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INITIAL DEVELOPMENT AND TESTING OF AN ADAPTIVE MISSION PLANNER FOR A SMALL UNMANNED UNDERWATER VEHICLE

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ABSTRACT

An Adaptive Mission Planner (AMP) was developed for the REMUS Unmanned Underwater Vehicle (UUV) in order to have the vehicle react to real-time sensor data and alter course for the purpose of chemical plume tracing. In order for a UUV to track a plume autonomously, it must implement search strategies in an intelligent manner as dictated by environmental circumstances without human intervention. Throughout the mission, the UUV will combine the sensed flow and concentration information to construct a map of likely source or plume locations. This AMP has been designed and tested in simulation at the University of California, Riverside, and has now been installed on the SPAWARSYSCEN-SD REMUS UUV. This paper will describe the search strategies and initial field tests which use the AMP to break away from the vehicle's pre-programmed missions. Two sets of experiments are described herein. The first uses bathymetry as the environmental driving input. The second uses chemical concentration as the primary input.

Keywords: Chemical Plume Tracing, UUV, AUV, REMUS

INTRODUCTION

In support of the Office of Naval Research's (ONR) Chemical Sensing in the Marine Environment Program (CSME), an Adaptive Mission Planner (AMP) was developed for the REMUS Unmanned Underwater Vehicle (UUV) in order to allow the vehicle to react to real-time sensor data and alter course. One purpose of the CSME program is to develop, test, and integrate chemical sensors onto mobile platforms. Another objective is to demonstrate chemical plume tracing by UUVs. A plume tracing demonstration requires an Adaptive Mission Planning capability so that the UUV can rapidly respond to odor detection events and changes in the fluid environment (e.g., flow direction). An AMP with the desired Chemical Plume Tracing (CPT) algorithms has been designed and tested in simulation by Dr Jay Farrell at the University of California, Riverside (UCR), in support of the DARPA/ONR Chemical Plume Tracing Program, which focused on the development of biologically-based plume tracking strategies for UUVs. Research supported by the ONR CSME program has further developed these capabilities and developed software suitable for on-vehicle testing.

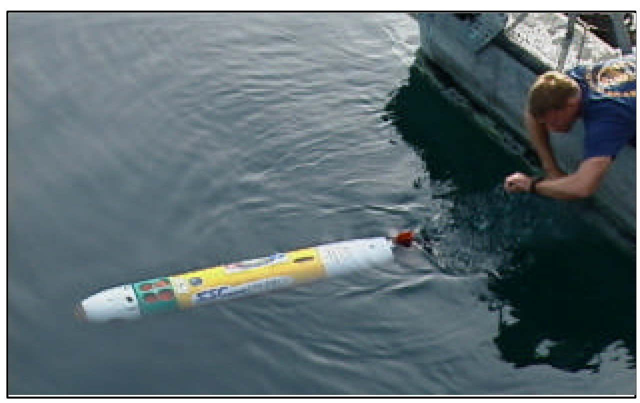

Figure 1. REMUS vehicle, Albacore, being launched.

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The AMP is a separate "brain", which has the ability to take control of the vehicle and provide it with external navigation and control commands. This AMP is installed on the Space and Naval Warfare Systems Center – San Diego (SPAWARSYSCEN-SD) Remote Environmental Monitoring UnitS (REMUS) UUV, named Albacore (built by the Woods Hole Oceanographic Institution (WHOI)). During normal operations, the standard REMUS vehicle executes a pre-programmed mission, navigating to pre-determined waypoints and water depths and/or altitudes above the bottom. However, for certain missions such as plume tracing, it is desirable for the vehicle to be able to adaptively modify its plan based on inputs received during the mission from vehicle sensors.

In order for a UUV to track a plume autonomously, it must implement search strategies in an intelligent manner as dictated by the mission circumstances without human intervention. Throughout the mission, the UUV will combine the sensed flow and concentration information to construct a map of likely source or plume locations. The AMP was integrated onto the REMUS UUV in mid-2002, and results of the initial field tests are presented herein.

AMP LOGIC

In UUV plume tracing applications, the mission objective is to locate sources of chemical odor. This objective will be achieved either by causing the vehicle to trace the odor plume to the odor source or by estimating the source location at a distance from the source based on characteristics of the plume and the measured fluid flow. The mission objective can be subdivided into the following sub-problems:

a. Plume Finding - The task of searching a potentially large area to detect the plume for the first time.

b. Plume Tracking - Once the plume has been detected, this portion of the strategy attempts to maintain, at least intermittently, contact with the plume, while traveling up the plume towards the odor source.

c. Plume Reacquisition - If contact with the plume is lost, this component of the strategy initiates a local search based on knowledge of the local flow and past detection locations to attempt to reacquire contact with the plume.

d. "Source Found" declaration - Accurately making this declaration is the ultimate goal of the strategy.

To solve the overall plume-tracing problem autonomously, the UUV will implement alternative strategies to solve each sub-problem and switch between the implemented strategies in an intelligent manner as dictated by mission circumstances, without human intervention. Throughout the mission, the UUV will combine the sensed flow and concentration information to construct a map of likely source or plume locations.

Plume Finding:

Under the assumption that the chemical source may be located anywhere in the Operation Area (Op-Area), finding the plume is a uniformed search problem. Therefore, finding the plume may require a complete search of the Op-Area. However, since chemical flows are typically long in the direction of the flow it is more beneficial to explore the entire search area in a cross flow pattern than it is to perform an extensive search across each sub-area. The finding behavior explores the Op-Area by reflecting off the Op-Area boundaries in a billiard ball fashion. The initial direction of the vehicle is selected to point the vehicle towards the quadrant containing the Op-Area corner that is farthest from the vehicle. The reflection angles of this behavior are selected to cause the vehicle to:

- frequently cross the Op-Area in the cross flow direction,
- explore the Op-Area in the along flow direction, and
- ultimately fill the entire Op-Area.

When the vehicle detects odor, it switches to the Plume Tracking Behavior.

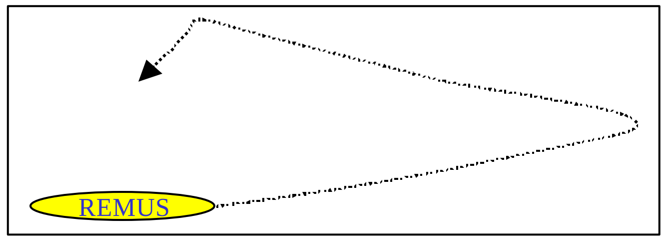

Figure 2. Illustration of REMUS path ‘bouncing’ off Op-Area walls.

Plume Tracking:

If the chemical plume has been detected recently (i.e., within T_w seconds), then the behavior based planner uses the plume tracking behavior. The objective of this behavior is to maintain at least intermittent contact with the chemical plume. Since the chemical plume develops in a flow that varies both spatially and temporally, the chemical plume may meander significantly. Plume meander may result in the local plume axis not being aligned with the local plume flow. Also, the local plume axis may not point back towards the source. Due to the turbulent flow, the plume is composed of mixed parcels of chemical and water that result in a highly intermittent sensor signature. Due to both the meander and the intermittency, gradient-following-based algorithms are not suitable for this application, as discussed in [1, 2].

The plume tracking behavior implements a counter-turning behavior similar to that described in detail as Strategy 3 in [1]. The direction of flow F in degrees is calculated onboard the vehicle using Acoustic Doppler Current Profiler (ADCP) data. For the L seconds following detection of chemical, the behavior maintains a direction that is F + 180 +/- B degrees where the sign of the operation in front of B is selected to cause the vehicle to cross the plume. If the vehicle fails to detect for L seconds, then the sign of the operation in front of B is reversed. This sign reversal causes the vehicle to reverse the cross-flow component of its velocity. This counter-turning tends to keep the up-flow progress of the vehicle centered on the local plume even when the plume is meandering. If the vehicle fails to detect chemical for a period of T_w seconds, then it switches to the Plume Reacquisition Behavior.

Plume Reacquisition Behavior:

The purpose of this behavior is to cause the vehicle to search locally within the vicinity of the last point at which the chemical was detected. When the planner switches to this behavior, three points are calculated that are separated by 120 degrees on a circle of radius 15 meters that is centered on the last detection point. Call these points P1, P2, and P3. This behavior will go to each of these points in the following sequence (P1,P2,P3, P1,P2,P3, P1,P2,P3,P1), unless odor is detected. If odor is detected, then the behavior immediately switches to Plume Tracking. If the above sequence completes without odor being detected, then the behavior switches to the Plume Finding.

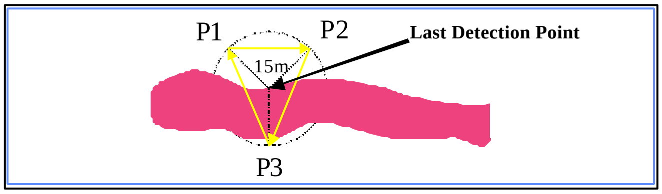

Figure 3. Illustration of Plume Reacquisition Points.

Source Declaration Behavior:

Each time the planner enters the Plume Reacquisition Behavior, the planner stores the location of the last detection. A list of the last N points at which plume contact was lost is saved. This list of lost detection points is used to make a source-found declaration. Once the source location is declared, the AMP disables and the REMUS returns to the preprogrammed mission. Two different source declaration behaviors were used during the set of experiments.

The initial AMP algorithm kept N=3 points. The source would be declared if the box defined by these three points had length and width less than R = 4 m. This version of the AMP was used for approximately 7 missions. This method failed to declare even though the vehicle spent significant time maneuvering near the source. The variable R could have been tuned. However, the correct value of R is somewhat dependent on the speed, since the speed determines the turning radius of the vehicle. Therefore, during the field tests, a new declaration approach was implemented. The next AMP version kept N=6 points. These six points were sorted by their up-flow position. If the three points most up-flow points were within R=5 m of each other in the direction along the flow, the source location was declared. This source declaration logic succeeded in 7 of 8 runs.

AMP-REMUS PROTOCOLS

The REMUS vehicle, Albacore, contains two computer systems. The first computer system, referred to herein as REMUS, is the standard REMUS control, navigation, and sensor suite. The second computer, referred to herein as the AMP, implements the CPT algorithms. The AMP sends guidance (i.e. heading, speed, and altitude) commands to the REMUS via serial port [3]. The AMP is responsible for interrupting a pre-programmed REMUS mission, performing its CPT task, and then returning the REMUS to its pre-programmed mission. General concepts of the communications protocol, developed to support external control of the REMUS vehicle, are described below.

The protocol does not restrict conventional REMUS mission programming. In the absence of mission override instructions, the vehicle operates in a normal manner. The override may be invoked by either of two methods:

1. The external system, the AMP computer, may send a message indicating that the external system wishes to take control of the vehicle. Using this method, the current operational objective is suspended until the override operation has been completed. At the conclusion of the override, the vehicle will continue with the regular mission from the point at which it was interrupted.

2. The vehicle may be specifically programmed with an objective that indicates when and where the override is to commence. At the conclusion of the override objective, the vehicle will continue with the next objective.

Regardless of the method of invocation, the override is normally exited by the external controller explicitly issuing a disable command to the vehicle. At this point the vehicle will transit back to the position (latitude and longitude) where the vehicle originally entered the override, and then resume normal operations.

At all times, the vehicle provides to the AMP information about the current operating state of the vehicle. This information includes data such as:
-operating mode (pre-launch, in mission, post mission)
-latitude and longitude
-depth and altitude
-heading and heading rate
-attitude (pitch and roll)
-heading and depth goals
-vehicle speed, rpm, and rpm goal

At all times the vehicle also provides to the AMP information from selected sensors, including:
-ADCP (altitude, current, along/cross track vehicle speeds)
-Chemical sensor data (fluorometer)
-C-T-D (conductivity temperature depth data)
-Battery status

The protocol provides support for control messages allowing setting or commanding of the following parameters:
-Heading, heading rate, or a latitude/longitude goal.
-Depth/Altitude or a combination of these modes (yo-yo)
-Speed (in RPM, meters/sec, or knots)
-Entering and/or exiting the control override mode.

Absence of control commands for a period of time will result in a timeout, and exiting from the override mode. The vehicle may ignore the commands as part of its normal procedure in order to protect and/or ensure proper operation, such as a command to go to a depth greater than some preset vehicle maximum. Other vehicle protection systems, such as aborting upon detection of a leak function normally, and are not adversely affected by the system, whether active or not.

FIELD TESTS

Three sets of field tests are presented in order to describe the initial development of the AMP on the REMUS vehicle. The 1st tests, performed near Woods Hole, MA, include the initial debugging and checkout of the integrated AMP-REMUS system in order to verify proper communications between the REMUS control computer and the AMP. The 2nd tests, performed in the southern section of San Diego Bay, CA, were to verify that the AMP's reactions to environmental parameters were appropriate and correctly implemented by the vehicle. The purpose of the 3rd set of field tests, performed off San Clemente Island, CA, was to assess and enhance the performance of the CSME Chemical Plume Tracing algorithm utilizing the REMUS Adaptive Mission Planner (AMP) under relevant environmental conditions.

Woods Hole Checkout Tests 12-13 August, 2002

The purpose of these tests was to perform the first in-water checkout of the modifications made to the SPAWARSYSCEN-SD REMUS vehicle, Albacore, after the installation of the AMP.

Before an in-water test was performed these 3 steps had to be performed:

-Verify proper communications between the REMUS control computer and the planner running on a notebook computer.

-Download and start the planner on the AMP and simulate an in-water run.

-Verify proper communications between the REMUS control computer and the AMP by simulating a run.

The final goal was to perform an in-water test of the AMP at WHOI by running a simple plan and driving the vehicle.

The first day at WHOI was spent working on and debugging the communications protocols between the REMUS control computer and the AMP.

Figure 4. The Albacore on the Bench.

After successful debugging and completion of bench tests, at-sea tests were performed.

Figure 5. Transiting to WHOI Op-Area.

For the initial at-sea tests, the AMP computer took control of the REMUS vehicle in mid-mission and redirected the vehicle. At the end of the AMP mission, the vehicle control was successfully transferred back to the REMUS computer. These runs demonstrated the transfer of control of the vehicle from the REMUS software to the AMP computer. The AMP computer issued commands from a file to the REMUS, such as the east-west runs shown below in Fig 6.

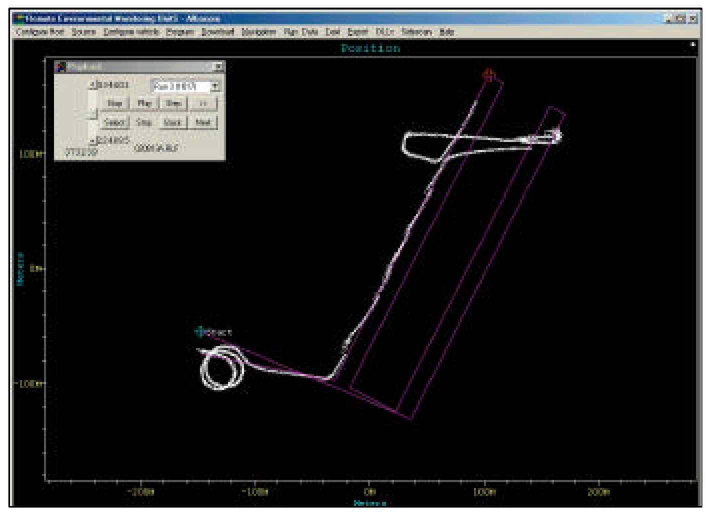

Figure 6. First Successful Run of Adaptive Mission Planner Computer.

Figure 6. shows the vehicle route for the mission. The thin purple line is the pre-programmed route and intended mission of the REMUS vehicle. The white line is the 'actual' vehicle path obtained primarily from the Long Base-Line (LBL) navigation system. After a programmed amount of time, the AMP computer took control and directed the vehicle to break path from the pre-programmed route and run east-west. When the AMP returned control to the REMUS computer, the vehicle correctly returned to the pre-programmed route and continued the original mission.

The following figures walk through the events of an actual AMP mission in Buzzards Bay. Again, the purpose of this run is to demonstrate the transfer of control of the vehicle from the REMUS software to the AMP computer. The AMP computer is issuing commands from a file to the REMUS.

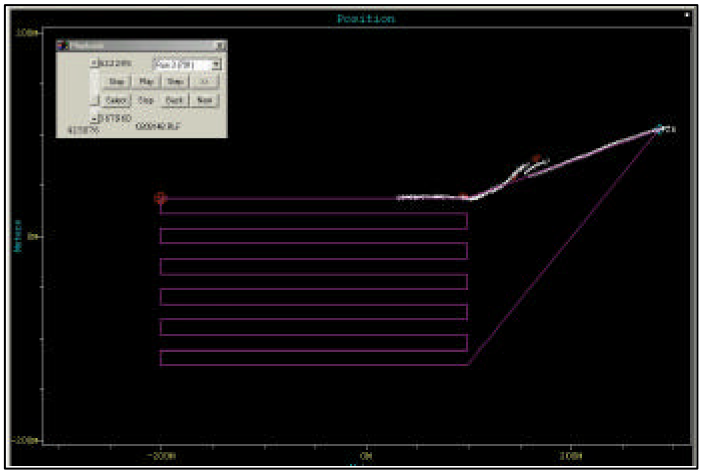

Figure 7. REMUS is programmed to 'Navigate Rows' east-west [purple lines] and the vehicle is following the track of the 1st row.

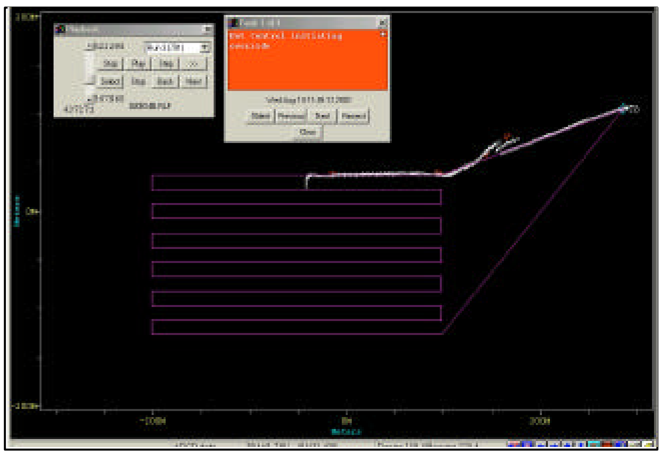

Figure 8. AMP Computer takes control and directs REMUS to swim south.

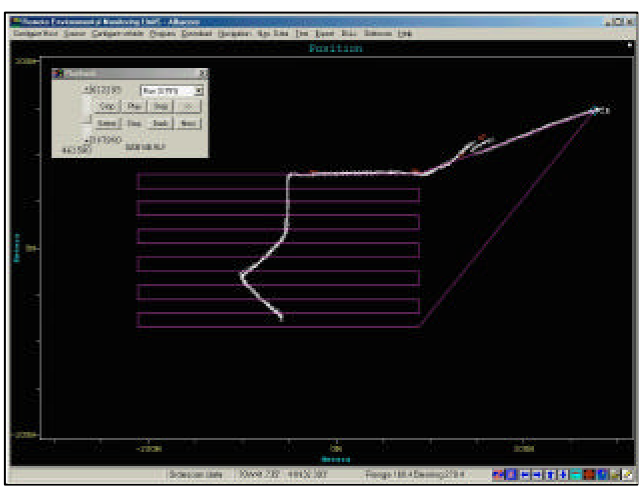

Figure 9. AMP directs the vehicle to swim a zig-zag path south.

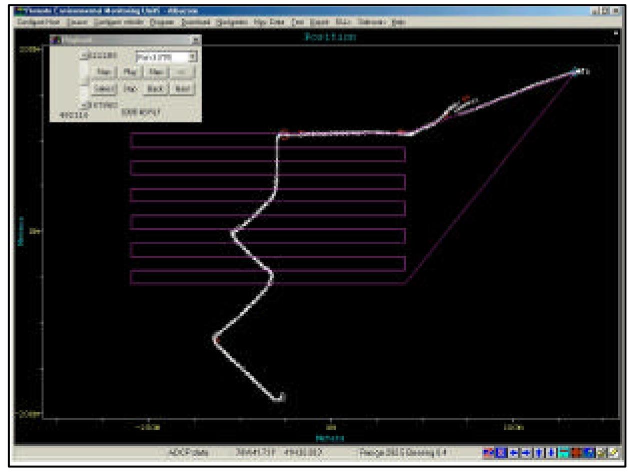

Figure 10. AMP continues directing for ~3 minutes and then relinquishes control back to the REMUS computer. The REMUS computer's 1st objective is to return to the initial breakoff point.

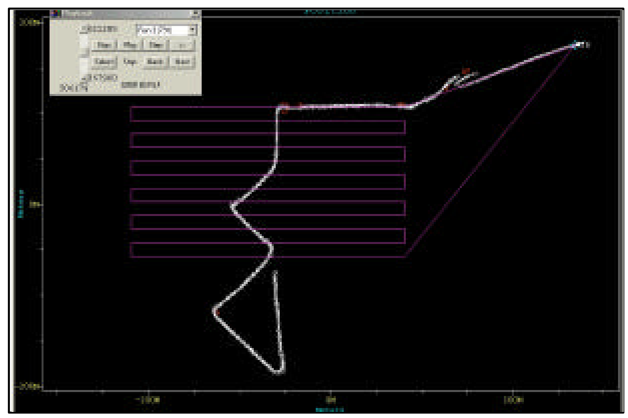

Figure 11. The vehicle swims back to the initial breakoff point.

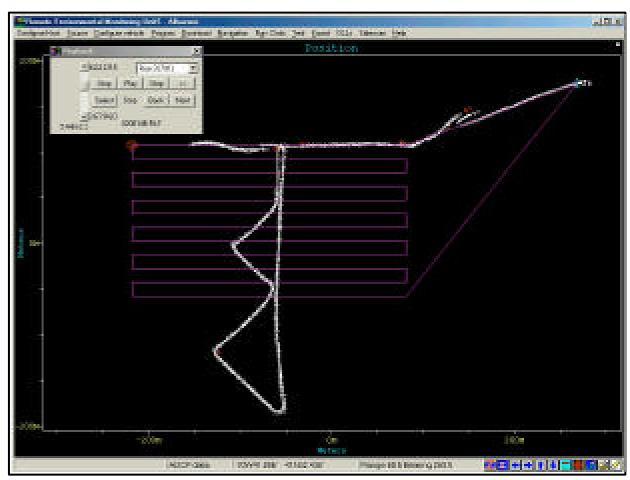

Figure 12. The vehicle then follows the original pre-programmed mission.

South San Diego Bay Bathymetry Runs 26-29 August, 2002

The purpose of this test was to demonstrate the AMP responding to environmental data to accomplish a task. This demonstration is preparatory to the task of chemical plume tracing. Since the cost of setting up a plume is high, the AMP objective of this experiment was to find the deepest location in the operational area based on sensed depth, altitude, and position data. These tests were performed in San Diego. The REMUS vehicle successfully ran search patterns to find local depth extremes within a defined area.

The San Diego Bay tests demonstrated the ability for a vehicle to detect a specified environmental parameter, such as water depth, and adapt its search pattern based on preset limits for that particular mission.

The objectives of these tests were:

-To find a local maximum depth within an operating area. The mission definition would need to include a time limit and a test box specified by coordinates.

-The planner should keep the vehicle within the test box. The mission will terminate either through a timeout, or by the vehicle succeeding and returning to the vicinity of its starting location.

-To start the AMP mission within the test box.

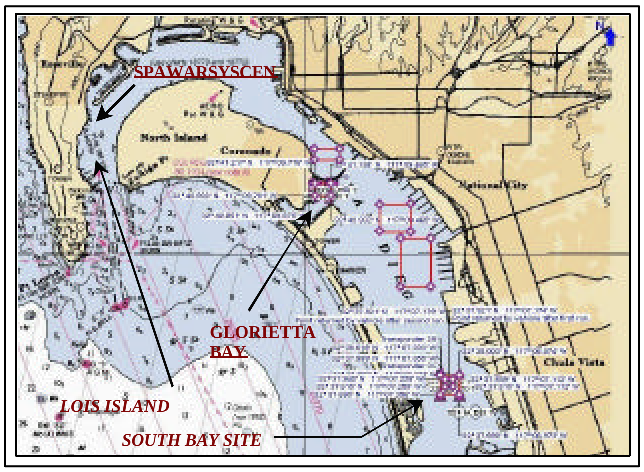

Figure 13. South bay op-area, near Chula Vista at the end of the boat channel.

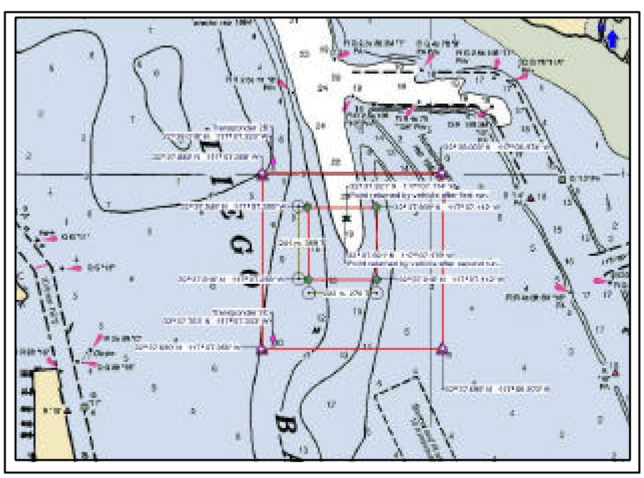

Figure 14. Chart of south bay op-area w/ bathymetry. Small box is op-area.

Two adaptive searches for the deepest point in the test area were completed. The first run returned with the point [32d 37.9273N, 117d 07.1744W]. The second run returned with the point [32d 37.9206N, 117d 07.1787W]. While the search patterns for the 2 runs were different, both resulted in locations which were within 13 meters of each other and matched the bathymetric data as shown in Figure 20.

Figure 15. Launch of the REMUS Vehicle.

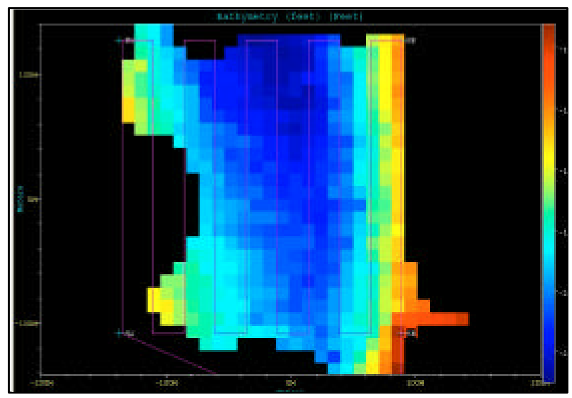

Figure 16. Bathymetry from REMUS run.

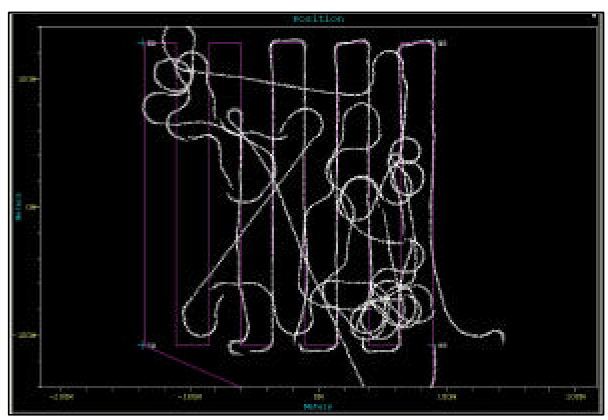

Figure 17. *AMP vehicle track.*

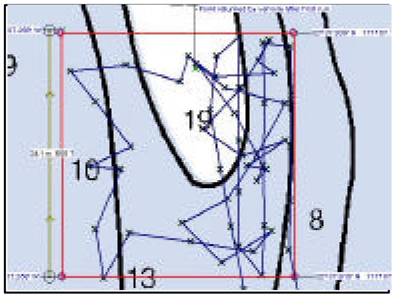

Figure 18. AMP 1st Run.

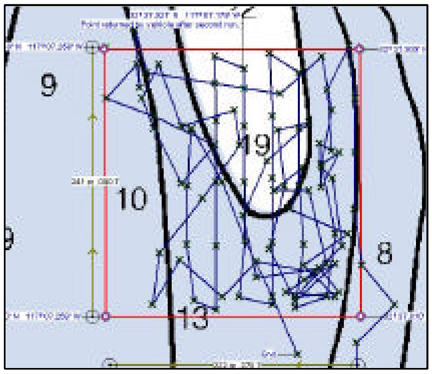

Figure 19. AMP 2nd Run.

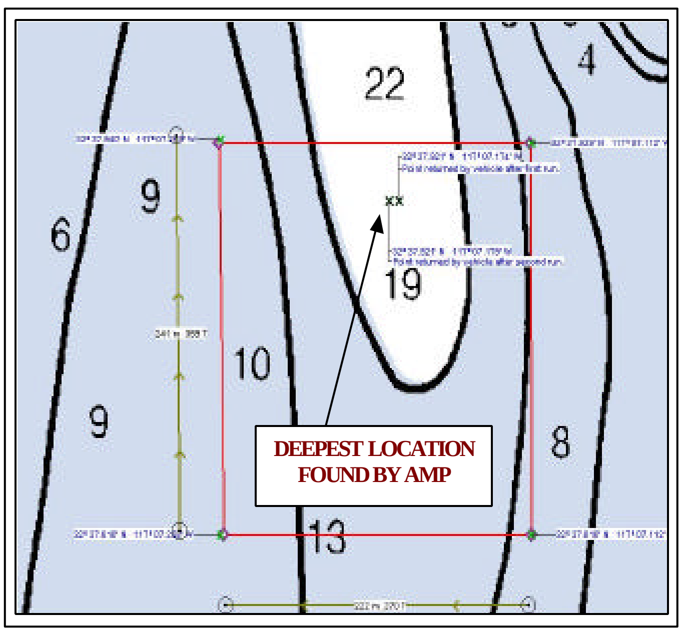

Figure 20. Output from 2 AMP runs. Points are with 13 meters of each other.

San Clemente Island Tests 13-19 Nov, 2002

The purpose of this experiment was to perform in-water evaluations of algorithms designed to locate the origin of chemical plumes in turbulent flows. For this experiment, the fluid environment is the ocean near the coast of San Clemente Island, California. The chemical of interest for these tests is Rhodamine dye, which is detected by a Seapoint fluorometer mounted in the nosecone of the REMUS vehicle.

Figure 21. REMUS vehicle swimming through dye plume.

The approach is to utilize the REMUS AUV, equipped with the AMP and a Seapoint fluorometer to run plume measurement and tracing missions. The vehicle must track the chemical plume, reacquire in case it leaves the plume, and finally declare the location of the source of the plume. During the experimental runs:

-the REMUS is programmed to perform its pre-programmed search mission;

-the AMP is enabled to take over the control of the vehicle after certain number of seconds;

-the AMP "drives" REMUS and performs chemical plume tracing using the information from vehicle's sensors until either it has declared the source of a chemical or it has reached its programmed time limit; and then,

-the AMP gives the control back to REMUS computer.

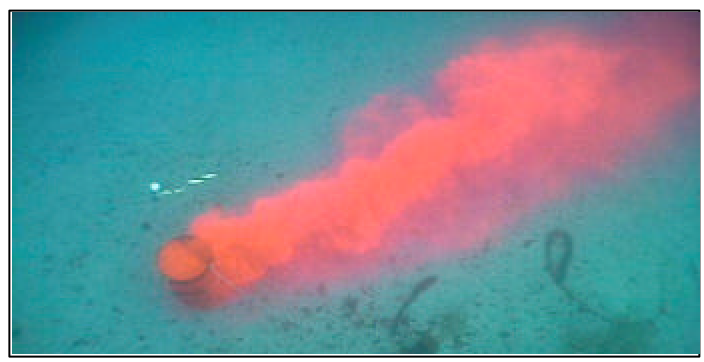

Figure 22. Dye plume dispersing from source.

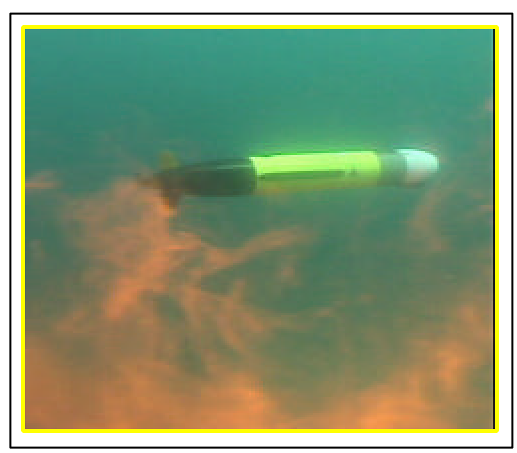

Figure 23. Vehicle on edge of plume.

Mission Runs

Fifteen AMP missions were run. The first four missions terminated short of completion due to setup modifications associated with navigational and AMP programming parameters. Following these trial runs, the next 3 missions demonstrated successful vehicle behaviors for plume finding, plume tracking, and plume reacquisition. However, while the vehicle was spending the majority of its mission searching directly in the vicinity of the source, and in one incident, actually glanced off of the source, no source declaration was occurring. Figures 24 and 25 illustrate data from one of these missions. Figure 24 shows a plume map generated from the vehicle's fluorometer data. The plume is accurately mapped showing the highest concentration. Higher concentrations are denoted by the red end of the color scale, at the source location (left middle of plot). Figure 25 illustrates the vehicle path during this mission with the transition from the pre-programmed "navigate rows" path (rows starting at the lower left and proceeding to middle right) to the "adaptive search" mission (AMP taking control at middle right). Note that that once the vehicle detected the plume on the middle right portion, it then swam directly up the plume and began circling the source location. Despite these behaviors, no source declaration was made during this run. This data was, however, used to implement an optimized source declaration algorithm.

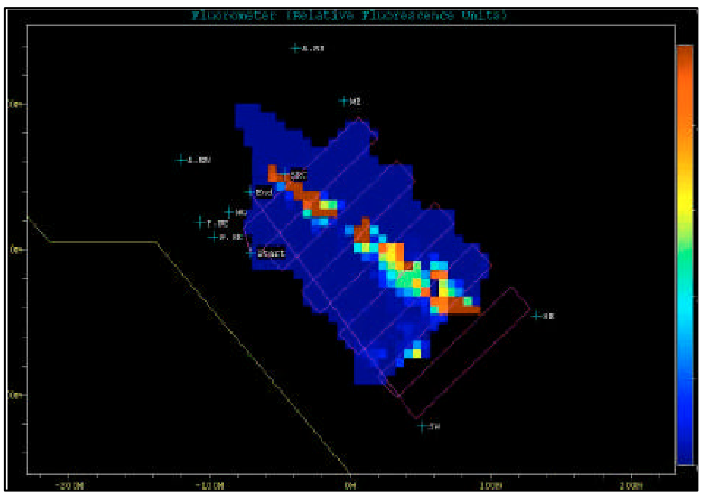

Figure 24. Plume Map.

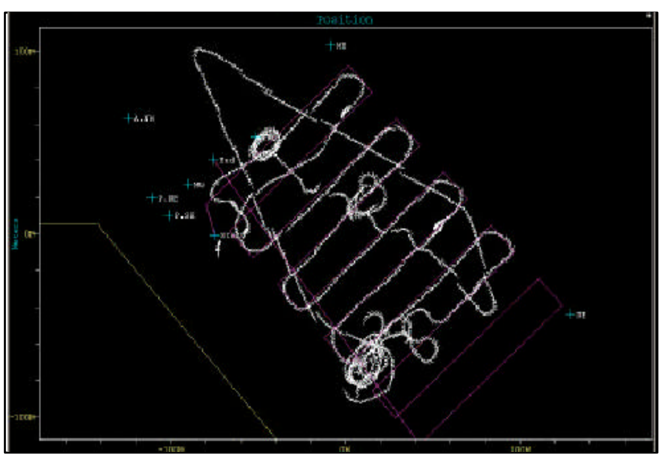

Figure 25. Associated Vehicle Path.

Figure 26. Vehicle Swimming by Source.

Figures 21, 23, and 26 are images of the vehicle performing its search in the direct vicinity of the source. While the UUV was unable to declare the source location during this mission, it remained in the direct vicinity of the source until the mission timed-out.

Following the 7th mission the declaration algorithm was revised. As a result of the revision, missions 8-15 resulted in a source declaration in 7 out of 8 missions. Accuracy from these 7 declared locations to the nominal source location range between 15 and 50 meters as illustrated in Fig 27.

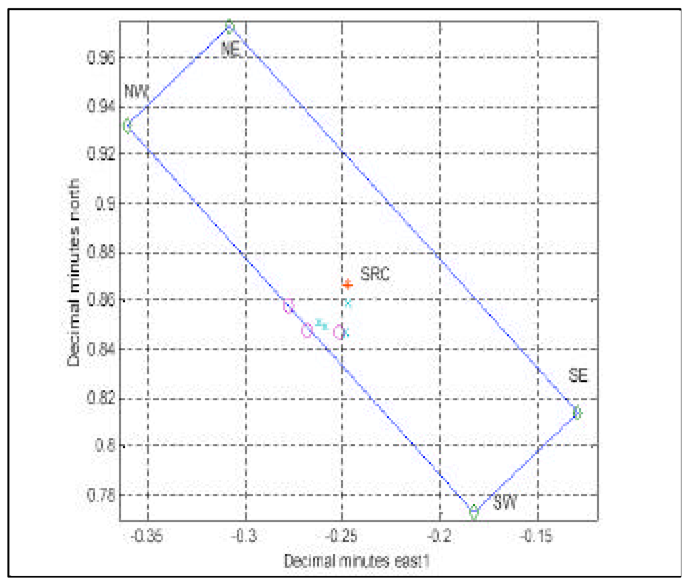

Figure 27. Source Declaration Marks in geodetic frame. An 'x' indicates a declaration point from 11/15/2002. An 'o' indicates a declaration point from 11/16/2002. SRC denotes the nominal source location.

Declaration Accuracy

There are four primary errors to consider when evaluating this declaration accuracy:

1. The source location, SRC, is obtained by placing the source with divers, surfacing and then taking a differential GPS fix. The measured surface location could differ by a few meters from the projection of the actual source location up to the surface.

2. The plume is in the bottom mixed layer and stays near the bottom for some distance in the down flow direction from the source. This distance is dependent on the actual flow characteristics. The REMUS cannot detect the chemical until the chemical is at the same altitude as REMUS. Therefore, the source declaration location is expected to be D meters in the down-flow direction from the actual source location. The value of D is unknown and is dependent on flow conditions.

3. The REMUS location is determined by a combination of dead-reckoning and a Long BaseLine (LBL) navigation system. The LBL works by measuring the travel time of acoustic signals between the vehicle and LBL transponders. Theoretically, the LBL transponders are stationary. In reality, the acoustic transponders are moored in the water column along lines connected between anchors and surface buoys. Therefore, the transponder locations shift with the flow. If the transponders move L meters from southeast to northwest, due to a reversal in flow, the entire coordinate system in which the REMUS location is computed moves with it. Since the source location is fixed, this would cause the source location in the REMUS coordinate system to move shift L m southeast. The actual value of L is not known.

4. The LBL locations are determined by dropping the transponder anchors near predefined differential GPS waypoints. This process should result in the anchor location being within a few meters of the desired anchor location.

The largest sources of error are the parameters L and D defined above. The determination was made that these experiments have advanced to a level where greater accuracy is required. In future tests, extensive effort will be made to calibrate the navigational and declaration errors. For instance, to calibrate L, driving the vehicle past locations with known side scan sonar signatures and geodetic locations would provide a baseline delta between the vehicle's assumed position and its relative position to a fixed item. To calibrate D, AMP could be programmed to drive the vehicle in the direction of the flow alongside the declared source location so that the side scan sonar image would show the source location.

SUMMARY/CONCLUSIONS

The Adaptive Mission Planner performed as advertised in all aspects of Plume Finding, Tracking, and Reacquisition. Additional modifications were made to the Source Declaration algorithm which optimized the vehicle's ability to declare the chemical source location. Additional efforts will be necessary to properly quantify near-real-time navigational errors in order to better judge the accuracy of the source declarations.

Future field experiments will assess and enhance the performance of the CSME Chemical Plume Tracing algorithm utilizing the Adaptive Mission Planner under relevant environmental conditions. Particularly attention will be placed on the optimization of the source declaration algorithm. The future experiments will also provide a more complex field by implementing multiple (2-3), independent, remotely controlled, autonomous sources. The AMP will have its first opportunity to prosecute and declare multiple contacts. Also, side scan sonar data will be utilized to implement ground truthing, thus providing more accurate analysis of source declaration locations.

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REFERENCES

[1] W. Li, J.A. Farrell, and R.T. Carde, “Tracking of Fluid-Advected Odor Plumes: Strategies Inspired by Insect Orientation to Pheromone,” Adaptive Behavior, submitted July 2001, accepted December 2001.

[2] J.A. Farrell, S. Pang, and W. Li, "Plume Mapping via Hidden Markov Methods", IEEE Transactions on Systems, Man, and Cybernetics.

[3] R Stokey, 2002, “Communication Protocol for External Control of REMUS Class Autonomous Underwater Vehicles, Version 1.1”, WHOI document.

