

MULTI-UUV MISSIONS USING RANGER MicroUUVs

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ABSTRACT

Groups of four UUVs have been used to validate a plume source localization algorithm and map the 3-D movement of a salinity front over time. These missions have demonstrated that not only are multi-vehicle deployments possible, but by using teams of cooperating vehicles, difficult tasks such as plume source localization can be performed quickly and that small volumes of the ocean can be simultaneously sampled with unprecedented spatial and temporal resolution. The key to the success of these missions is the small, inexpensive and easy to operate Ranger MicroUUV from Nekton Research. We report on the results of recent multi-agent missions and provide information about the UUVs used during these missions.

INTRODUCTION

The past ten years have seen an increase in the number of applications employing UUVs, particularly in the fields of oceanography, bathymetry, pipeline-inspection, diamond mining, MCM and other military operations. [1] While substantial progress has occurred in the fields of aerial and terrestrial multi-vehicles systems [2,3] and a substantial body of theoretical work exists on algorithm optimization, [4] software architecture optimization, [5] group behavior, [6] and communication, with limited exceptions we are not aware of any full scale experimental work underwater. [7,8]

In order to bridge the gap between simulation and field-testing, Nekton Research is continuing development of the Ranger MicroUUV, and the Underwater Multi-Agent Platform (UMAP), which is comprised of N-Rangers and the supporting software infrastructure. In order to facilitate multi-agent testing, Ranger is not only capable of autonomy, but also of sharing, accepting, and responding to real-time data with/from other vehicles. For this reason, Ranger and UMAP pave the way to a host of underwater applications from distributed search algorithm research (MCM, lost asset search), to formation flying (beam forming ranging flexible array), and to general oceanography (bathymetry, mixing



Figure 1: Four Rangers beginning a Multi-vehicle, collaborative mission

studies, search, localization, characterization of underwater plumes, etc).

To date, we have deployed UMAP for two different types of missions. The first set of deployments tested a multi-agent collaborative plume localization algorithm developed by Sandia National Laboratory. The second mission was to map a salinity front moving through the Newport River Estuary on the coast of North Carolina. This work was done in conjunction with the NOAA Center for Coastal Fisheries and Habitat Research. The vehicle, system, and deployments are discussed in this paper.

RANGER MicroUUV

Ranger was designed to cater to two groups of users: single-vehicle users - typically environmental monitoring agencies-, and multi-agent researchers. These users have very different needs: portability, ease of use, and sensor expansion in the first case, and communication, reliability, and processing power in the second.

To meet these needs, we have incorporated the following features into Ranger:

Sensors

- CTD standard.
- Options for DO, nitrate/nitrogen, PH, turbidity, chlorophyll, and rhodamine.
- Reconfigurable logic to allow complete flexibility for sensor expansion (analog i/o, RS232, RS422, IrDA, parallel, synchronous serial, FireWire, ethernet, etc.)

Standard Features

- 600 MFLOPS DSP (pin compatible up to 1.4 GFLOPS). The processor is programmable in C using Ranger's API and consumes less than 1/6 the power of a PC-104.
- C-Band MicroModem developed at Woods Hole Oceanographic Institute (currently under development: passive LBL positioning and underwater communication).
- 440kbps RF modem
- WAAS enabled GPS
- Compass and attitude sensors
- Internal battery recharging system.
- 64MB Flash expandable to 40GB

Other features are summarized in Table 1.

Table 1: Ranger Specifications

Length	92 cm
Diameter	9 cm
Weight	4.5 kg
Turning Radius	1.5 m
Available Power	172 W hr
Average Duration	8.4 hr
Nominal speed	2 knots
Maximum speed	4 knots
Range	30 km



Figure 2. Because of their small size, Rangers are easy to deploy and recover.

UMAP RANGER INFRASTRUCTURE

Fast and efficient interfacing between the user and the fleet is done by a proprietary software package called the Fleet Logistical Interface and Control System (FLICS). FLICS

was created to manage vehicle preparation, deployment, oversight, and recovery. During preparation, FLICS initializes systems and sensors in parallel, a laborious task when repeated sequentially on a series of vehicles. During deployment, the vehicles are provided mission instructions and issued a simultaneous start command. In-mission oversight includes tracking vehicle location and systems status. Re-tasking involves issuing new instructions to a single vehicle or a group of vehicles mid-mission. Recovery mirrors deployment and has added shutdown steps. These tasks are time consuming when a single vehicle is deployed. Clearly, they rapidly impose unsupportable burdens if multiple vehicles are not managed by an appropriate logistical support system.

Without FLICS support:

- An unaided operator cannot readily issue coordinated start commands to a series of vehicles while preparing the subsequent ones for deployment without the aid of a fleet logistical system.
- An unaided operator cannot readily oversee the mission of deployed vehicles while at the same time initializing others for deployment.

Our software addresses all aspects of efficient multi-agent logistical support. FLICS is subdivided into sub-systems called the Fleet Data Management Controller (FDMC) and the Fleet Control Software (FCS). The FDMC allows a user to upload programs to, and download data from a single vehicle or the fleet as a whole. The FDMC also includes a module for performing calibration and diagnostics on individual vehicle systems such as the compass, servos, or depth sensor.

When the mission is underway, the FCS module provides a topside interface to the vehicles via either RF (surface) or acoustic (subsurface) communication. Dual display windows show both a simple representation of the entire mission area and a more detailed view of selected areas. Data collected before or during the mission is presented to the user in a real-time visualization. Missions can also be recorded for play back at a later time. Finally, the FCS provides the ability to send commands to either individual vehicles or groups of vehicle.

To initialize mission parameters, the FCS accepts a set of files containing the estimated initial location of the vehicles, the location of baseline buoys and other objects of interest, bathymetric data previously collected for the mission area, and up to two other data sets representing sensor information about the area. The formats for each of these files are text – based and easily understood.

During missions, the FCS shows the location of each vehicle, sensor values, heading, depth, and the time of last contact with each vehicle.

User commands may be sent to a single vehicle or group of vehicles. Example commands are: deploy, home, start, stop, resume, abort, hold, and set heading. Group commands are automatically sent by broadcast to the entire fleet, and single vehicle commands are sent to the vehicle(s) selected in the large display window by the user.

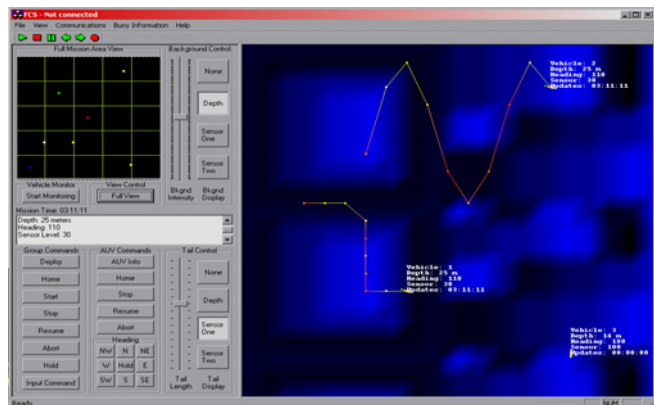


Figure 3. FCS Fleet Controller Screen View

We have recently added a networking module to FLICS called RangerNet. RangerNet allows the control of several Rangers from any networked PC. RangerNet client programs may connect to the RangerNet server and request either full access to control or read-only access to observe any of the available vehicles. Advantages of this client-server model are the ability to set up multiple stations for deployment and maintenance and a seamless transition for the vehicles from station to station (or station to deployment) while still connected via RF to RangerNet.



Figure 5. Monitoring and control of the fleet from a single station.

MULTI-AGENT MISSIONS

A. Plume Source Localization

A collaboration with Sandia National Labs was initiated to demonstrate collaboration between underwater vehicles. The format of this demonstration was plume localization using three vehicles. A gradient algorithm developed at Sandia

was ported to the vehicles. A detailed description of the algorithm can be found in [8].

To demonstrate collaboration, we set up a protocol where each vehicle is given an independent start point and an end point to establish three parallel track lines. The track lines are spaced such that one vehicle travels through the center of the plume, one vehicle comes near the periphery of the plume, and one would, in the absence of collaboration, swim outside the plume boundary. The goal was for all three vehicles to converge to the plume source. The plume intensity was a spherically symmetric distribution that peaked at its center.

Because acoustic positioning and communication were unavailable, navigation was done via dead-reckoning with periodic surfaces (30s intervals) to update the position with a GPS fix. While at the surface, the vehicle downloads a subset of the data collected on the previous dive via the RF modem to the FCS, and interrogates the FCS to obtain data posted by other vehicles. Data collected by the vehicle is logged at 10Hz. The data subset transmitted to the other vehicles includes five samples spaced over the dive interval.

Figure 6 shows the vehicle trajectories where the plume is set at 10m North, 10m West, and 1m down. The circle represents the plume boundary. V1's trajectory takes it through the plume. V2 begins a parallel path which would take it through the plumes periphery, but initiates a deliberate turn towards the center of the plume while still outside; post-mission examination of the data shows that the deliberate turn is a direct result of data received from V1. V3 reaches its endpoint and hovers until it receives enough data from V1 and V2 to determine the gradient of the plume, and then moves toward its center. As far as we can tell, this conclusively constitutes the first demonstration of collaborative behavior by UUVs.

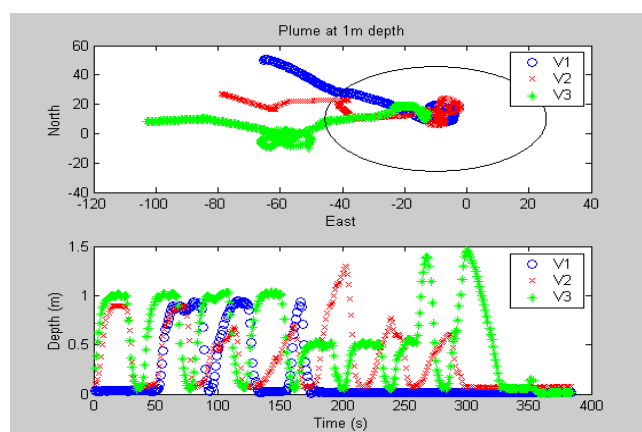


Figure 6. Position and vehicle depth vs. time plots for a plume at 1m depth.

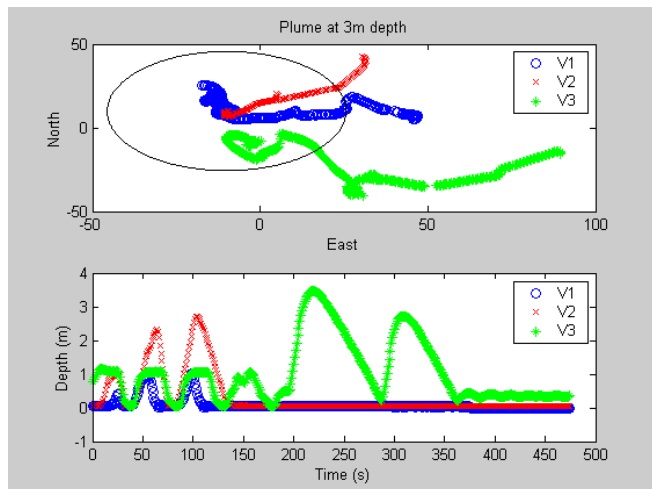


Figure 7: Position and vehicle depth vs. time plots for a plume at 3 m depth.

Figures 7 and 8 show collaboration with plume depths of 3m and 5m respectively. The 5m case (Figure 8) is interesting because it illustrates an important element of multi-agent systems, i.e. soft failure. One feature common to torpedo shaped UUVs is difficulty in getting off of the surface, especially in calm environments. Ranger requires nearly straight-line motion to get off of the surface; i.e. if it is circling, it is difficult to dive. This is particularly problematic as the vehicle approaches the plume source. As can be seen in Figure 9, once a vehicle approaches the plume source, it hovers about the point trying to determine the exact location. When the dive timer expires, the vehicle resurfaces for a GPS fix and data exchange. As it surfaces, it is still approximately at the correct North and East coordinates of the plume, but at the wrong depth, and as a result it does not terminate its mission. Since the vehicle is essentially hovering about a point in the horizontal plane, it cannot get enough straight-

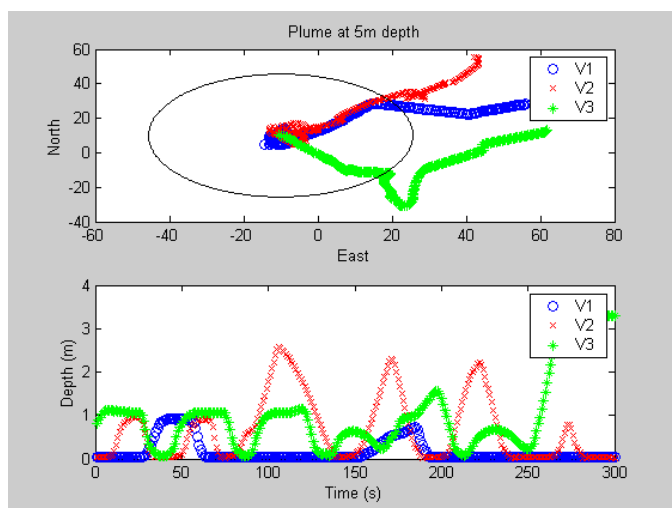


Figure 8. Position and vehicle depth vs. time plots for a plume at 5m depth.

line motion to dive. Figure 7 shows that V1 gets close to the plume in the horizontal plane but then becomes constrained to the surface, unable to reach the plume center at depth. V2 uses V1's information and gets closer to the plume origin, but again gets constrained to the surface. V3, having started farther from the plume, uses the information collected by V1 and V2 to get within 2m of the plume in the vertical direction. Thus, although two of the three vehicles died, the group was able to complete the mission.

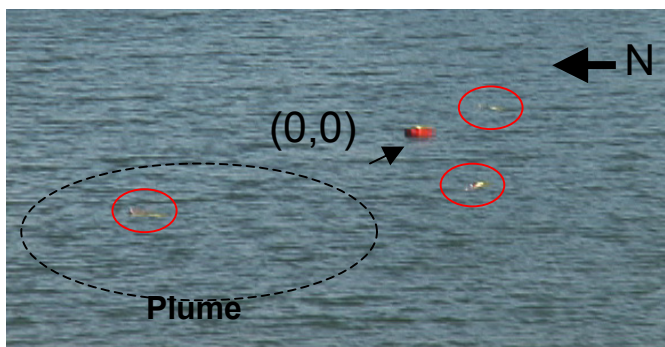


Figure 9: One vehicle inside the plume (located at (10N,-10E) and two vehicles approaching.

B. Front Mapping

Recently, we teamed up with NOS/NMFS CRCFH-Beaufort to demonstrate real-time profiling of a salinity front. The tests were performed in the mouth of the Newport River (NC) using four Rangers navigating autonomously along parallel tracklines and relaying data during the mission. Although only temperature and conductivity were tracked in this demonstration, the various sensors on Ranger permit multi-sensor 4D profiling of the water column.

In this demonstration, the Rangers were deployed from NOAA's R/V Hilderbrand in approximately three meters of water in the center of the estuary. The Rangers navigated on parallel tracks 0.4 km long, 40m apart. The mission lasted 2.5 hours and the vehicles followed a saw-toothed path.

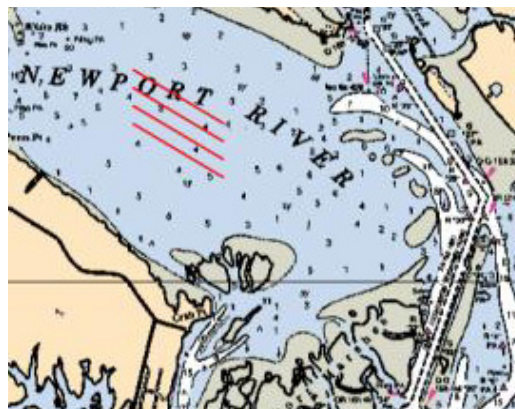


Figure 10: Map Showing the Tracklines Used for the Salinity Front Mapping Mission in the Newport River Estuary in Eastern North Carolina.

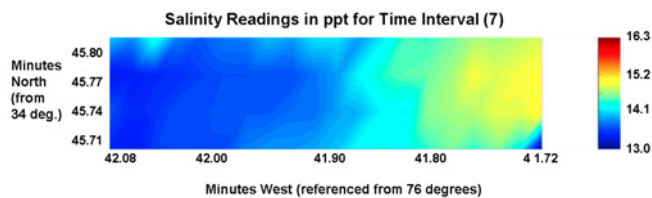


Figure 11: Plan View of the Work Site Showing the Salinity Front Moving from East to West (right to left). A Single Time Slice From the Middle of the Mission is Shown and the Salinity was Averaged Over the Depth.

In this demonstration, the Rangers were deployed from NOAA's R/V Hilderbrand in approximately three meters of water in the center of the estuary. The Rangers navigated on parallel tracks 0.4 km long, 40m apart. The mission lasted 2.5 hours and the vehicles followed a saw-toothed path between the surface and a depth of 1m, with a spacing between surfacing of about 30m.

During the demonstration, underwater navigation was done by GPS-assisted compass-based dead-reckoning. Both conductivity and temperature were sampled at 5 Hz, time-stamped, assigned a geo-location, and stored in memory. Each time Ranger surfaced, it would transmit data back to the ship-based server via the RF-link and zero its dead reckoning drift with a fresh GPS position fix.



Figure 12: Salinity Front Mapping; Nekton and NOAA Crew

NOAA scientists acquired CTD profile data at the perimeter of the search volume to ground truth the Ranger data. Since a sample of the CTD readings logged on board Ranger were radioed to the research vessel and displayed on FCS display, the position of the salinity front could be monitored as it moved across the search volume. Once the front passed, the Rangers were instructed via RF to return to the ship where they were successfully recovered and stowed.

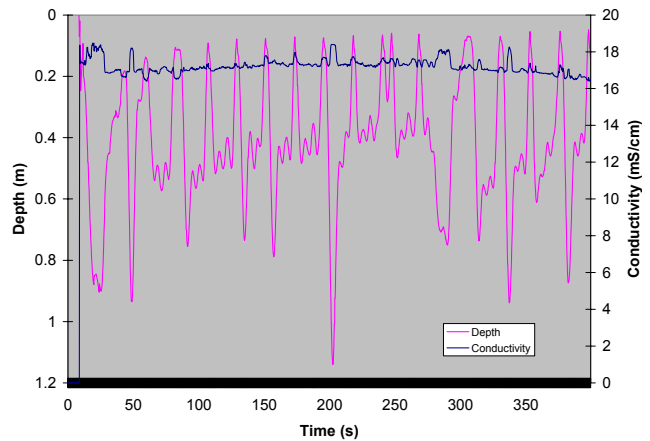


Figure 13: Conductivity as a Function of Time and Depth for One Trackline of One Vehicle

A subset of the data collected is shown in Figures 11 and 13. The movement of higher conductivity (saltier) water can be seen moving from right to left on the time series shown in Figure 11. Figure 13 shows a variation of conductivity with depth. Variations can also be seen over time, corresponding to the position of the vehicle as it travels on the East-West transits. A trend (which is partially shown in the figure), shows the expected cyclical conductivity measurements as the vehicle reverses course at $t=200$.

A thorough analysis of the data is currently being performed by the NOAA team and will be reported elsewhere.

CONCLUSIONS

The results of these studies show great utility and promise for MicroUUVs.

- We have shown Ranger to be a competent and robust platform, with the ability to incorporate a wide variety of sensors.
- We have conducted missions where the vehicle's route is determined not by a preset list of waypoints or external commands, but based on in-flight observed data, pushing the level of autonomy demonstrated by UUVs.
- We have shown Ranger to be a robust platform for testing multi-agent algorithms.
- We have shown coordinated, fault-tolerant behavior of a group of UUVs.
- Because of its size, capabilities, and record of mission success, Ranger is becoming an effective tool for the oceanographic and military communities.

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