boat equipped with a GPS and compass as sensors.
    A set of GPS locations ($location_{target}$) for the boat to follow in the order specified.
    {INITIAILIZATION: Obtain initial GPS fix. Calibrate compass.}
Output: (i) Path traversed by the boat. (ii) Position and time-stamped temperature and chlorophyll data and water samples.
    {Select a GPS way-point as the target for the boat}
while more gps way-points specified do
    select next way-point as ($location_{target}$)
    repeat
        $location_{current}$ = GetCurrentLocation()
        $heading_{current}$ = GetCurrentHeading()
        GenerateControlCommand($location_{current}$, $location_{target}$, $heading_{current}$)
        CollectSample($temperature$, $chlorophyll$)
    until ($location_{current} = location_{target}$)
    CollectSample($water$)
end while
```

Algorithm 2 GetCurrentLocation(). Get the current Latitude and Longitude of the boat.

```
Input: A boat equipped with a GPS sensor.
Output: Current location of the boat ($location_{current}$).
$gps_{currentReading}$ = Read($gps$)
if ($gps_{currentReading} \neq gps_{previousReading}$) then
    $location_{current} = gps_{currentReading}$
    {Current location is the new state of the boat}
    SetState($gps_{currentReading}$)
else
    $location_{current}$ = GetStateEstimate($location$)
end if
```

Algorithm 3 GetCurrentHeading(). Get the current heading of the boat with reference to geographical North.

```
Input: A boat equipped with a compass.
Output: Current heading of the boat ($heading_{current}$) wrt. geographical North.
$compass_{currentReading}$ = Read($compass$)
if ($compass_{currentReading} \neq compass_{previousReading}$) then
    $heading_{current} = compass_{currentReading}$
    {Current heading is the new state of the boat}
    SetState($compass_{currentReading}$)
else
    $heading_{current}$ = GetStateEstimate($heading$)
end if
```

Algorithm 4 GenerateControlCommand(). Set Rudder.

```
Input: Current location of the boat ($location_{current}$), specified target location ($location_{target}$), current heading of the boat ($heading_{current}$)
Output: Turn command for rudder ($command_{turn}$).
$error_{latitude} = location_{target}.lat - location_{current}.lat$
$error_{longitude} = location_{target}.lon - location_{target}.lon$
{Desired heading from North direction}
$heading_{desired}$ = 90 - atan($error_{latitude}$, $error_{longitude}$)
$heading_{error} = heading_{desired} - heading_{current}$
$heading_{PID-fix}$ = PIDCorrection($heading_{error}$)
$command_{turn}$ = GenerateCommand($heading_{PID-fix}$)
```

Fig. 6: Algorithm 1 is the main loop for navigation and sampling which makes calls to Algorithms 2 (location tracking), 3 (heading tracking), and 4 (rudder control).

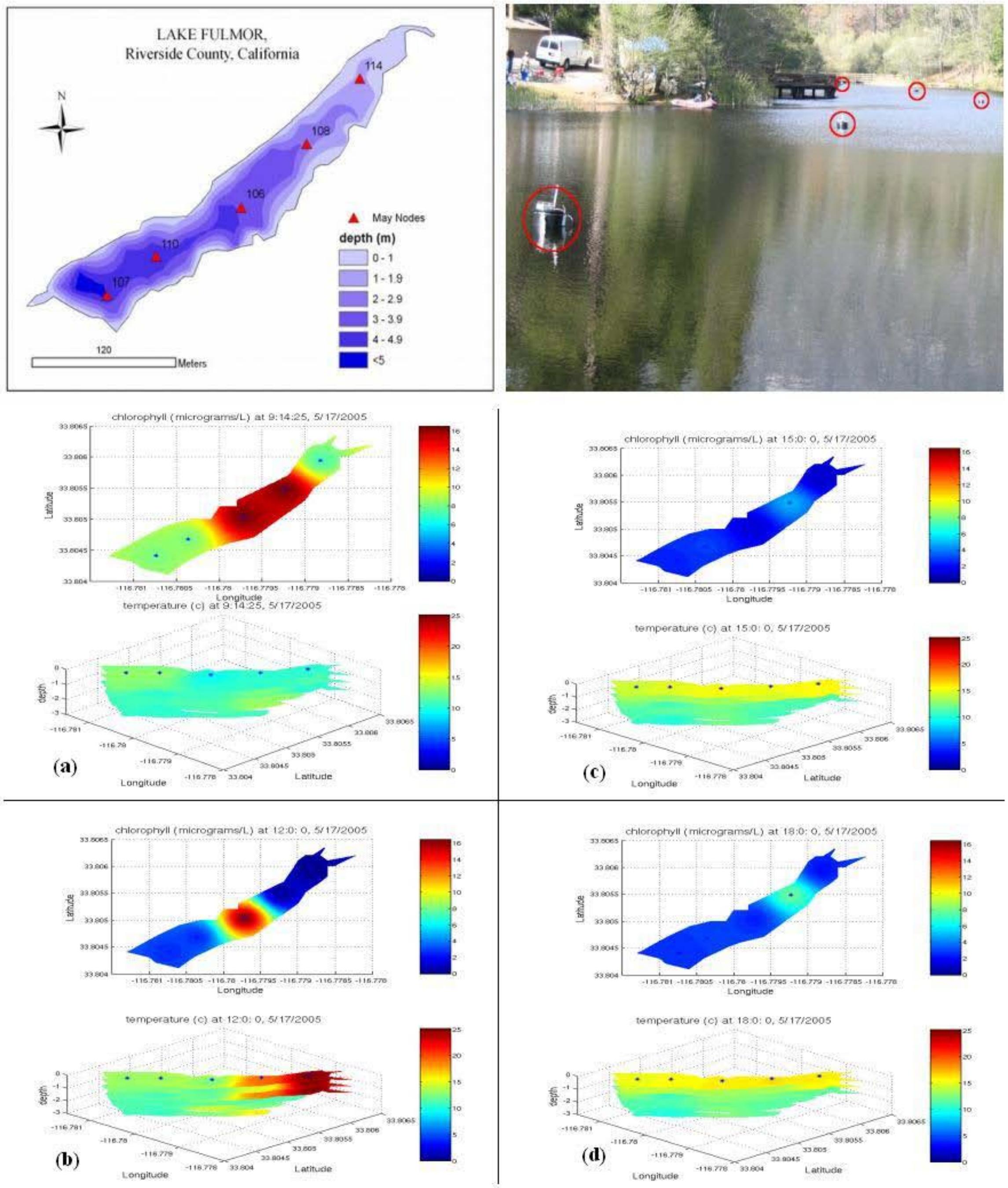


Fig. 7: Fluorometric and temperature data from May 17, 2005 NAMOS deployment in Lake Fulmor. Top left: Lake bathymetry with node locations indicated by triangles. Top right: Photograph of the lake showing stationary nodes; circles). Patterns of chlorophyll (upper figure) and temperature (lower figure) downloaded from the stationary sensor network at (a) ~9am, (b) ~12pm, (c) ~3pm and (d) ~6pm.

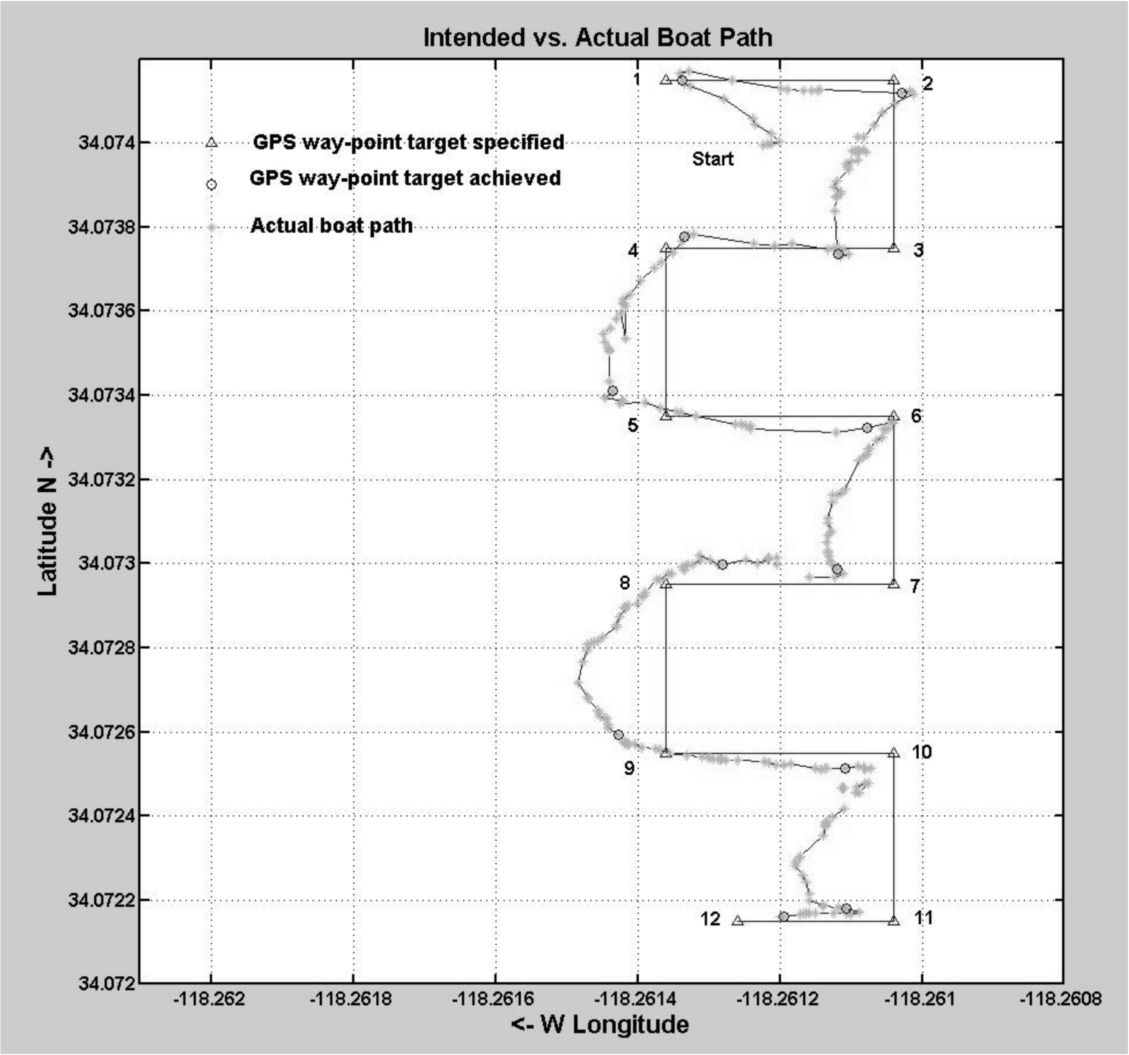


Fig. 8: A radiator pattern navigation trace for the boat operating in autonomous waypoint-following mode.