USC CINAPS Builds Bridges

Observing and Monitoring the Southern California Bight

More than 70% of our earth is covered by water, yet we have explored less than 5% of the aquatic environment. Aquatic robots, such as autonomous underwater vehicles (AUVs), and their supporting infrastructure play a major role in the collection of oceanographic data (e.g., [11], [17], and [29]). To make new discoveries and improve our overall understanding of the ocean, scientists must make use of these platforms by implementing effective monitoring and sampling techniques to study ocean upwelling, tidal mixing, and other ocean processes. Effective observation and continual monitoring of a dynamic system as complex as the ocean cannot be done with one instrument in a fixed location. A more practical approach is to deploy a collection of static and mobile sensors, where the information gleaned from the acquired data is distributed across the network. Additionally, orchestrating a multisensor, long-term deployment with a high volume of distributed data involves a robust, rapid, and cost-effective communication network. Connecting all of these components, which form an aquatic robotic system, in synchronous operation can greatly assist the scientists in improving our overall understanding of the complex ocean environment.

The Center for Integrated Networked Aquatic PlatformS [CINAPS (pronounced as sin-aps)] is located at the University of Southern California (USC). The goal of CINAPS is to bridge the gap between technology, communication, and the scientific exploration of local and regional aquatic ecosystems. Specifically, CINAPS is focused on providing timely dissemination of information related to harmful algal blooms (HABs) and general water quality to scientists, policy makers, and the general public. To accomplish this task, the CINAPS team has designed and deployed an embedded sensor network to monitor and observe the coastal regions of Southern California. In this article, we present the recent developments of an aquatic robotic system, with the goal of providing a reliable and cost-effective data transfer framework that forms a bridge between each of the pieces of coastal observing system, allowing for optimization of sensing and sampling strategies, and to provide information about the performance of the system as a whole. CINAPS attains this broad goal by

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bringing together the resources of experts in robotics and computer science [Robotic Embedded Systems Laboratory (RESL); http://robotics.usc.edu/resl/], applied oceanography (usCLAB; http://usclab.usc.edu/), and phytoplankton ecology (Caron Lab; http://www.usc.edu/dept/LAS/biosci/Caron_lab/index.html). This highly collaborative group combines diverse expertise to work toward the common goal of tackling some of the difficult problems facing aquatic ecosystems today. Although this article focuses on the CINAPS buildout and recent experiments with aquatic robots, this collaboration extends beyond USC to a network of partners, as we aspire to wholly integrate the public into our understanding of Southern California's complex coastal ecosystem. To this end, CINAPS maintains a Web site (http://cinaps.usc.edu/) for the presentation of acquired data as well as background information on the center, the collaborations on which it is built, and technical information about our ongoing projects.

Robotic Sensor Networks

Robotic sensor networks [15] are networks in which some or all nodes can move either under their own control (autonomous or robotic mobility) or under the control of other agents in the environment (teleoperated or human-portable nodes). These systems combine advanced concepts in perception, communication, and control to create computational systems capable of interacting in meaningful ways with the physical environment, thus extending the individual capabilities of each network component and network user to encompass a much wider area and range of data.

Several challenges exist in the design of a static sensor network. Examples include deployment, energy management, routing, to name a few. Approaches to solve some of these problems, while not comprehensive, are starting to become available [5], [6], [9], [10], [12], [13]. However, naively, using these solutions for robotic sensor networks is usually ineffective. In some cases, mobility may exacerbate what is usually a fairly difficult problem to begin with (e.g., routing). In other cases, however (e.g., data dissemination), mobility may be leveraged in interesting ways to solve the problem.

Robotic sensor networks have several advantages over static networks. First, the ability to move allows them to support multiple modalities of sensing and spatiotemporally focusing sensor attention according to the task and environment. The network could change sensing modalities and density according to sensory feedback. Second, such systems can autonomously self-organize to best match the network topology [20] required by the application and to adapt to the environment. Third, these networks are fault tolerant. The network can use redundancy in its nodes, coupled with adaptive control algorithms, to extend its lifetime. Fourth, these networks can function as distributed information repositories for the task and the environment. Fifth, and finally, these types of networks can support seamless failure and addition of new nodes, and constitute long-lived systems whose functionality can be changed incrementally, without taking the entire system down.

The CINAPS system is heterogeneous. It is composed of two different kinds of underwater and surface vehicles as well as ground stations and static floating buoys. The overarching objective of CINAPS is to build an aquatic observing system for the purpose of measuring physical (e.g., temperature, pressure, seismic activity, ocean currents) and chemical (e.g., salinity, nitrate levels, contaminant concentration) phenomena and biological processes (e.g., algal growth and mortality), leading to technical innovations in algorithms and systems for networked robotics, new scientific discoveries, and useful information regarding the human impact on the environment and its mitigation via effective and timely public policy.

CINAPS is focused on the tools and algorithms to design and understand large-scale, distributed, networked robotic systems with a particular focus on the aquatic environment. A key issue in networked robotics is to understand how coordinated behavior arises from an aggregate of individual robotic elements, where each robot is constrained in the fidelity and accuracy of its sensors and actuators, has limited communication range, and a finite energy reservoir. CINAPS develops this understanding by designing efficient, robust algorithms for networked multirobot coordination and state estimation that cope with these constraints. We have focused on two major areas: communication-constrained, multirobot coordination algorithms (see the subsections of "Algorithm and Software Development") and perception, estimation, and control multirobot algorithms.

As a whole, the CINAPS network provides a small area of coverage in a larger global ocean observation initiative. Global ocean monitoring is vital to the future of mankind, as the ocean is a vast resource that provides transportation and food, as well as regulates the earth's climate. Rising sea temperatures, overfishing, and pollution pose threats that need to be constantly measured and monitored. An integrated ocean observation system could provide early warning of storms (e.g., hurricanes and tsunamis), safer maritime operations and conservation of fish stocks, as well as a collection of the vital signs of the ocean needed to monitor and assess long-term climate change. Starting in 2008, the National Science Foundation proposed to spend US$309.5 million over six years to build an integrated ocean observatory network; an additional US$240 million will be spent on maintenance and operations [30]. This project will be managed by the scientist-led Ocean Research Interactive Observatory Network (ORION), which will contract with oceanographic institutions and companies to build the separate pieces. As this project is in the initial stages, it is currently up to the individual institutions to raise money and construct regional observing systems, e.g., the CINAPS network. As more centers are constructed, we can integrate our center into a larger ocean observing network, aggregate our collected data, and contribute to the assessment of the world's oceans. Currently, we are in collaboration with MBARI as well as the California Coastal Ocean Observing System (CCOOS), which contains the Northern, Central, and Southern (NCOOS, CenCOOS and SCCOOS, respectively) regional components.

Oceanography Background

The primary region of interest of the CINAPS team's research is a coastal region referred to as the Southern California Bight (SCB). The SCB is the coastal ocean region contained within 32° N to 34.5° N and –117° E to –121° E. The SCB is a densely populated (∼20 million inhabitants), highly urbanized coastal region, representing approximately 25% of the nation's coastal population. This area of Southern California represents a critical locale to assess how changes driven by urbanization and climate impact the physical and biological state of the coastal region. Given the ecological and socioeconomic importance of coastal regions [27], it is important to be able to accurately assess, and ultimately predict, these changes.

Anthropogenic impacts on both terrestrial and marine ecosystems are associated with the rapid rate of urbanization and the accompanying changes in land use and land cover. For example, nearly 90% of the coastal wetlands in Southern California have been lost. Watersheds draining into these wetlands have likewise been altered, with a significant observed increase in impervious surfaces. These changes in land cover and land use impact both the quantity of freshwater runoff and its particulate and solute loadings (nutrients, sediments, pollutants, pathogens, etc.). These changes and their impact on the physical, biogeochemical, biological, and ecological conditions of the coastal ocean remain largely unknown [28].

Superimposed on these regional anthropogenic disturbances are poorly described coastal fluctuations driven by climate variability [14]. Southern California experiences significant decadal and internannual variability associated with the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) [7]. These climatic phenomena impact the frequency and intensity of the regional episodic storm events and greatly control the physical and biogeochemical dynamics of the coastal marine ecosystem.

Based upon the complex ocean dynamics and the many factors affecting the variability of the SCB, we focus our research efforts in answering the following open questions about the region.

- What are the effects of anthropogenic inputs on the coastal processes in the ocean? This includes issues of (harmful) plankton blooms.
- Can we distinguish between anthropogenically affected processes and natural variations and effects?
- What are the effects of major climate change issues facing the Southern California coastal ocean, including but not limited to ocean warming, ocean oxygen, and acidification issues and sea level rise?
- What is the region's biogeochemistry and what are the fluxes of carbon and nitrogen associated with the coastal margin of Southern California?
- What is the optimal placement and sampling regimen necessary for the evaluation and monitoring of the long-term prosperity of marine-protected areas?

Ultimately, it is the goal of the CINAPS team to understand the processes that occur in the SCB, how these processes are affected by climate variability and change, the role of coastal urbanization, and how we can best preserve the marine resources presently available. Such a task requires the orchestration of many expert scientists, available technology, and local government. By deploying multiple sensor platforms connected with a reliable communication infrastructure, we present a module to facilitate this collaboration in the observation and monitoring of the intriguing coastal ecosystem of the SCB.

Deployed Marine Robotic Systems

In 2005, a red tide (commonly used name for an algal bloom) resulted in a massive fish kill in King Harbor Marina, City of Redondo Beach, California. This event created a major nuisance for commercial and recreational use of the harbor for several weeks [16]. In response to this event, a monitoring program was developed for King Harbor and the neighboring coastal region (i.e., SCB) to help predict and avoid future toxic blooms [4]. The CINAPS team is a major contributor to this effort.

The components of the CINAPS network are selected to address specific scientific questions related to regional issues in the SCB. Each posed question defines associated sampling region(s), which are outfitted with the necessary equipment and instrumentation to acquire the appropriate data. By design, the deployed platforms can be outfitted with a variety of sensors that specialize in measuring variables such as temperature, salinity, depth, optical properties, surface and subsurface currents, chlorophyll fluorescence, dissolved oxygen, turbidity, to name a few. The collected data are then transmitted via a communication network to a central storage location at USC for detailed analysis and dissemination. Next, we present the hardware and software implementations currently employed within the CINAPS network.

Robots, Platforms, and Hardware

CINAPS utilizes a combination of commercial-off-the-shelf (COTS) hardware, complete internal fabrications, as well as slightly to fully modified COTS components to comprise the sensor nodes that make up the embedded sensor network throughout the SCB. These are some of the major sensor platforms available for deployment or currently in use.

Static Buoys

Static sensor nodes in the CINAPS network are marina buoys and coastal moorings, as seen in Figure 1(a) and (b), respectively. The marina buoys are assembled by the CINAPS team, and are currently deployed in King Harbor Marina, with future installations planned for Huntington Beach, Marina del Rey, and Newport Beach marinas. Two coastal moorings, products of AXYS Technologies, are located off of Redondo Beach and El Segundo in approximately 50 m of water.

Each marina buoy consists of a Gumstix Verdex computer (Intel 400 MHz PXA270 CPU), analog-to-digital converter board, battery, fluorometer, and an array of six thermistors, all of which are mounted on a wooden chassis and sealed in a waterproof housing. These static nodes are also capable of accommodating two water quality instruments (e.g., Hydrolab MS5 and DS5 Sondes). The fluorometer we use measures the concentration of chlorophyll a, which is indicative of the density of certain photosynthetic microorganisms in the environment (i.e., toxin-producing species). The six thermistors measure the water temperature accurately to 0.1° C at uniform depths ranging from 0.5 to 2.5 m. The sensor data are stored locally on the node and transmitted wirelessly to USC. Each buoy is powered by a standard, 12-V car battery that is recharged by an external solar panel (solar backed). The buoy is configured to operate for up to one week on a single battery charge.

The coastal moorings are in place to continuously monitor physical and biological properties of the SCB coastal waters. The solar-backed, battery-powered moorings are outfitted with sensors that measure temperature, salinity, dissolved oxygen, oxygen saturation, chlorophyll fluorescence, and turbidity at depths of 1 and 13 m. These are a ruggedized version of the marina buoys and are fabricated to handle harsh, open-ocean conditions.

High-Frequency Radar and Communication Installations

Environmental variability of the coastal ocean is partially determined by the wind and surface currents in the local area. To assess these factors, we employ four Ocean Sensors Coastal Ocean Dynamics Applications Radar (CODAR) High Frequency Radar (HFR) sites located at Malibu Beach, Dockweiler Beach, Point Fermin, and Santa Catalina Island. Two additional sites are planned for HFR installation: Torrance Beach and Newport Beach. Each site operates at a frequency of 25 MHz, which gives a radial coverage area of approximately 40 km. The installation located on Catalina Island operates at 12 MHz and provides a radial coverage area of approximately 70 km. The spatial resolution of the acquired data is 1 km. These radar systems measure ocean surface currents (restricted to the upper 0.5 m) using continuously transmitted/received radio waves. Each site produces a radial estimation of the currents in the SCB, which is then combined with the overlapping data from the other sites to produce a current vector map for the entire area. Each site is networked, and the data are updated hourly. Collected data are also transmitted to the Jet Propulsion Laboratory, California Institute of Technology, for assimilation into their regional ocean modeling system for the SCB.

To facilitate low-cost, high-bandwidth communication throughout the SCB, we have installed Freewave radio modem base stations at each of the HFR sites. The base station hardware consists of a Freewave 900 MHz FGR-series modem, antenna, and an Internet-connected computer (Intel Atom CPU-running Linux). Generally, large-scale marine sensor networks rely upon satellite communication because of the reliability and global coverage. However, satellite communication experiences low bandwidth and can be very expensive. Since our main region of interest is a coastal environment, we are able to take advantage of technologies not feasible in open-ocean research. Specific details and network coverage are presented in [19] and [25].

Autonomous Underwater Vehicles

One example of a slightly modified, commercially available, mobile sensor platform used in this study is a Webb Slocum autonomous underwater glider, as seen in Figure 1(c). The CINAPS team owns and maintains two of these vehicles. A Slocum glider is a 1.5 m (length) by 21.3 cm (diameter), 52 kg, torpedo-shaped vehicle. Autonomous gliders are driven entirely by a variable buoyancy system instead of a propeller. This integrated instrument platform is designed to operate in coastal and open-ocean scenarios by adjusting its volume-to-weight ratio. Wings and control surfaces convert the vertical motion, resulting from an alteration in buoyancy, into forward velocity. Inflection points occur at depths and altitudes set by the mission planner. A typical glider trajectory is a sequence of dives and climbs that form a vertical sawtooth pattern. This combination of horizontal and vertical movement through the water column is an optimal way to generate high-resolution spatial and temporal data with minimal energy expense [21]. Powered only by 300 alkaline, C-cell batteries, the Slocum glider can be deployed for 30 days at a range of 1,500 km. It travels at an average speed of 0.4 m/s and can reach depths of 200 m.

Because of their endurance and robustness, Slocum gliders do not require a surface mother ship and provide round-the-clock

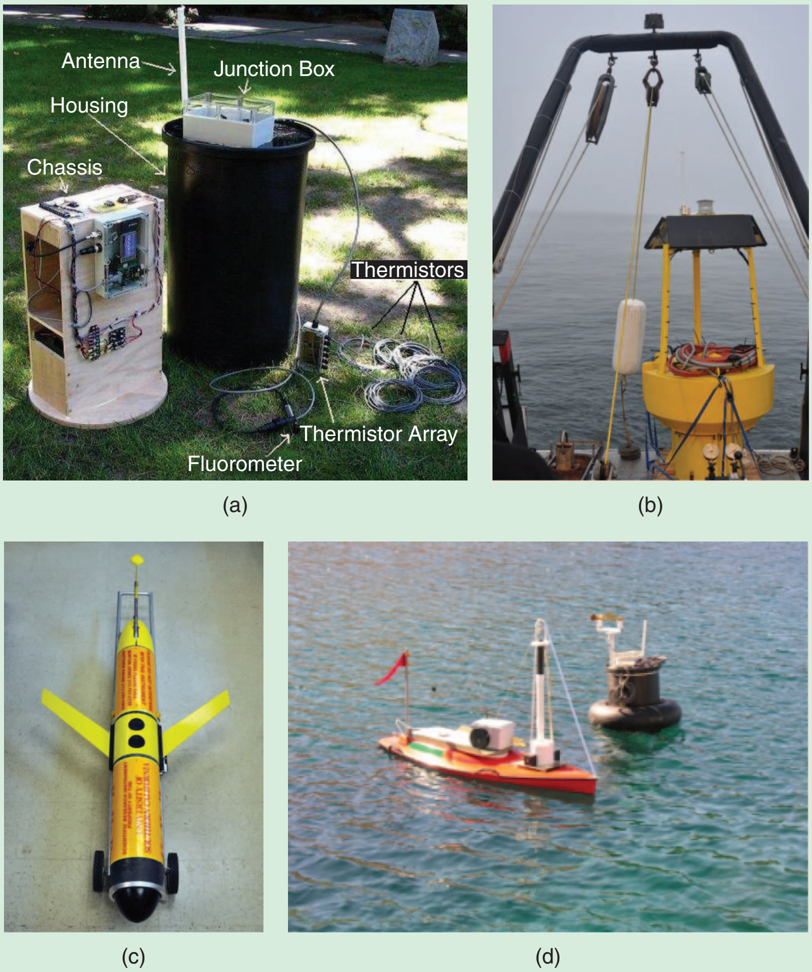

Figure 1. *Deployed marine sensors. (a) Marina buoy components, (b) coastal mooring, (c) Webb Slocum autonomous glider, and (d) ASV and deployed marina buoy.*

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data collection without constant human supervision or intervention. Subsurface navigation is performed by use of a magnetic compass, altimeter, and internal dead reckoning. While underway, the vehicle periodically surfaces, as specified by a user-defined mission, to obtain a global positioning system (GPS) fix for localization and data transfer. Communication capabilities onboard the vehicle consist of a two-way RF modem, an iridium satellite modem, and an emergency ARGOS locator. We have upgraded the communication capabilities of our gliders to make them a node in our network [19], [25]. The standard sensor suite consists of a Seabird conductivity, temperature, and depth (CTD) sensor. Additions to the standard sensor package include a Wetlabs three-channel fluorometer and three-channel backscattering sensor to analyze chlorophyll, colored dissolved organic matter (CDOM), and rhodamine.

Autonomous Surface Vehicles

Autonomous surface vehicles (ASVs), based on the Q-Boat-I from OceanScience, represent an example of a sensor platform whose internal components are designed and assembled in-house. The commercially produced hull (2.1 m long with a maximum beam of 1.2 m) is designed to be a radio-controlled, surface craft. The vehicle is actuated by electric motors driving two propellers and a rear rudder for attitude control at high speeds. The CINAPS team owns and operates two Q-Boats, one of which can be seen in operation near a harbor buoy in Figure 1(d).

Autonomy was added to the vessels by incorporating an x86-based Linux computer, 802.11 g wireless capabilities, and navigation sensors (i.e., three-axis gyrocompass, three-axis accelerometer, and a GPS). Each surface craft is monitored and supervised via a PC-based front end, equipped with tools to create new missions, display data from the vehicle, or remotely operate the vehicle. The ASVs are a portable, mobile platform that can be equipped with different instrumentation based upon the monitoring needs. For example, in some missions, the ASVs are equipped with sonar and/or stereovision systems to perform bathymetric surveys and reactive obstacle avoidance. Additionally, each craft is equipped with a winch system to control the deployment of aquatic sensors. This feature enables three-dimensional (3-D) sampling capabilities. Navigation and guidance software were developed in-house. Examples such as adaptive sampling and multivehicle coordination are discussed in the subsections of "Algorithm and Software Development."

Figure 2. Locations of pier-side sampling within the King Harbor Marina identified by green dots. The location of a Freewave base station is given by an orange dot. Image created by use of Google Earth.

Pier and Marina Sampling

The aforementioned mobile and moored, large-scale sensing platforms provide information on the broad vertical and horizontal distributions of chemistry and physics. It is also vital to monitor these parameters and the resulting biological responses at small scales. In general, large-scale patterns are a result of processes taking place at the organismal level. To characterize short-term, temporal and spatial variability within King Harbor, we employ six Hydrolab water-quality sondes, deployed at three locations within the harbor (see Figure 2). Each site consists of two instruments located at depths of 0.5 m and 0.5 m above the sea floor (3–4 m depth). These sensors continually acquire depth, temperature, turbidity, dissolved oxygen, chlorophyll a fluorescence, and conductivity measurements; up-to-date time-series plots can be found at http://cinaps.usc.edu/sites_data.html.

Weekly, water samples collected from the harbor have provided a two-year, continuous time series of algal species and community composition within the harbor. This information and ancillary chemical/physical data collected by the sensor platforms are used to plan and conduct experimental studies to measure rates of population growth and mortality of important harmful algal species. In addition, high-resolution temporal (every few hours for two-day periods) and spatial (0.5–1 m depth intervals) observations provide information regarding examined algal dynamics as a consequence of tidal mixing and vertical migratory behavior of the algae. Discrete water samples are also analyzed for major nutrients (e.g., phosphate, nitrate, ammonia) and specific algal toxins to examine relationships between these factors, algal community composition, and chemical and physical parameters measured using the CINAPS network.

Algorithm and Software Development

Placing and operating multiple sensors in the field to collect data is only a portion of the robotic system necessary to produce products and information that can be used for management, decision making, and policy development by local, regional, state, and federal agencies. Some major, but physically invisible, components are the software and algorithms that are responsible for actions such as data routing, vehicle control, data acquisition optimization, data analysis, and presentation of results. As in "Robots, Platforms, and Hardware" section, CINAPS uses a combination of COTS software and internally designed algorithms to create the infrastructure necessary to orchestrate a multiplatform, dynamic data acquisition deployment. In this section, we present some of the software tools and algorithms employed by the CINAPS system.

Sampling Based on Scalar Field Estimation

In general, optimal path planning for mobile sensors depends heavily on the estimation or a priori knowledge of the region and parameter to be sampled. Model-based estimation (and hence optimal sampling design based on linear or nonlinear models) has been well studied [22]. In the environmental monitoring context, a prior model is normally unknown, and it might even be the goal of the project to develop or learn a model from the data collected by the sensors. Therefore, nonparametric estimation is appropriate. In recent work [31], CINAPS members present an adaptive sampling algorithm based on local linear regression, which is guaranteed to be optimal in the sense of minimizing the integrated mean square error (IMSE) of the field reconstruction. The energy consumption model depends on the dynamics of the mobile sensor platform. The adaptive sampling algorithm does not depend on the energy consumption model; however, this is considered in the generation of the optimal paths. Tests of the algorithm were performed on robotic boats executing optimal trajectories (exceeding an aggregate of 3 km in length) operating with data collected from the harbor buoys. Initial experiments ignored temporal variability of the field, however, this component is an area of active research.

Station-Keeping Algorithm

Vertical profiling from an ASV (as presented in "Autonomous Surface Vehicles" subsection) with a sensor attached to a winch system requires the vehicle to remain at a particular location for up to 5 min. Local winds and surface currents make it impossible to stay on station for long durations without external corrective action. For such sampling missions, we have developed a station-keeping algorithm to prevent the ASV from realizing large displacements during sampling. The algorithm consists of a controller that stabilizes the ASV by use of a combination of line-of-sight measurements and alignment with the external disturbances. For this application, local winds are the primary reason the vehicle will drift off station. By aligning itself in the direction of the oncoming wind, the underactuated craft can take advantage of its available controls to maintain position. Field experiments have shown that the designed controller can maintain the position of the ASV to within 2 m of the desired location under moderate wind conditions (2.5 m/s). Complete details of the algorithm and its implementation can be found in [18].

Model-Based Retasking Algorithm

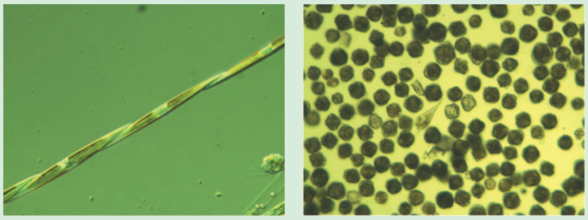
One long-term goal is to enable real-time, optimal trajectory design based on predictions from a regional ocean model for the use of tracking dynamically evolving ocean features (e.g., HAB, fresh water plume, and eddy). A milestone on the path to this goal is the iterative algorithm OPTA-BLOOM-Pred [26], which generates trajectories for a mobile sensor platforms based on the predicted movement of a feature of scientific interest, while continually assimilating collected data into the ocean model to increase the accuracy of future predictions. Briefly, OPTA-BLOOM-Pred first identifies a feature of interest in the SCB and gets a prediction of its evolution for a 12–16-h period from the ocean model. This prediction output is passed as input to a waypoint-generation algorithm to produce the trajectories that steer the AUV to regions of high scientific interest based on the given feature. Four-dimensional (three spatial plus time) predictions of velocity (ocean currents), temperature, salinity, and chlorophyll are used in the trajectory design process. The algorithms have the ability to handle multiple vehicles sampling in multiple locations throughout the feature of interest. The computed mission plan for each vehicle is uploaded to the sensor, and the planned trajectory is executed. During execution, collected data are uploaded and assimilated into the ocean model. A new prediction is generated and the process is iterated until the feature dissipates or is no longer of interest. Algorithm development and proof-of-concept field experiments can be found in [23]–[26].

Multirobot Collaboration Algorithm

To further investigate methods for efficient and optimal sampling, CINAPS has considered the coordinated control of multiple, autonomous, marine vehicles to gather data throughout a defined area of investigation. In particular, both surface and underwater vehicles have been used to cooperatively achieve prescribed sampling missions. For the ASV case, two vehicles were used to visit a set of sampling locations in a lake. During the mission, the vehicles were required to respect multiple constraints. First, each sampling location must be visited exactly once. Second, the vehicles were required to maintain a prescribed intervehicle distance and constantly guarantee their wireless communication. Additionally, we required that the vehicles do not collide with each other or with any known obstacles within the survey region. We employed a behavior-based approach, namely, the null-space-based behavioral control (NSB) [2], to manage the multiple tasks and constraints composing the mission. Moreover, high-level supervisor controllers onboard each vessel dynamically selected the sequence of the locations to visit, managed the communication between vehicles, and activated the mission directives depending on the environmental constraints. A low-level controller was developed to apply the NSB control strategy to the underactuated ASVs presented in "Autonomous Surface Vehicles" subsection. Experimental results from multiple field deployments are reported in [3].

Communication Infrastructure Development

The base station computers at the HFR sites and the computers inside each sensor node run communication software to transmit data wirelessly to USC. Static sensor nodes generally utilize wireless fidelity (Wi-Fi) technology, while the mobile sensor platforms transmit by use of the Freewave network. For the later scenario, the sensor node treats Freewave modems as an



(a) (b)

Figure 3. *Two species of toxic phytoplankton found in Southern California waters. (a)* Pseudo-nitzschia *and (b)* Lingulodinium polyedrum*.*

unreliable serial link. We employ a custom-built lightweight communication protocol with incoming and outgoing packet queues that provide feedback to vary both interpacket delay and packet sizes. The protocol supports both guaranteed delivery as well as nonguaranteed mode of transmission. On the sensor platform, our software parses text output and retrieves data files from the onboard computer. System status and data files, after being compressed, are then sent to the base stations. Upon receipt, the base stations relay these messages via transmission control protocol/Internet Protocol (TCP/IP) to the central data server at USC. This data server is also designed to send commands and missions out to the deployed platforms. Details on the communication protocol can be found in [19].

Ocean Sampling in Southern California

Noxious or toxic blooms of certain species of algae (e.g., *Pseudo-nitzschia*) can cause outbreaks of marine animal and human illness and death via the accumulation of toxins through marine food webs. These events have increased in frequency and severity in recent years and have become a topic of intense research activity [1]. Even with all of the aforementioned technology, we are still confronted with the problem that algal blooms are not predictable in their occurrences. For HABs in California, we know that we are looking for chemical markers, such as an increased concentration of the marine toxins domoic acid or saxitoxin. Or, physically detecting the existence of harmful algal species such as *Pseudo-nitzschia* [Figure 3(a)], *Lingulodinium polyedrum* [Figure 3(b)], *Alexandrium* spp., *Dinophysis* spp., *Phaeocystis* spp., *Cochlodinium* spp., or *Akashiwo sanguinea* in collected water samples. Although several of these species generally appear during specific seasons, the dynamics and environmental factors initiating bloom development, maintenance, and toxicity are still poorly understood. Through the implementation of the tools described in "Deployed Marine Robotic Systems" section, we intend to build a continuous time series of data for the SCB to better guide future sampling efforts and provide ground truth for biological models. This will help us understand and predict the formation and evolution of harmful and other algal blooms. We continue this section by presenting some of the data collected to date.

Large-Scale Data Analysis

Autonomous underwater gliders provide one approach to observing the processes that occur in the SCB. Gliders are capable of long-term deployments; remaining out in the ocean for periods of time ranging from several weeks to several months (cf. [8]). Although their horizontal speeds are only about 1 km/h, their longevity, coupled with the use of multiple gliders, can compensate by providing an extended temporal and spatial series of observations.

To examine some of the local and regional processes in the SCB, we have deployed gliders on smaller-scale, coastal missions, typically with 25–30 km alongshore scales and 20 km cross-shelf scales. A recent effort focused on monitoring the development of phytoplankton blooms that have the potential to include harmful algal species. The examples in Figure 4(a) and (b) show a glider survey from a deployment in early April 2009. The portion of the SCB surveyed was in a region south and east of San Pedro and Long Beach Harbors with a preset trackline along the shelf region. Figure 4(a) and (b) shows the distribution of

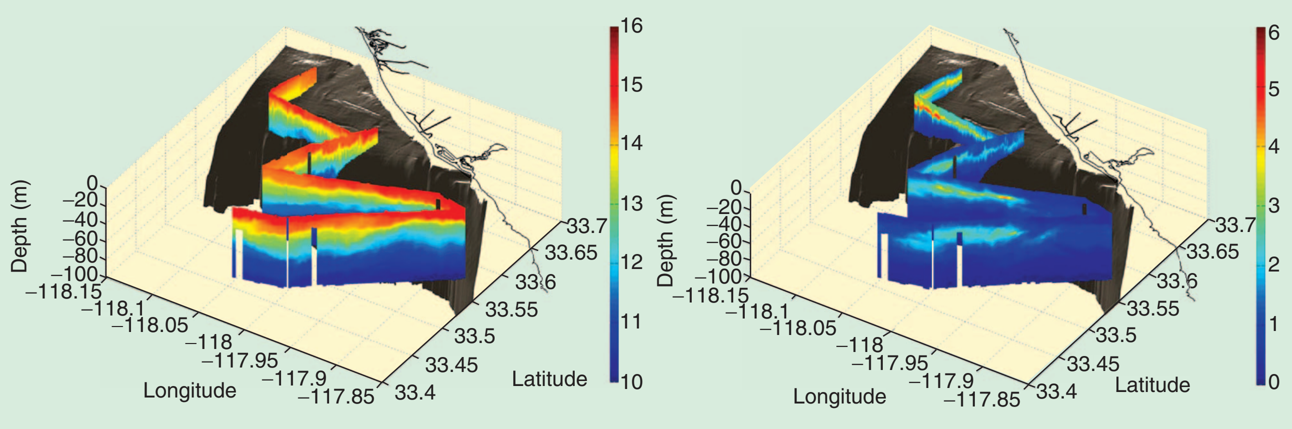


Figure 4. *Three-dimensional depiction of data collected along a glider trajectory during a deployment in April 2009. (a) Temperature (°C) and (b) chlorophyll-a fluorescence (μg/L).*

temperature and chlorophyll a fluorescence, an indicator of phytoplankton biomass. These observations provide a guide for targeting sampling to evaluate whether harmful algal species are present or not. From this deployment, we see three important patterns emerging from the data. The first pattern apparent throughout the data set is that the maximum chlorophyll concentration is located below the surface, at a median depth of about 15 m. Second, we notice a general decline in maximum chlorophyll concentration from the most northern to the most southern portion of the survey. Lastly, where the shelf narrows in the southern portion of the survey, we see low chlorophyll concentrations near the coast, with increasing levels further.

The April 2009 deployment in the SCB had at least one glider continuously observing the region for two months. This time series of spatial maps enables us to couple variations in these distributions with the processes occurring in the region. This allows us to evaluate the dependence of algal blooms on various meteorological and oceanographic processes that contribute to the variability in the coastal ocean. A complete investigation of this data set is still ongoing.

Deploying sensor platforms for longer periods will enable the possibility to begin resolving seasonal, annual, and longer time scales of variability. Because gliders provide a 3-D view of the distributions and the observations are telemetered in near real time, their data can be used to target sampling from a ship for measurements that cannot be made by the glider. In particular, data collected by the optical sensors on the gliders may reveal an area potentially containing a population of *Pseudo-nitzschia*. A ship can then be deployed to this area to collect water samples to validate the existence of toxin-producing organisms.

Small-Scale Data Analysis

One contribution of the CINAPS network is an improved understanding of the biological processes taking place in nature and the dynamics of the micro- and macroorganisms carrying out those processes. This is facilitated by the acquisition of chemical, physical, and biological information at scales that are appropriate for the organisms under study. Continuous, high-resolution, spatial, and temporal measurements, provided by our networked sensors, facilitate the identification of causal relationships between aquatic biological processes and their environmental forcing factors. Chemical and physical factors stimulating population growth or fostering mortality of planktonic microbes can vary at spatial scales vertically and horizontally of less than one millimeter to meters and on temporal scales of less than one second to days. Observations performed at large scales (temporal scales of days–weeks; spatial scales of kilometers) provide a valuable, integrated view of biology, but the response of microbial populations to their environment typically takes place on much smaller scales.

The response of toxic and noxious algal species is strongly affected by the physical and chemical parameters that vary with depth and time, and these features can be adequately captured using dense sensing and sampling approaches. In Figure 5, we present four environmental parameters (temperature, chlorophyll fluorescence, salinity, and dissolved oxygen) measured by one marina buoy in King Harbor Marina. Here we show 12 days

Robotic sensor networks are networks in which some or all nodes can move either under their own control or under the control of other agents in the environment.

of data collected at two depths (0.5 m and 3.8 m) in the same location. The dynamics of these chosen markers are controlled by tidal currents and various other nearshore water movement, including longshore currents, waves, eddies, and fronts. The diurnal oscillations (low-frequency periodicity) occur as a result of both physical and biological forcing mechanisms. For temperature and salinity, the fluctuations are largely coincident with the local tidal cycle forcing. Additionally, note the larger pulses of colder and saltier offshore waters evident at the deeper sensor from days 7 to 11, which may be a result of upwelling or local kelvin waves. The fluctuations in chlorophyll (a proxy for primary production and an indicator of algal biomass) and dissolved oxygen are also somewhat tied to this physical forcing. However, these are dominated by biological forcing due to photosynthetic and respiratory activity that are highly light dependent. The colder, nutrient-rich waters recorded early in the time series may have increased productivity at depth, causing more photosynthetic organisms to migrate to the surface, resulting in the large values of chlorophyll and dissolved oxygen observed from days 15 to 18. The data from Figure 5 is compared to water samples and other data collected from within and outside the marina to

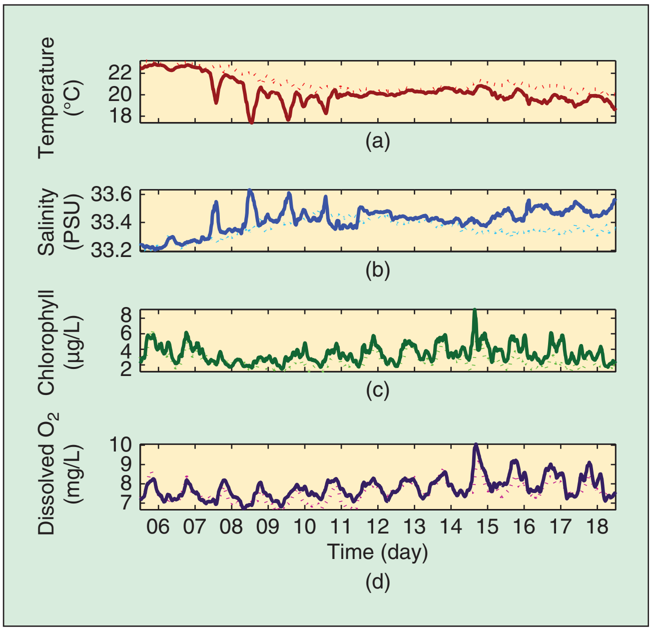


***Figure 5.** Plots of (a) temperature, (b) salinity, (c) chlorophyll fluorescence, and (d) dissolved oxygen versus time over a 12-day period from a buoy located in King Harbor Marina. The solid line represents data collected by the sensor at 3.8 m depth (deep), and the dotted line represents data collected by the sensor at 0.5 m depth (shallow).*

Global ocean monitoring is vital to the future of mankind, as the ocean is a vast resource that provides transportation and food, as well as regulates the earth's climate.

create an entire picture of the overall dynamics and forcing involved. Characterization of these forcing factors is essential to understanding the response of planktonic microbes and the development of bloom events.

Algal blooms are also affected by microorganismal behavior. Directed algal motility (upward or downward) in response to the availability of light and nutrients, or life cycle events such as aggregation for sexual reproduction, often leads to significant, nonrandom distributions of algae in a water column. These aggregations are typically subsurface and not readily apparent by sampling/sensing at the water surface and are often ephemeral in time and space. This is exemplified in Figure 6(a), a two-dimensional (depth versus time) contour plot of the vertical distribution of algal biomass (depicted by chlorophyll fluorescence) in the water column. Here, high concentrations are shown in red. Note the large variations in the subsurface chlorophyll distribution between 2 and 3 m over the course of less than 24 h. Two pronounced subsurface maxima of algal biomass were observed, with the absolute magnitude of the maximum changed dramatically during the examination period. In Figure 6(b), we present the tidal cycle variation for the region during the same time period. Tidal height is measured in meters above the mean lower low water (MLLW) level. Note that local maxima seem to occur near local maxima of the tidal cycle. Again, it is of interest to examine all forcing factors (physical or biological) involved in determining migration (vertically or horizontally) of these organisms. The data for this experiment were collected during a two-day period in King Harbor during August 2008. Algal behavior, population growth in response to nutrient/light conditions, and population mortality due to physical dispersal, sinking, and consumption by herbivores combine to make prediction of bloom dynamics a difficult task. These features also make the study of HABs an ideal testbed for the application of embedded sensor networks in aquatic ecosystems.

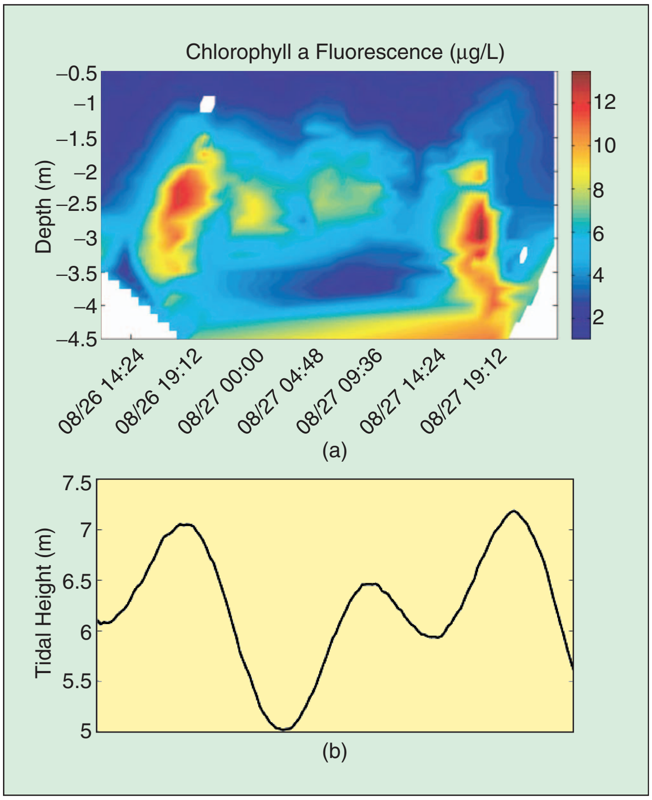


Figure 6. *Contour plot of the (a) vertical distribution of algal biomass versus time, with the (b) corresponding tidal cycle variation for a pier-site located in King Harbor Marina for a duration of 36 h. The time scale for (b) is the same as that given in (a).*

Future Applications and Deployments

Understanding the intricacies of algal blooms, even in a regional area like the SCB, requires examination of both the small- and large-scale ocean processes applicable to the region. Such examination cannot be effectively accomplished by the use of a single, stand-alone sensor platform but is best handled through the long-term, collaborative acquisition and analysis of data collected via a networked aquatic sensor system, consisting of multiple sensor platforms. One goal of the USC CINAPS team is the development of robotic approaches for documenting the movement of river discharge into the coastal ocean, coordinating these measurements to establish the movement of river plumes into the coastal ocean, and observing the consequences of these releases vis-à-vis the stimulation of algal blooms. We are also using this approach for characterizing natural sources of nutrients for phytoplankton by documenting upwelling events. The dynamic feature mapping and tracking represented by these topics are being tackled by use of wirelessly networked static sensor packages (moorings, buoys, and pier-mounted sensor packages), as well as dynamic, mobile sensor platforms (e.g., autonomous gliders and ASVs). Data collected from these instruments is used to characterize and track water movement and thereby directing the mobile platforms (and human-assisted sampling) to document the biological response.

We have chosen this important environmental problem as a model scenario for the development and application of our environmental sensor network, because we believe that this approach can greatly improve decisions by municipalities, counties, and states for dealing with coastal pollution and HABs. However, this sensor network is not strictly limited to phytoplankton research. With the exception of a few specialized sensors, the majority of the acquired data are important in the study of any regional, coastal ocean process. Additionally, the individual nodes of the system, and accompanying network infrastructure, are not based upon the existing sensor packages. In particular, we are able to add or replace data acquisition devices, based upon the scientific interest, with no impact upon the overall network.

Collaborative and adaptive sensor systems provide us with important data relating to the health of the SCB's coastal ocean. However, an overall assessment cannot be accomplished by a single group. Our efforts dovetail with the efforts of the Southern

California Coastal Ocean Observing System (SCCOOS). SCCOOS is one of the 11 regional associations comprising the coastal component of the Integrated Ocean Observing System (IOOS). Our scales of measurement within the SCB fit well within the geographic breadth of SCCOOS and provide a detailed data set to the IOOS. For example, we make use of the larger-scale, SCCOOS surface current data to provide overall context and meteorological information for the SCB. In turn, our studies provide a more fine-scale resolution of plume tracking and biological response.

With the proof-of-concept phases for each piece of our robotic, marine network system nearing completion, we are poised for a full-scale monitoring effort within the SCB. This undertaking will play an important role within the SCB Regional Marine Monitoring Program planned for Spring 2010. The Bight study is a regional (Santa Barbara to the U.S.–Mexico border) study conducted once every five years. The main coordinator is the Southern California Coastal Water Research Project (SCCWRP), a public agency charged with assessing the condition and factors that affect the condition, of a 500 km section of Southern California's coastal environment. One stated focus of the Bight study is an analysis of the importance of natural and anthropogenic nutrient sources (upwelling, river discharge, water treatment discharge, storm drain runoff, etc.) to the promotion of HABs in the SCB and surrounding regions. Implementation of the feature-tracking algorithms based on data acquired by the entire aquatic robot network will constitute a significant contribution to this overall investigation.

One planned aspect of our contribution to Bight 2010 will be the continuous operation of up to four autonomous gliders in the SCB for the duration of the study. During deployment, we will implement the algorithms presented in "Model-Based Retasking Algorithm" section to retask currently deployed gliders to track and monitor a freshwater plume, waste water outfall or HAB event. Through careful planning and a bit of luck, we are planning to capture the conditions in the SCB leading up to, and the development of, a HAB event. Upon completion of the successful tracking of a HAB from beginning to end, all data will be compiled for analysis to determine anthropogenic, environmental, or other triggers that may exist.

One planned aspect of our contribution to Bight 2010 will be the continuous operation of four autonomous gliders in the SCB for the duration of the study.

Keywords

Marine robotics, networked robots, control architectures and programming, adaptive control, networked teleoperation.

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