Project Title: SENSORS: RiverNet - Distributed Sensor Nets for Environmental Monitoring
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Annual Project Report - 2007

During 2007, the RiverNet Project continued with the development of distributed sensor networks integrating mobile autonomous underwater robotic vehicles applied to problems of environmental monitoring with special emphasis on the Hudson River and Estuary.

Algorithms and technology have been developed within the RiverNet project with the overall goal of analysis and design of distributed sensor networks for observing data from complex and geographically extended regions. These three principal activities are:
1. Distributed spatial and temporal sampling of distributed variable fields incorporating fixed and mobile sensor nodes. Significant progress has been achieved on the design of parametric and non-parametric methods and these are being used in both simulation and experimental testing of distributed sensor systems.
2. Research conducted in conjunction with The Beacon Institute will lead to extensions to the deployment of a Hudson River sensing network that provides physical and chemical sensing variables on the Hudson River and retrieves data by wireless connections. This sensor network will include conductivity, temperature, depth, turbidity, chlorophyll, and dissolved oxygen. This effort is being further augmented by a pending partnership with the IBM Corporation.
3. Progress in the development and deployment of the Solar autonomous underwater vehicle (SAUV) in a series of test phases is designed to validate vehicle performance and develop reliable mission planning and navigation capability. As of 2007, five SAUV vehicles have been manufactured, and further testing is planned over the next 12 months to demonstrate the capabilities of the vehicles for sensing, communications, and cooperative navigation. These results and test activities are described in more detail below. Cooperating organizations involved in the work described include Rensselaer Polytechnic Institute (RPI), AUSI, Technology Systems, Inc. (TSI), Falmouth Scientific, Inc. (FSI), the Naval Undersea Warfare Center (NUWC)-Newport, The Beacon Institute and the University of New Hampshire (UNH).

1. SAUV Platform

The SAUV, shown in Figure 1, is a solar-powered AUV designed for long endurance missions that require monitoring, surveillance or station keeping, with real time bi-directional communications to shore [1,2,3]. The SAUV is designed to operate as a normal AUV when submerged but will also reside on the surface while recharging batteries.

While on the surface, the SAUV is designed to communicate remotely via Iridium satellite or RF communications link to upload collected data and to allow remote reprogramming of mission profiles. A typical mission scenario would include submerged operation at night for about 12 hours and surface recharging and communication for about 12 hours during the daytime. This mission could last weeks to months with daily updates provided to the user from anywhere in the world. The vehicle can be pre-programmed to submerge to depths of 500 meters, to transit to designated waypoints, or to operate on the surface during conditions suitable for battery charging via solar energy.

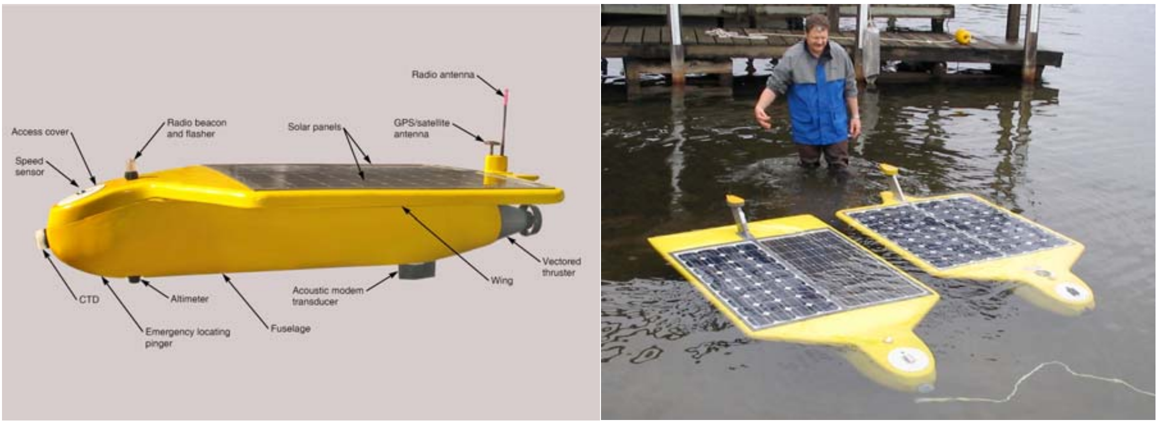

Figure 1. Solar-powered AUV (SAUV) platform.

The SAUV system employs a comprehensive and flexible set of capabilities for communications and remote data transfers. Real-time vehicle performance and state data are logged internally and are available through ftp transfer while the SAUV is on the surface. During a mission, payload, sensor and state data are available on a periodic or polled basis through the acoustic channel. The data typically is picked up by a gateway buoy (or gateway SAUV) and relayed via RF to the remote land site where it is displayed on a computer using the Mission Planner software application.

Mission Sensors

The basic SAUV mission sensor suite includes sensors for altitude, pressure (depth), conductivity (salinity) and temperature. One of the key design goals in the development of the SAUV was as a platform to host various sensor systems. Recent sensor surveys have depended upon the collection of additional science data. For example, the MB06 science mission undertaken in Monterey Bay, CA in 2006 relied upon the installation of an OxyGuard 505 dissolved oxygen sensor and a WET Labs ECO Puck combined fluorometer/turbidity sensor, in addition to the standard FSI NXIC CTD sensor on each vehicle.

Hardware Development

Several aspects of the SAUV system hardware have evolved during the period of performance of this NSF Program. The performance and stability of the vehicle have been heavily dependent on the placement of trim weights. Small changes in configuration require tedious re-trimming. Steps to address this issue have been undertaken which include increasing the vectored thruster shroud diameter and exploring the use of vertical fins, and are based upon a careful study of the hydrodynamics of the vehicle [4].

Another area where vehicle performance has been improved is in the Li-Ion battery subsystem. In 2007, transition from the Mathews battery system to another system built by SouthWest Electronic Energy Corp was completed. This new system has proven to be more reliable and much easier to handle, resulting in less operational down time.

Software Development

The software capabilities of the SAUV platform have also evolved over the past several years, with changes primarily in two areas. In 2006, the capability to perform "system in the loop" testing of the SAUV high-level software was developed. Along with this addition came the capability to more easily plug in new mission sensors, enhancing the ability of the SAUV to be used in different kinds of sensor surveys.

The second area which has evolved is in the high-level control of the SAUV. Focus areas include design and implementation of a common control language (CCL) for AUVs and development of a distributed control environment (DICE) as well as high-level vehicle behaviors.

2. Tools and Technologies Supporting Multi-vehicle Cooperation

A set of enabling tools and technologies which allow us to test and evaluate multiple cooperating AUVs has been developed. These technologies are critical to enabling a fleet of AUVs to perform cooperative tasks such as adaptive sampling and surveying. The following is a summary of those technologies which were partially funded by this NSF support.

SAUV "System in the Loop" Simulation

During 2006, researchers augmented the Cooperative AUV Development Concept (CADCON) environment to provide "system in the loop" capability for testing and evaluating SAUV system components and multiple cooperative vehicle mission profiles before going in the water [5]. This simulation facility allows for complete testing of SAUV onboard high-level software, including underwater networking protocol logic. The facility also has a training functionality in that top level mission planning and vehicle monitoring applications used by SAUV operators can also be tested as if they were in a field setting. Hardware components, such as radio frequency (RF) and acoustic modems can also be tested within the systems context. In this harness, the SAUV PC-104 system, running a Linux OS and the high-level software, can be tested as a networked bench-level component. In addition, significant portions of the standalone SAUV can be put into simulation mode, thereby allowing the testing of other on-board vehicle electronics and subsystems.

Common Control Language (CCL)

Multiple vehicle cooperation relies upon the ability of vehicles to communicate and understand each other. AUSI and NUWC are developing a CCL to provide (1) a common messaging interface to different AUVs, (2) an operator to vehicle group mission specification interface, (3) a sufficiently rich vocabulary and grammar to permit development of high level behaviors from lower level behaviors, and (4) support for optimization strategies for multiple AUV cooperation [6]. The message specification in particular draws heavily upon past work in "generic behaviors" [7] and other AUV command languages, as well as work done in intelligent agent communications. It is explicitly designed to support a wide range of vehicle types in its command and informational structure. In addition, this protocol allows for arbitrary execution of behaviors (parallel, sequential, adversary, general choice, cost choice) and, when combined with $-calculus, allows vehicles to accept a goal, jointly plan how to achieve that goal and carry out the plan. CCL has been field tested in the past on both a REMUS and a Mid-size Autonomous Research Vehicle (MARV). The newest revision is currently implemented on the SAUV and the TSI modular mission planning toolkit (MMPT) application for glider platform mission planning, monitoring and control.

Distributed Control Environment (DICE)

In 2005, the DICE environment was implemented on the SAUV platform as an enabling technology for executing multi-vehicle cooperative behavior. NUWC has developed the Distributed Control Environment (DICE) as a tool for developing behavior-based distributed control systems [8]. It enables communication between distributed system components as well as communication between different systems. DICE has many features specialized for behavior-based systems, thus, it can be useful for development of a wide range of architectures from reactive to deliberative. It supports coordination of processor-intensive tasks, such as high-level planning interacting with responsive low-level control. DICE designers developed this framework to facilitate implementation of multiple autonomous systems that operate with noisy and range-limited communication, rapidly-changing real-world situations, and variations in resource availability. DICE extends subsumption-style tasking with message passing to the multi-agent domain and provides for a wide variety of behavior-arbitration techniques. It allows a great deal of run-time system flexibility including dynamic reconfiguration of behavior structure. DICE is well suited for fast data-driven control strategies. It provides for rapid code development and effective code re-use. Behaviors can be multiply-instantiated and interact through abstract "ports", which can be dynamically connected to other ports at run-time. Behaviors can be distributed across hosts without code changes.

Cooperative Behaviors

The ability of the SAUVs to participate in cooperative role swapping missions has been demonstrated in a "reference mission" as depicted in Figure 2. In general, this mission involves an area which is to be constantly surveyed by a group of SAUVs. In the reference mission, a single SAUV having the highest initial energy takes on the survey role. Those SAUVs not performing the survey maintain a watch circle on the surface recharging their batteries or take on new roles (e.g. mobile communications gateway).

The reference mission builds on the set of behaviors required to implement the mission defined in a related DEPSCoR project entitled "Highly Accurate Temporal and Spatial Mapping of Coastal Regions Using Long Endurance AUVs" (ONR Grant #N000140510666). These include behaviors to support gateway functionality, the survey task, background navigation (including inter-vehicle ranging), networked communications and energy management. These will augment a set of cooperative behaviors already developed, including watch circle, box and lawnmower survey behaviors. These behaviors leverage our CCL and DICE efforts, providing us the ability to implement and test using AUVs in the water.

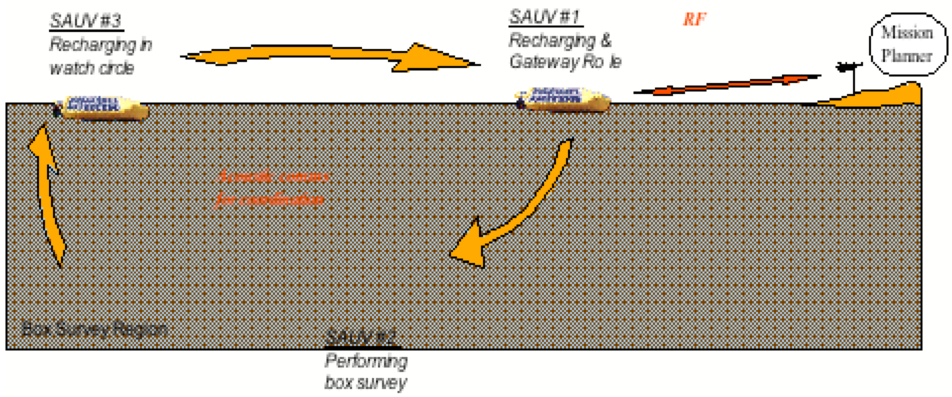

Figure 2. Energy-based role swapping.

Networking/Media Access Control (MAC)

An underwater Media Access Control (MAC) layer collision handling mechanism which supports ranging as well as communication, while in parallel exploring ad hoc network protocol designs will complement the *Autonomous Undersea Systems Network* (AUSNET) [9] or *Controlled Flooding for Small Networks* (COFSNET) [10] designs. Based upon these results, a MAC-layer/network-layer protocol with ability to support system level inputs (e.g. energy, navigation, and mission) and support non-trivial gateway functionality such as packet type queuing and store-and-forward is being developed [11]. This evolved protocol will provide the communications infrastructure necessary to allow platforms to communicate in an ad-hoc, peer-to-peer manner, while supporting the underlying navigation (ranging) requirement and permit platform system inputs to optimize efficiency.

Navigation

Inter-vehicle ranging will improve underwater dead reckoning (DR) navigation and enable vehicle acoustic ranging. A Time Division Media Access (TDMA) scheme with special "ranging intervals" for each node in the acoustic network has been designed. In this scheme, a node's time slot for transmissions is divided into a communicate interval for normal transmissions and a ranging interval for ranging on all other modems in the network. During its communication interval the source node sends its normal transmissions. During its ranging interval, the source node ranges on all other nodes in the network, collects and stores the results. The resulting information is used by the source node to maintain an understanding of where the other nodes are in relation to it. Preliminary testing of this scheme took place at Lake George, NY in June, 2006. As part of this effort, collaboration with Teledyne-Benthos, Inc. supports an underwater GPS system [12].

Advanced Operator Planning/Monitoring Tools

A collaboration with TSI is developing a Modular Mission Planning Toolkit (MMPT) application to support AUV mission planning. This application provides for planning, monitoring, command and control of multiple heterogeneous AUVs, particularly long endurance glider platforms, with a particular emphasis on incorporating environment data (e.g. currents) into the planning process. Prototype versions of MMPT were used during the 2006 Lake George, NY and Monterey Bay, CA experiments. During the recent AUVFest'07 testing, MMPT was used exclusively to monitor and control a fleet of 3 SAUVs, as well as demonstrate mission planning aspects based on water current METOC data supplied by NRL/Stennis [13].

3. Cooperative Multi-vehicle Field Tests

Two recent major field events involving test and demonstration of multiple vehicles and the technologies previously described are summarized below [14].

Lake George, NY (June 2006)

In June of 2006, cooperative behaviors were wet tested in Lake George off Bolton Landing, NY at the RPI Darrin Fresh Water Institute (DFWI). The cooperative mission given to a pair of SAUVs was for one of them to run a box shaped survey while its partner maintained position in a charging mode. The cooperative mission statement specified only that the vehicle with the most energy was to run the survey and the other was to charge. The vehicles were to decide which one would take on the survey role at runtime. The successful experiment demonstrated several autonomous role switches based on the vehicles' relative energy levels. This indicated that the initial design of the high level behavior logic as proven under simulation conditions transitioned well into the real world. It also demonstrated the utility of the COFSNET underwater networking protocol for three nodes (2 SAUVs and a gateway buoy/operator).

Figure 3 shows a screen shot taken during that experiment. The entire image shows the Macromedia Breeze system in use, where the output of various applications appears in Breeze sub-windows. Shown to the right is an early prototype MMPT application plotting the vehicle positions along with data pulled out of the vehicles' status messages. The column of sub-windows on the left shows an ongoing live chat-like interaction between MCAUV team members at Bolton Landing, NY, Wiscasset, Me (TSI), and Newport, RI (NUWC) as well as photos taken on the lake. Using this system, collaboration of remote participants with onsite operators in an on-going multi-vehicle field event was demonstrated.

AUVFest'07 – Panama City, FL (June 2007)

In June of 2007, at the ONR sponsored AUVFest'07 in Panama City, FL, three SAUVs running a more complex version of the cooperative survey mission were demonstrated; this time involving three roles: survey, recharge, and networker (for gateway services). As in previous versions of this type of mission, the group's primary role was to provide continual coverage of the survey area. In doing so, the vehicles were to decide among themselves at runtime which one was to run the survey, which one was to simply recharge, and which one was to become a RF-acoustic communication gateway node for the other two. Since the actual gateway software was not completed, this new gateway role focused only on the positioning aspects of the role.

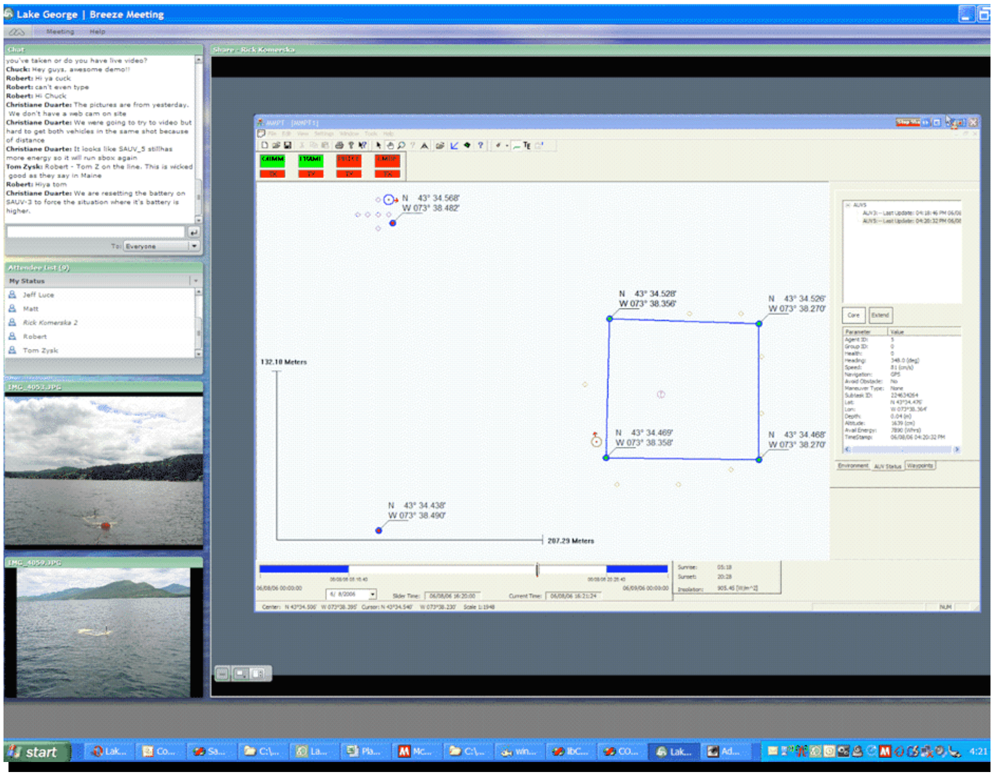

Figure 3. Breeze room screen showing collaborative mission planning and monitoring.

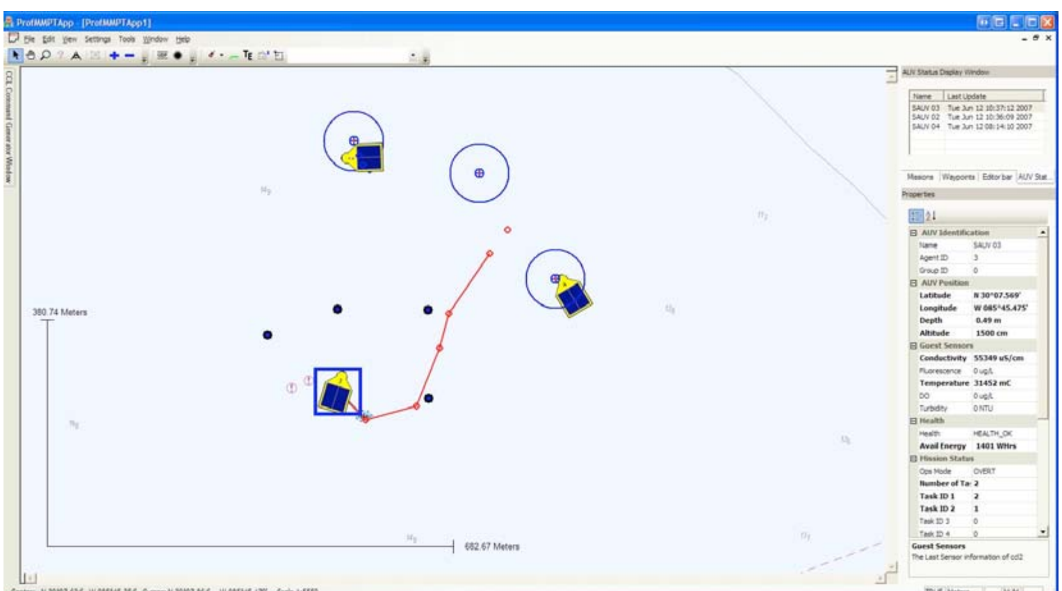

Figure 4. Three SAUV energy-based role swapping (MMPT operator display).

At AUVFest‘07, the COFSNET networking protocol, in this case stress testing the protocol by placing three AUV nodes within a relatively small area, was tested. Since neither the acoustic modems nor the protocol have provisions for media access control, a time division media access (TDMA) scheme of sorts was implemented manually by setting each to broadcast its status acoustically every three minutes, staggered at 1 minute intervals between vehicles. Note that this sets up what amounts to only “half” of a true TDMA scheme. While the initiation of each node’s broadcast was time division controlled, the COFSNET forwarding of packets was not.

This strategy worked well operationally, but apparently fell victim to the lack of TDMA control on the COFSNET retransmissions. At some variable time (roughly 10 minutes or so) after the third vehicle joined the group, one of the three would then become “deaf and dumb” relative to the other two. This problem is likely caused by multiple packets being simultaneously received at the affected node’s modem.

This experiment demonstrated an important feature of ad hoc networking: the capability for agents to enter and leave a functioning network without damaging that network. COFSNET was able to automatically deal with the deaf/dumb node being momentarily taken offline and then put back online as it was reset by human intervention. This operational adjustment also illustrated the importance for agents being able to reason about the “freshness” of the data, on which they are making their decisions. In several instances, due to missed status packets while one vehicle was being reset, we observed the other SAUV platforms utilizing outdated status information from that reset vehicle.

4. **Sensor Surveys**

Adaptive Sampling Algorithm Development

To support the research and development of adaptive sampling algorithms integrated with multiple cooperating AUVs, an effort was undertaken to enhance the CADCON simulation environment [15-21]. As a stand-alone simulator, CADCON employs a distributed multi-agent simulation, visualization system, and control harness designed to simulate the underwater environment, which can be shared via the Internet. CADCON clients are available via the Internet for others to use and it has been employed by independent workers in industry and academia to support their own research projects. Through a dynamic link library (DLL) interface to MATLAB, an adaptive sampling algorithm written in MATLAB and running on a computer at RPI in Troy, NY was used to direct a fleet of simulated underwater vehicles on a sampling mission. The adaptive sampling algorithm was interfaced to an AUVSim CADCON client, which emulates a single AUV platform, through the DLL mechanism. The AUVSim application was connected over the Internet to the CADCON simulation environment executing on a server located in Lee, NH. The AUVSim/MATLAB applications share the AUV’s location and on-board sensory information: desired sampling locations were transmitted to the AUV as transit waypoints. Visualization was done using the CADCON Visualizer client, which also connects to the CADCON server over the Internet.

Multiple AUVs can be instantiated and visualized using CADCON, and a high degree of detailed functional specifications can be customized for each vehicle, including energy available, sensor types, and maneuvering capabilities. One of the simulated AUV models is the SAUV platform.

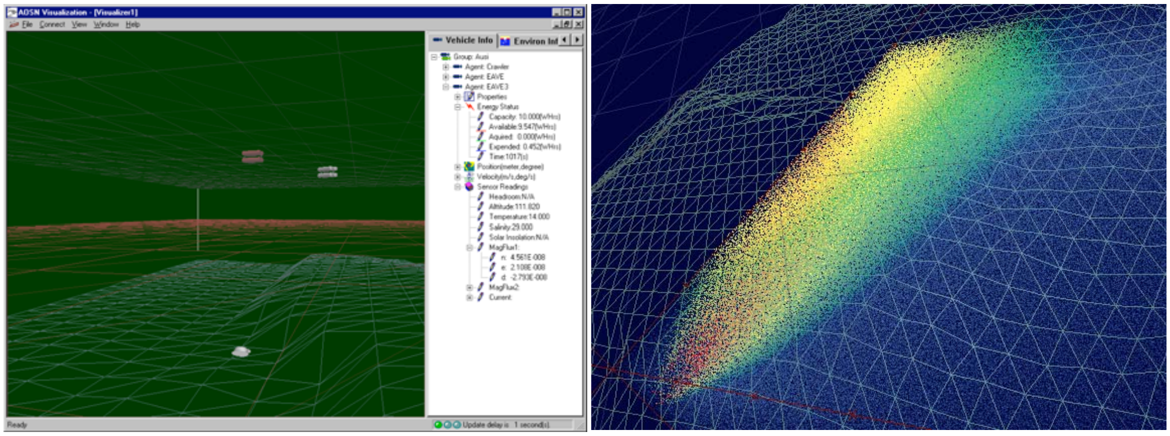

Figure 5. CADCON Visualizer client with simulated plume.

Another variation of this work involved interfacing the MATLAB application containing the adaptive sampling algorithm to a prototype *Autonomous Systems Monitoring and Control* (ASMAC) application to direct a fleet of AUVs to sampling locations. ASMAC allows a remote user to plan a mission, configure the AUVs that are going to accomplish that mission, initiate the mission, monitor the mission while it is underway, analyze received mission data and vehicle status and, as a result of that analysis, modify the mission while it is underway [22]. The collected sensor data is analyzed by the adaptive sampling algorithm, which then generates an output that helps re-plan the mission to better achieve the goals of the mission.

Another component of the simulation environment was the use of NetCDF as a common database format to facilitate the importing of real and simulated data into the simulator. Unidata's NetCDF (Network Common Data Format) is a data model for array-oriented scientific data access, freely available software that implements the data model in several programming languages, and a machine-independent file format. Figure 5 shows the visual aspect of a simulated plume in the Visualizer application. The plume was generated using a "chimney" model that utilizes a diffusion differential equation on two coordinates, and a flow differential equation on the third coordinate. Publicly available C and MATLAB code was used to perform I/O with NetCDF data in both the CADCON environment server as well as MATLAB.

Hudson River, NY (June 2006)

A single SAUV platform was deployed in the Hudson River near Fort Edward, NY, June 5, 2006, as part of a two week field test conducted out of the DFWI facility in Lake George, NY. For this test, the SAUV was equipped with instruments for measuring depth, temperature, salinity, dissolved oxygen, chlorophyll a, and turbidity. The SAUV measured the profile of these variables over a one kilometer range both downstream and upstream in the river at approximately one meter depth. This deployment illustrates the versatility of the SAUV technology for deployment in new environments with minimal preparation and support required. These measurements are valuable in order to characterize a critical water resource such as the Hudson River, and the approach may be extended to map contaminants or detect toxic materials that may have impacts on large local populations. Figure 6 illustrates the test region and provides a snippet of the type of data collected during this mission.

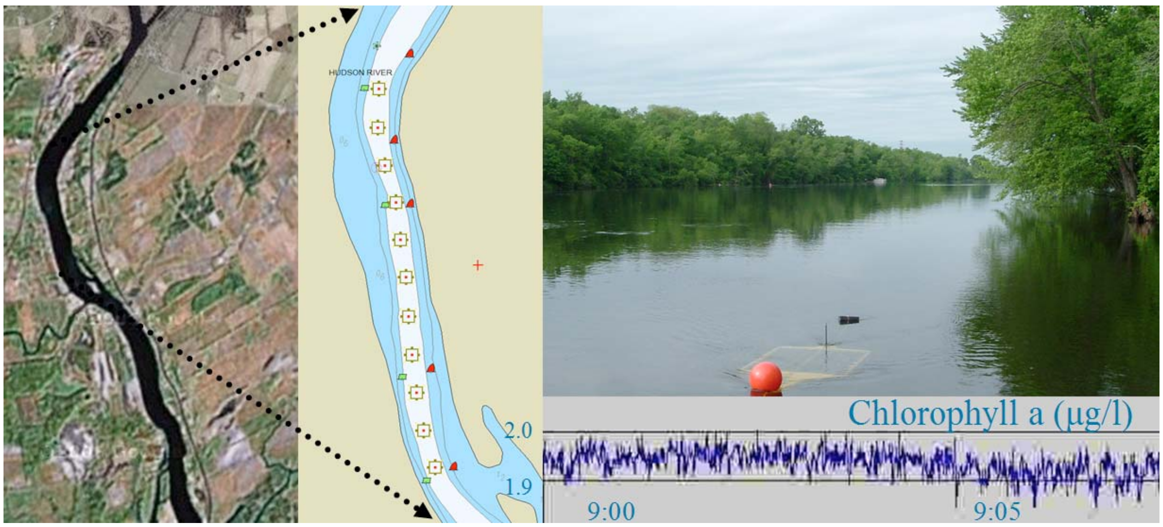

Figure 6. SAUV sampling Hudson River near Fort Edward, NY.

MB06 – Monterey Bay, CA (July 2006)

In July of 2006, the MCAUV team participated in a data gathering exercise as part of the Monterey Bay, CA AOSN experiments. Here, two SAUVs were to loiter on station in the immediate neighborhood of a set of fixed vertical profilers operated by researchers with the Layered Organization in the Coastal Ocean (LOCO) group. In this experiment, LOCO personnel operated their profiler systems normally, uploaded collected data to shore, and then analyzed that data to determine if any so called "thin layers" of biological activity had been detected in the water column. Upon finding such a layer, the approach was to have LOCO personnel contact SAUV mission control and provide the coordinates and depth they wanted the SAUVs to investigate. SAUV planners would then craft the proper cooperative mission and issue it to the SAUV group with the intention that the SAUV with the most energy available would undertake the mission, while the other would continue to charge. Again, the vehicles were to make the role decision at runtime. Although damage to one of the SAUV platforms early in the test forced operations to continue with a single vehicle, the MCAUV and LOCO teams were able to carry out the basic test paradigm demonstrating a human-in-the-loop adaptive sampling strategy [12].

The plot shown in Figure 7 shows the results of a quick response effort to a request to conduct a survey in a localized area. The SAUV proceeded to the area and conducted a dive from the surface to 11 meters and back to the surface. The scientists had detected a thin layer of chlorophyll and asked for a profile of the area to better define the anomaly. Figure 7 clearly shows the resulting thin layer spike in chlorophyll at about 4 meter depth attained during the quick response maneuver.

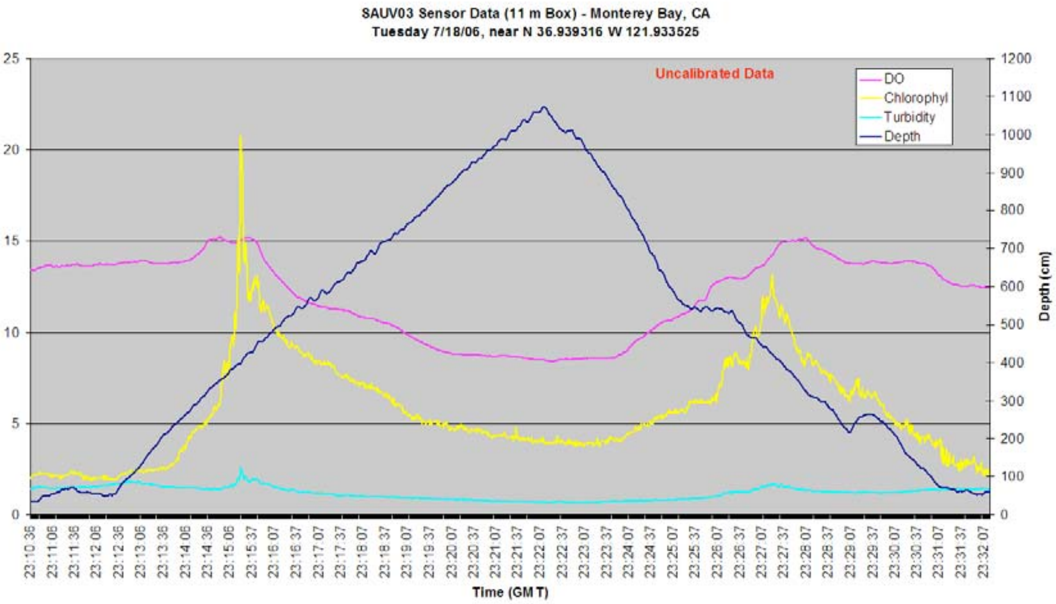

Figure 7. SAUV data showing chlorophyll spike at 4 m.

An important lesson learned from this experiment was that the SAUV can be successfully integrated into a mixed sensor network of both fixed and mobile nodes and carry out the role of a responsive sensor platform. Over the course of two days, the SAUV was able to gather science data within the LOCO region. The positive results from this test have led to team discussions with Dr. Percy Donaghay (University of Rhode Island) exploring the idea of combining autonomous profiler arrays with the SAUVs to create a distributed network system for adaptively sampling coastal systems. This concept, shown in Figure 8, would build upon the initial capabilities demonstrated during this field test.

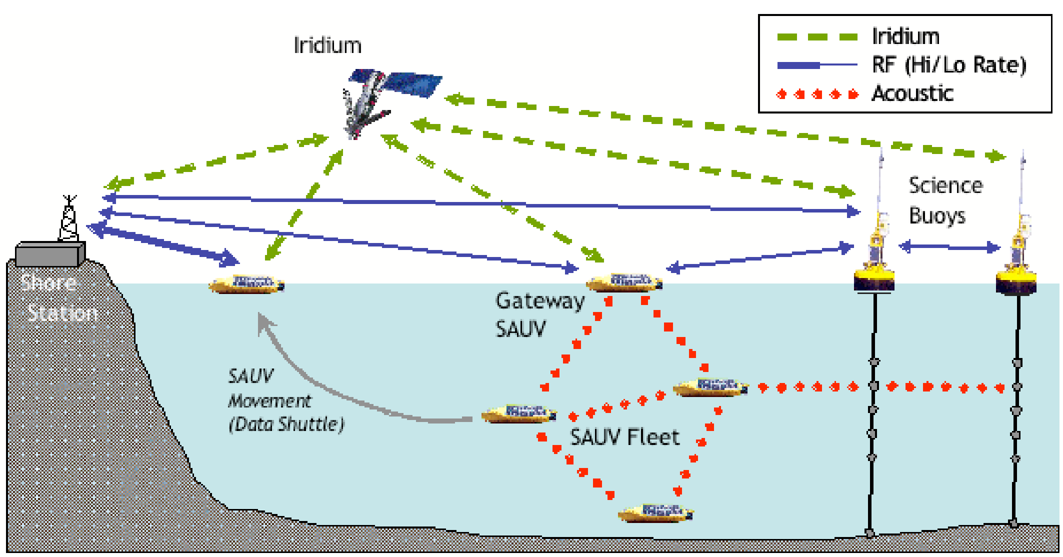

Figure 8. Adaptive sampling within a mixed sensor fleet.

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