FIELD RESULTS OF MULTI-UUV MISSIONS USING RANGER MICRO-UUVS

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Abstract. **The Ranger micro-UUV from Nekton Research has been deployed successfully in various multi-agent mission demonstrations, including formation flying to map a salinity front and adaptive cooperation to localize the origins of test plumes. The low cost and simplicity of using the 5 kg Rangers make possible multi-agent missions and algorithm testing that is beyond the economic reach of alternative UUVs. Efficiency and utility of the Ranger-UMAP multi-agent system derives in part from Fleet Logistical Interface and Control Software (FLICS) software created for preparation, deployment, monitoring, mid-mission re-tasking, and recovery of multiple vehicles used in cooperative missions.**

I. INTRODUCTION

The past ten years have seen an increase in the number of applications that employ UUVs, particularly 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,[7] with limited exceptions[8] we are not aware of any full scale experimental work.

In order to bridge the gap between simulation and field testing, Nekton is continuing development of the Ranger micro-UUV, and the Underwater Multi-Agent Platform (UMAP), which is comprised of N-Rangers and the supporting infrastructure that allows rapid configuration, deployment, and monitoring of multiple vehicles by a single operator. 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. This potent combination opens the door to the three fundamental multi-agent handles, i.e. the abilities to control group geometry, to share data, and to react collectively. For this reason, Ranger and UMAP pave the way to a host of underwater applications ranging from distributed search algorithm research (MCM, lost asset search), to formation flying (beam forming, flexible array), and to general oceanography (bathymetry, mixing studies, search/localization/characterization of underwater plumes, etc).

At present, we have constructed nine micro-UUVs and the supporting infrastructure called Fleet Logistical Interface and Control Software (FLICS) and tested the system under two operational scenarios. The first set of deployments tested a multi-agent collaborative plume localization algorithm developed by Sandia National Laboratory. The second set of deployments, done in conjunction with NOAA, performed 4D mapping of a salinity front in the Newport River on the coast of North Carolina. The vehicle, system, and deployments are discussed in this paper.

Figure 1. Four Rangers beginning a mission

II. RANGER

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: simultaneous LBL positioning and underwater communication).
- 440kbps RF modem
- WAAS enabled GPS
- Compass and attitude sensors
- Internal recharging system.
- 64MB Flash expandable to 40GB

Other features are summarized in Figure 2.

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. Ranger Specifications

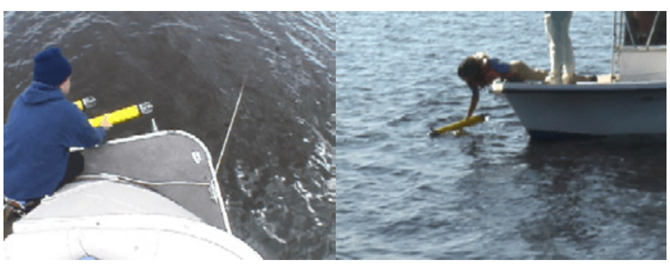

Figure 3. Because of their small size, Rangers are easy to deploy and recover.

III. UMAP RANGER INFRASTRUCTURE

Fast and efficient multi-agent missions depend on a fleet management support system, such as the Fleet Logistical Interface and Control System (FLICS) 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 the vehicles mid-mission. Recovery mirrors deployment and has added shutdown steps. Such tasks can be time consuming when a single vehicle is deployed. Clearly, they rapidly impose unsupportable burdens if multiple vehicles are not managed by a FLICS-like logistical support system.

Examples of practical complications that occur without FLICS support include:

- 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.

The FLICS software developed by Nekton 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. Also included in the FDMC is the ability to calibrate and perform diagnostics on individual vehicle systems such as the compass, servos, or depth sensor. Figure 4 shows a picture of the FDMC layout.

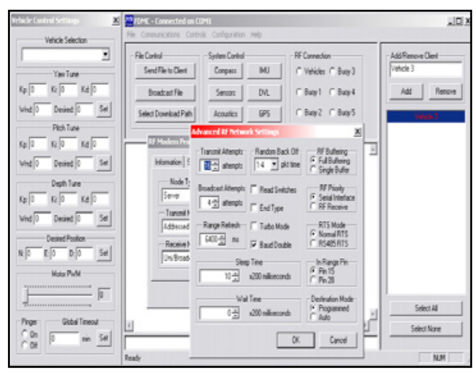

Figure 4. FDMC Screen View

When the mission is underway, the FCS module provides the topside interface to the vehicles via either RF (surface) or acoustic (subsurface) communications. With dual display windows to show both a simple representation of the entire mission area along with 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. Add to this simple initialization and the ability to send commands to either individual vehicles or groups of vehicle, and the FCS provides a very useful tool for communicating to vehicles in the water.

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 along with information such as sensor values, heading, depth, and the time of last contact with each vehicle.

Mission commands for user intervention are also provided by the FCS and 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.

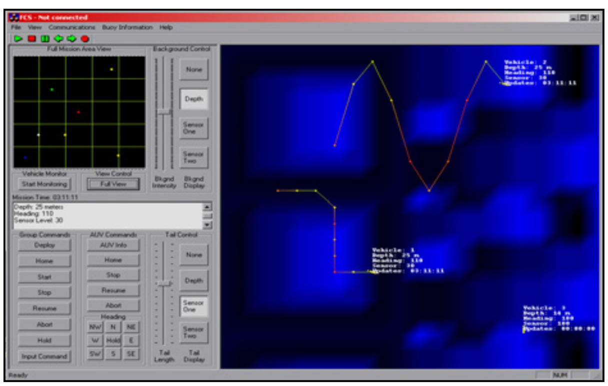

Figure 5. FCS Fleet Controller Screen View

Ongoing work on the FLICS software package has resulted in the addition of network capabilities to the system in the form of RangerNet. This allows the operation of several Rangers on the same RF network to be accessed from any networked PC. Any RangerNet client program may connect to the RangerNet server and request either full access to control or read-only access to observe any of the available vehicles. The result is the centralization of all RF network drivers to the RangerNet server and a common interface to build client programs with access to the vehicle network upon. Advantages of this client-server model include the ability to set up multiple stations for deployment and maintenance and a seemless transition for the vehicles from station to station (or station to deployment) while still connected via RF to RangerNet.

Figure 6. Monitoring and control of the fleet from a single station.

IV. MULTI-AGENT MISSIONS

A. Plume Source Localization

In order to demonstrate collaboration of underwater vehicles, an algorithm developed at Sandia National Labs was ported to three vehicles. The algorithm is essentially a gradient search algorithm that uses both data collected by the vehicle and data collected by other vehicles. A detailed description of the algorithm can be found in [8].

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 track line keeps the vehicle far outside the plume boundary. The goal was for all three vehicles to converge to the plume source.

The plume intensity is based on an artificially generated source where intensity is defined as:

$$sensor = \frac{1275}{R^2 + 5} \qquad (1)$$

where R is the distance to the plume source.

For this effort, acoustic positioning and communication was 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 is logged by the vehicle at 10Hz. The data subset transmitted to the other vehicles via the FCS is five samples and is kept in the same packet format as would be used by the acoustic system. Figure 7 shows the vehicle trajectories where the plume is set at 10m North, 10m West, and 1m down. The circle represents the plume boundary.

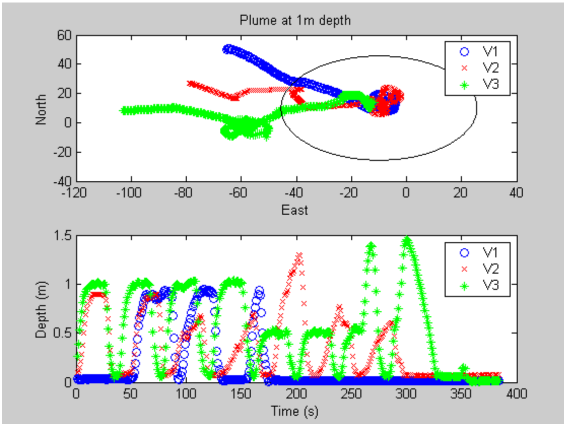

Figure 7. Position and vehicle depth vs. time plots for a plume at 1m depth.

As can be seen from Figure 7, 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. The bottom graph (Figure 7) shows the depth profiles of each vehicle. The periodic surfacing is readily seen. We note that the vehicles tend to stay around 1m, the depth of the artificial plume. Figures 8 and 9 show the same mission with plume depths of 3m and 5m respectively. As the plume depth increases, we find that the depth excursions grow deeper.

An interesting feature can be seen in the 5m case (Figure 9). 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 has an extremely difficult time getting off of the surface to begin a dive. This

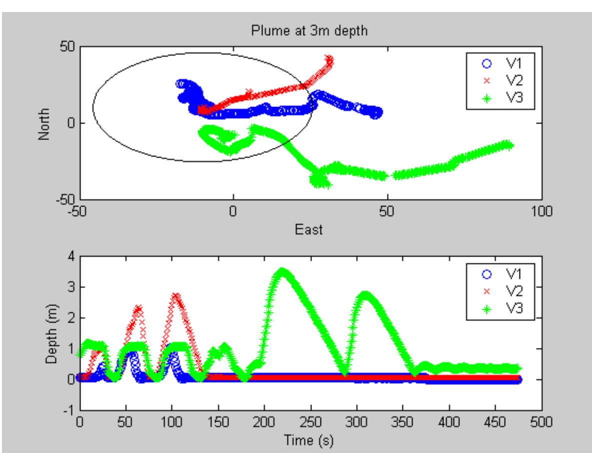

Figure 8: Position and vehicle depth vs. time plots for a plume at 3 m depth.

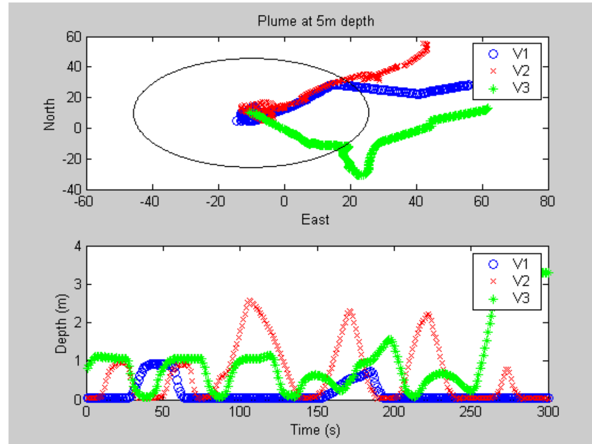

Figure 9. Position and vehicle depth vs. time plots for a plume at 5m depth.

becomes 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. Whenever 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, it cannot get enough straight line motion to dive. However, as can be seen in the Figure, V1 and V2 have collected enough spatial data that V3, still relatively far away from the plume source, is able to not only home onto the plume source, but also get closer in depth. This shows the robustness of the multi-agent approach.

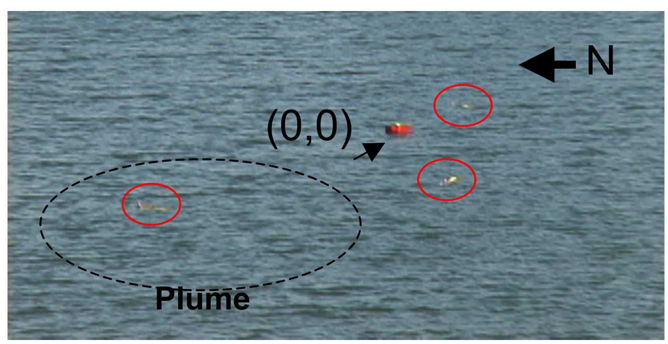

Figure 10: One vehicle inside the plume (located at (10N,-10E) and two vehicles approaching.

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 Ranger micro-UUVs navigating autonomously in formation 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.

Figure 11. Salinity Front Mapping;
Nekton and NOAA Crew

In this demonstration, four Rangers were deployed in schools 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, and 0.5m deep in multiple runs over a 2.5 hour period.

During the demonstration, navigation was done by compass-based dead-reckoning. Both conductivity and temperature were sampled at 5 Hz, time-stamped, assigned a geo-location, and stored in memory. Each Ranger communicated data via the RF link and received a GPS position update to correct dead reckoning drift during a brief visit to the surface following each 30-second data collection interval.

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.

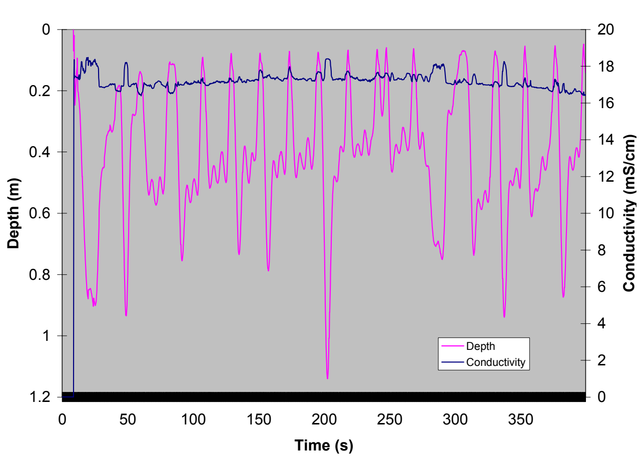

Figure 12: Conductivity and Temperature recorded as a function of time.

A subset of the data collected is shown in Figure 12. A preliminary review of the data given shows a variation of conductivity with depth, with conductivity readings increasing 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 cyclical conductivity measurements with an average period of approximately 15 minutes, the time required to travel from the east waypoint to the west waypoint and back given the currents experience.

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

V. CONCLUSIONS

The results of these studies show great utility and promise for micro-UUVs.

- 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.

VI. ACKNOWLEDGMENTS

The Ranger micro-UUVs were developed with support from DARPA. Steve Eskridge of Sandia National Labs, Johnny Hurtado of Texas A&M University, Lee Freitag of Woods Hole Oceanographic Institute, and Pat Tester and her crew at NOAA NOS Beaufort were also instrumental in the success of this effort

VII. REFERENCES

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