Integrating In-situ Chemical Sampling with AUV Control Systems

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***Abstract* – The utility of autonomous underwater vehicles continues to expand as powerful new in-situ sensor technologies are developed for AUV operation. However, these analytical sensors are typically configured to collect and log data as independent payloads -without the benefit of feedback from other payload sensors or vehicle navigation systems. This paper explores conceptual frameworks for integrating payload sensors in various degrees of real-time data assimilation and adaptive operation. Several of the challenges to coupling chemical sensor payloads in closed-loop architecture with acoustic, visual and navigation control systems are examined. Specific examples are provided as to how information sharing and coupled decision making processes may improve payload data interpretation and validation as well as increase the overall efficiency of AUV mission strategies.**

Data is presented from deployments of the Seabed submersible, a passively stable, hover-capable AUV designed for operation to 2000 meters. During these deployments the Seabed vehicle was arrayed with a payload of optical, acoustic, and chemical sensors to identify and map structures associated with ocean bottom methane sources on the Atlantic slope of North America. Results from these deployments are discussed and a collection of general principles is suggested for integration of biological and chemical sensors as payload with active feedback aboard AUVs. The authors conclude with suggestions for possible scientific applications that can be addressed using levels of technology presently available as well as how incremental advancements in AUV payload integration will present profound new opportunities to explore and understand our world.

I. INTRODUCTION

The value of intelligent sensors for oceanographic chemical survey is clear when considering the cost of data collection in terms of bytes of scientifically valuable data per research dollar. Sampling is often conducted without prior knowledge of the environment, leading to temporal and spatial aliasing, or sometimes completely overlooking significant chemical parameters. Furthermore, measurement is usually an iterative process, wherein measurements are made with increasingly fine resolution. The measurement process can be greatly accelerated by information sharing and automating decision steps within the sensor, decreasing time and human work requirements.

In-situ sensor technologies have undergone significant advancement in the past several years, allowing a broad suite of chemical analyses to be carried out in real-time aboard AUVs and ROVs. These sensors include venerable in-situ tools such as CTDs, and polarographic electrodes (e.g. redox potential electrodes) as well as new sensors with extensive capabilities such as mass spectrometers [1, 2], Raman spectrometers [3], fluorometers [4], and solid-state trace gas sensors. In-situ sensing avoids the drawbacks of sample collection and transport off-site for analysis, a process that is generally labor intensive and time-consuming. Additionally, error often arises because of chemical and physical changes occurring to the sample during transport such as degassing and biological or photochemical degradation.

Conventional AUV deployments use disparate scientific sensors operating as isolated units aboard a single vehicle; a common time-stamp correlates the various observations for post-dive processing. Operating in this way a sharp divide exists between the payload sensors, where incoming information is simply stored for later use, and navigation sensors, where incoming information is combined in real-time and used to guide or control the vehicle's operation. To fully realize the capability of in-situ oceanographic instrumentation, we must blur the line between payload and navigation sensors, using more of the available information for control, guidance, and re-tasking.

The research that we present here investigates aspects of sensors and sensor network development for autonomous in-situ chemical exploration in the deep-ocean and seeks to advance a generalizeable understanding of how payload instruments can be included in the control of autonomous underwater platforms. The AUV can be considered a miniature self-contained network incorporating a relatively limited number of oceanographic sensors, but challenged to assimilate the disparate information sources into a cohesive framework appropriate for supporting real-time decision processes. A consensus has emerged regarding the technological need to develop sensor packages for rapid event response to episodic natural phenomena [5-7]. The ability to simultaneously search a wide area and then focus sensor attention through sensor management and vehicle guidance will speed up the reaction time

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of our science support. This ability to couple oceanographic payload sensors with vehicle navigation will increase the efficiency and effectiveness of deep-ocean science conducted from autonomous platforms and is potentially important for large scale observatories such as the Ocean Observatory Initiative (OOI)[5, 6].

II. THE SEABED AUV

The Seabed autonomous underwater vehicle has been used extensively to explore and map deep ocean environments. Although Seabed's cruising speed is approximately 1½-3 kts. (0.75-1.5 m/s) which effectively constrains the detectors response time to something on the order of seconds to allow for adequate spatial resolution, this AUV is unique in that it is passively stable and has the ability to hover. This capability is advantageous because of the relatively slow time-response of in-situ chemical detectors, permitting the vehicle to linger during the requisite sampling time. Overall, the vehicle is capable of operation to depths of 2000 meters and mission durations of up to 8 hours.

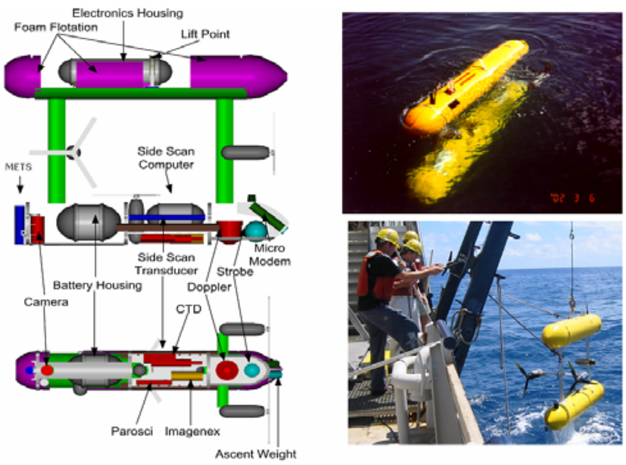

Fig. 1: At left, component diagram of Seabed, at right photos of Seabed during deployment and recovery phases of missions.

Seabed's sensor payload is modular, allowing various instruments to be interchanged, according to mission requirements. As a rule of thumb the vehicle can accommodate science payloads requiring no more than 30 watts of power for a given sensor. Typically the payload includes a high dynamic range digital camera system, side scan sonar, pencil beam sonar, CTD, Doppler velocity log, and Capsum METS methane sensor. The methane sensor is capable of quantifying methane in concentrations ranging from approximately 1nM to 10μM, with a response time of less than 1 minute (detection without precise quantification occurs within 10 seconds). Other new generations of trace gas sensors are currently being developed for the vehicle, including a mass spectrometer and an array of low power solid-state sensors for real-time in-situ analyses.

III. NON-ADAPTIVE SURVEYING

Dissolved methane, temperature, and conductivity data from deployments in the Saanich Inlet in British Colombia, Canada have demonstrated that temperature and chemical concentrations may vary orders of magnitude on spatial scales as small as centimeters, indicating that sensors should be co-located in close sampling proximity and that the response time of each instrument should be well characterized. To address these considerations for operation aboard the Seabed AUV, the METS methane sensor has been modified so that it is fully integrated with an onboard SeaBird FastCat CTD, wherein a flow through system continuously pumps a stream of water (inlet at the bow of the vehicle) first to the METS sensor, and then to the CTD. The inlet system is designed to avoid fouling from particulates and signal fluctuations caused by the introduction of bubbles from plumes. Both detectors collect and interpret data in real-time, allowing the Seabed AUV to identify local concentration maxima within approximately seconds of encountering a chemical anomaly. The chemical data set is logged and synchronized with imaging data from a high dynamic range optical imaging and sonar data, allowing post-mission analysis of combined chemical data and imagery for identification of seafloor structures such as fissures, bubble plumes, exposed hydrates, carbonates, etc.

With this configuration the Seabed vehicle was used to explore and characterize pockmarks of presumed methane hydrate eruptions approximately 100km off the Atlantic coast of North Carolina and Virginia [8]. These pockmark craters are located at the edge of the continental shelf by the shelf break in water depths from 100 to 150 m. A total of 18 missions were executed with the Seabed AUV, covering a total of approximately 60 linear km of the seafloor. These dives were executed based on a pre-programmed mission plan which used a bottom following behavior that instructed the vehicle to maintain an altitude of 3 m above the seafloor. During these deployments the vehicle was equipped with a suite of science sensors that included the METS, CTD, digital camera, pencil beam sonar, and Doppler velocity log.

Initial results show the major points of methane seepage to be at the edges of the pockmarks. Significant variability was noted in the water column methane concentrations, from less than 10 nM to over 100 nM. The baseline methane concentrations appear to be affected by tides and periodic storm events. In several cases the methane anomalies were localized to areas less than 75 m in diameter. Fig. 2 illustrates a dive mission in which the vehicle conducted a grid pattern survey on the northwest slope wall of a seafloor crater, followed by a box pattern around the crater's perimeter. Methane data collected indicate a local maximum in the northwest corner of the grid area. The 3-D dive tracklog is reconstructed from acoustic Doppler velocitimeter, sonar altimeter, dead reckoning, and multibeam sonar bathymetric data.

Although these deployments successfully revealed previously unobservable oceanographic processes, the methane data collected from these dives clearly demonstrate the difficulty in devising the best sampling regime and mission plan a-priori. In several cases the pre-programmed mission plan caused the vehicle to over-sample in areas that were chemically unremarkable, while in other areas sampling at a resolution less than satisfactory to adequately characterize the chemical features of interest. These shortcomings were largely due to the fact that the average mission lasted from 3 to 5 hours and that the methane anomalies appeared to vary over durations as short as a single tidal cycle. Thus, it was difficult to accurately predict where feature of interest are to be found, much less the spatial extent of a feature, even when attempting to use a previous dive's data to localize a subsequent dive's mission plan.

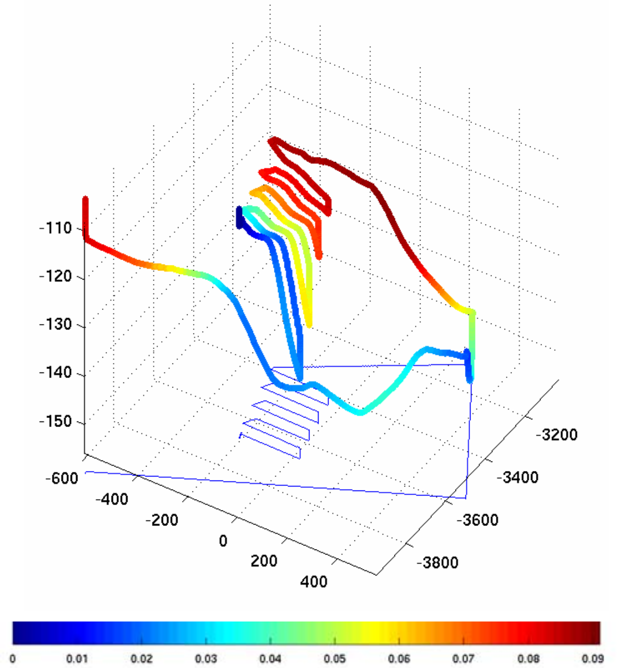

Fig. 2: Three-dimensional tracklog of a survey using the Seabed AUV. Methane concentration is expressed by color variation; X, Y and Z axes distances are in meters, methane concentration is expressed by color bar concentrations in micro molar.

IV. SAMPLING SCALE AND FLOW REGIME

Primary considerations for developing a sampling strategy and overall mission planning are the transport processes at work and the heterogeneity in a given sampling environment. This is because the structure of chemical features in the water column depend both upon the characteristics of background flows in the environment and upon the characteristics of the source. These factors together determine the spectrum of spatial and temporal scales present in the feature. As a sampling platform, an AUV imposes restrictions on which of these scales can be resolved. An AUV's speed, trajectory, sampling rate, and the duration and spatial extent of the survey all interact to determine which scales present in the environment will be strongly present in the data, and which will be obscured or aliased.

The most important implications of the environmental scales are encoded in the Reynolds number associated with the mean flow. The Reynolds number can be considered to quantify the relative magnitude of a turbulent time scale to a molecular time scale that would prevail in the absence of turbulence in a regime with the same length scale [9]. Flows with low values ($Re<1$) are laminar when molecular diffusion provides the only mechanism for chemical tracers to cross the streamlines of the mean flow. Tracer fields whose evolution is dominated by molecular diffusion produce well-defined gradients in concentration toward the source. Flows with large Reynolds numbers are dominated by turbulence which, by stretching and twisting by eddies of various scales, results in a much faster mechanism for mixing than molecular diffusion and hence dominates the evolution of the tracer field. The macroscopic flow scales in the ocean that we are concerned with are turbulent.

In contrast to laminar flows, turbulent flows occupy a spectrum of scales. Within the context of point-source chemical plume tracing, Liao and Cowen [10] identify the relevant scales of turbulent diffusion as: the size of the largest eddies; the smallest length scale of turbulent motion (Kolmogorov length); the scale of the largest isotropic eddies; the width of plume; the smallest size of a scalar fluctuation (Batchelor length), and the time scales associated with all of the above. Bathymetry and water depth constrain the largest eddy scales.

In the presence of mean advection, the tracer field produced from a point source consists of a plume of discrete high-concentration filaments of tracer trailing downwind from the source. This instantaneously 'patchy' structure of a turbulent plume is the result of small-scale eddies that intersperse uncontaminated fluid with fluid bearing tracer. Large-scale eddies cause the plume to meander such that the plume appears as an instantaneously thin, wandering, ribbon of tracer packets downstream of the source. Over sufficiently long time-scales, profiles of concentration perpendicular to the mean flow appear Gaussian. However, this manifestation of a chemical plume would not be observable by surveying AUVs moving fast, relative to dominant advective velocities.

The physical size of a source also plays a role in determining the characteristics of the tracer field produced. The notion of a point source is an idealization, but it is an appropriate one if the survey domain is large relative to the dimensions of the source. In the immediate vicinity of a diffusive source, the concentration field will be dominated by the characteristics of the source rather than by advective flow.

The preceding paragraphs have tacitly assumed a constant mean advective flow. Constant mean flows are unlikely to exist in ocean settings, principally because of the influence of tidally induced variability in ambient currents. This fact has two major ramifications for AUV-based oceanographic surveys of chemical features: (1) Over the course of a typical multi-hour survey, the characteristic speed and direction of advective currents cannot be considered constant. (2) If tidally induced oscillations dominate other advective influences, the tracer field will represent the accumulated output of several tidal cycles worth of tracer. The latter extends the range of temporal scales contributing to the structure of a chemical feature considerably. For instance, the chemical evolution of non-conservative tracers may play a role in determining the tracer field. Also, concentrations generally appear more continuous than would be expected in the presence of a constant mean flow, because mixing and molecular diffusion continue to operate; however, local concentration maxima may not correlate with proximity to the source. This is often the case for the neutrally buoyant portion of hydrothermal plumes whose characteristics depend strongly on flow history over scales of days [11].

V. AUTONOMOUS ADAPTIVE SURVEYING

While payload-vehicle networking can fundamentally transform our ability to measure chemicals in the ocean, it presents particular challenges making this work both timely and important for advancing technologies for chemical oceanography. Examples of challenges include: relative large amounts of power will be required to operate multiple instruments continuously, observational delay time caused by slow sensor response, fidelity of communication is uncertain between sensors and vehicle control, and sensor errors or failures may be unknown to control systems. More broadly defined, automating an adaptive survey presents technical, scientific, and operational challenges. Operationally, for an adaptive sensing strategy to be beneficial, it must be shown to be robust with respect to environmental uncertainties, such that the method must not under-sample important processes and must be shown to add capabilities to the operations while avoiding increases in power demand and or mission duration beyond that of an equivalent large area high resolution survey.

Automating the process of a data-driven nested survey is challenging because a nested survey typically involves three general phases: a wide-area search, a re-location for identification, and a small-scale survey of particular sites. Nested survey operations presently demand human analysis and decision making at each iteration to refine the sensing strategy, along with different sampling platforms (towed, remotely operated, submersibles, etc.), each with its own operational and support requirements. This model is consistent from archaeology to geology where scientists interpret the findings from each step in the survey and formulate a new survey based on the delivered data. We seek a capability to perform these tasks simultaneously from a single vehicle on a single dive, i.e., performing a data-driven survey. We envision an AUV as a host for an array of payload sensors operating in concert and adding information to the autonomous guidance. The ultimate goal of this research is to concurrently perform all of these steps from a single platform without external human intervention.

Abstracted and encapsulated representations of information (i.e. sensor data, vehicle mission representation, and control commands) are critical for the interdependent operation. These representations, which specify the interaction between sensory feedback and navigation control should be compact, complete, and computational (i.e., enabling communication of sensor data and autonomous reasoning for navigation). Existing methods of representation are useful, but insufficient for integrating payloads with navigation. For example, feature maps, which are used in simultaneous localization and mapping [12], are extremely compact, but not rich enough for communicating the information content from a chemical sensor. Topological maps [13] are efficient for path planning, indicating the sensor-based connection between locations in the map, but do not scale well and would be challenging for multiple sensor information with co-registered navigation data. Occupancy grids [14] are a simple example of a sensor and environment-specific representation, building a representation of an environment through expanding exploration; they can be used to formulate a robotic exploration framework based on a particular representation [15]. However, occupancy grids assume a static environment, which is not necessarily an accurate representation in highly dynamic marine environments. Therefore, a framework for information representation must be built that is appropriate for coupling chemical sensor data with navigation data and mission specifications.

The vehicle mission, generally represented as a collection of sequential or layered tasks, must also be made dynamic by incorporating the ability to re-task and adapt the mission based on sensor observations. The current practice with autonomous underwater vehicle operations is to specify a mission through a program or mission script that is primarily based on sequential tasks, although some approaches add layered (parallel) tasks [16]. This highly structured approach differs from the behavior-based methods which build complex behavior from simple, low-level feedback operations. A system capable of re-tasking itself based on sensor data requires a new interaction between operators (payload sensors) and vehicles. Consequently, it must build upon the layered control systems of today, taking advantage of their robustness and ease of use, but extend these systems so that operators can specify higher-level goals and begin to let the robot determine its tasks based on these goals and the incoming information.

To address these challenges we have coupled payload sensors and navigation by incrementally adding feedback loops to the layout of AUV sensor systems. This utilizes a network to interface payload with navigation and extend the current procedural or layered architectures by succinctly representing sensor data that is then used to modify AUV mission specifications. This interdependent sensing and navigating network has distinct characteristics from that of typical environmental monitoring sensor networks. Large-scale sensor networks are often highly distributed and communication limited with ad-hoc topology [17]. In contrast, an integrated AUV sensor network has relatively few nodes, a fixed topology, and high communication bandwidth. The central challenge is to simultaneously control the sensor operation and vehicle navigation for efficient exploration of an unknown environment. Our approach to this problem is to specify the abstractions, define an autonomy strategy, and analyze the performance and robustness of operation.

VI. ADAPTIVE BEHAVIORS AND TRIGGERING

Data-driven adaptive sampling typically requires the aid of human intervention for data interpretation, asset management, and mission planning [18]. Our approach has been to embed the data-interpretation and decision making processes into the vehicle's mission planner as a segment of the vehicle's closed feedback control system. Many differing control system modifications are possible, including alteration of vehicle heading and velocity. In the case of sensors that make complex, multi-component measurements, such as is the case with many types of spectrometers, modification of payload instrument sampling strategy may be possible. For example, adjustments to the extent of spectral domain covered, the sampling interval, signal averaging/dwell time, or power management [2] may be considered. Additionally, adaptation can be used to coordinate complex sampling strategies involving multiple vehicles and/or sensors.

Autonomous implementation of an adaptive behavior requires activation via a decision process that utilizes some type of logic state comparison. To simplify this process we have developed a threshold type response trigger, wherein an adaptive operation is enabled when a critical threshold is met or exceeded. Several levels of threshold complexity are possible, the simplest being a static value, which requires no memory of prior values or forecasting of trends.

Preliminary experiments have demonstrated that this type of behavior and triggering can be useful for localization of structures such as advecting chemical plumes. Fig. 3 illustrates one such adaptive AUV experiment. In this experiment a plume of propane gas was bubbled from a shallow point source at a depth of approximately 16 meters, at coordinates (0,0). The tidal currents in this area then acted upon the bubble source to advect dissolved propane Eastward, away from the source, creating an artificial two-dimensional plume of dissolved propane. The Seabed AUV was made to swim a counter-clockwise square box pattern, 50 meters on a side, at a constant depth of 7 meters, beginning at the North most corner of the box[1].

During this mission, a rudimentary adaptive behavior was enabled, permitting the vehicle to disengage from its current track line and begin a grid type survey if a propane concentration of more than 15nM was detected (each grid consisting of 10 perpendicular track lines, 20 meters in length, at a spacing of 2 meters). The adaptive behavior allowed for a maximum of one adaptive grid to be executed within each leg segment.

In the first and second legs of the mission, areas where the propane plume was not expected to be, the measured propane concentrations were below the 15nM threshold and the adaptive operation was not triggered. During the latter half of the third leg the vehicle began to enter the plume and detected propane values exceeding the threshold, triggering an adaptive grid. After completing the third leg, the vehicle immediately commenced an adaptive grid within the fourth leg of the survey.

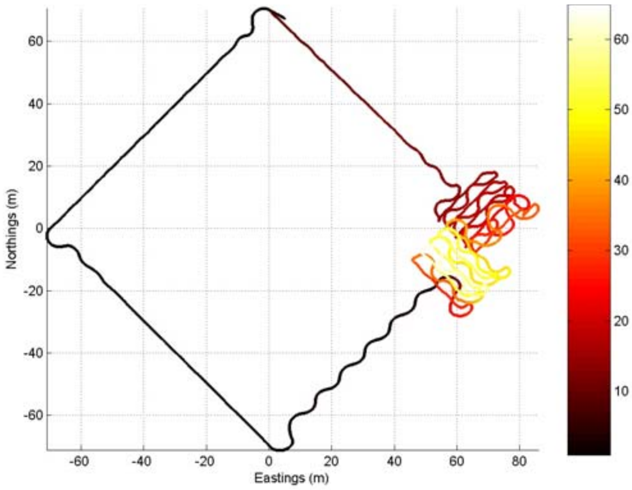

Fig. 3 An adaptive box survey of a dissolved propane plume, showing grid triggering at the end of the 3rd leg and beginning of the 4th survey leg. This triggering is caused by an increase in measured propane concentration.

Although straight-forward, this type of trigger can pose a number of problems in that assumptions must be made as to the appropriate value of the triggering threshold. Simply put, the threshold may be too high or too low to be effective. Furthermore, if a sensor has a slow response time, the time delay may cause inappropriate triggering.

[1] For clarity, the DVL track log of the Seabed vehicle is used to describe the vehicle mission path. However, passively collected acoustic long baseline navigation data indicate that while in this high current environment (the water column advecting at rates up to 60 cm/s) the vehicle experienced a drift on the order of 2.2 cm/s. Nonetheless this figure is reasonably accurate for our limited purposes of behavior demonstration.

To circumvent these problems an alternative can be to make a non-static trigger that relies on the rate of change in concentration measured within a specific period of time, instead of a fixed threshold value. This technique has been used successfully to adapt the control parameters (i.e. sampling interval and signal processing) of the NEREUS mass spectrometer [19]. Triggering of this adaptive NEREUS behavior relies on dynamic feedback parameters that are calculated as functions of the change in the ion signals over time. This system first identifies the ion peaks of interest, then quantifies the rate of change of these ion peaks. The processed spectral data is then feed back into the mass spectrometer's control system to adjust the interval between successive scans and allows system components to enter and exit power saving standby modes according to the calculated time interval between samples. For example scheduling of sampling time intervals are calculated in inverse proportion to the rate of change of the various ion peaks. This behavior has demonstrated a reduction in data storage and power requirements of 30-40% without temporally aliasing chemical gradient data (Fig. 4).

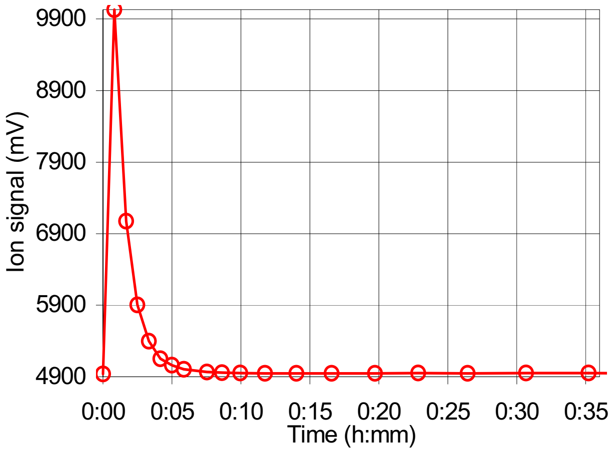

Fig. 4: Sampling response to a benzene pulse using an adaptive tracking algorithm to control the NEREUS instrument. The circles indicate the time of sampling, illustrating an interval between scans that autonomously scales in proportion to the rate of change in ion signal [19].

Although the adaptive NEREUS behaviors are resident within the sensor, these types of dynamic parameters are easily extensible to vehicle control. For instance, a change in concentration over time (i.e. gradient change) can be used to calculate vehicle control parameters such as velocity (i.e. slowing the vehicle's velocity in response to a rapid change in measured chemical concentration), as well as less deterministic, complex behaviors that dynamically modify vehicle trajectory in proportion the chemical gradient detected. For example, the mission planning system could be made to re-task with an adaptive behavior that is generated in real time, rather than relying on a deterministic, pre-programmed adaptive behavior.

Advancing in scale of complexity, multiple chemical sensors can be networked together aboard the AUV, thereby providing capabilities (i.e. estimates and triggers) appropriate to the spatio-temporal scale of interest. This network can potentially make use of higher-bandwidth sensors (for example CTD, optical backscatter and fluorometer data) to identify the rapid change characteristic of high turbulent flow regimes, while relying on lower-bandwidth sensors with high specificity to identify and track longer term gradient trends of individual chemical tracers. This technique approximates the sensory physiology of many terrestrial and aquatic fauna, wherein lower frequency olfactory signals are used for far field localization estimates and higher frequency sensory input such as visual and electo-magnetic (e.g. ampullae of Lorenzini) cues are utilized predominantly in the near field.

VII. BIO-MIMETIC TECHNIQUES

Generally speaking, our objective is one of optimization -to survey localized chemical features with high resolution without resorting to dense coverage over an entire survey area. Many animals are known to perform remarkable feats of chemical source localization by tracing the emitted plumes to their source, a capability potentially relevant to this objective. Lobsters, crabs and moths in particular all have extensive literatures devoted to elucidating the aspects of their behavior that allow these animals to routinely execute robust and efficient tracking of odor sources (for recent overviews, see [20, 21]).

For example, the environmental conditions in which male moths seek out females emitting pheromones are characterized by wind-driven turbulent advection. Behavior tuned to advective timescales makes sense because wind direction provides the most direct clue about source location relative to the searching male moth. The principal complication in tracking odor plumes at these scales is the intermittency of the pheromone signal caused by small-scale turbulence in the mean flow [20, 22-24]. Meso-scale eddies on the order of meters result in meandering plumes [25] such that maintaining intermittent contact with the plume becomes a critical component of the tracking strategies employed by moths [26].

Though there is some debate as to the underlying mechanism of this process, it can be generally segmented into a surging behavior and a casting behavior [26]. Surging is the means by which the moths make progress upwind, and casting is the local search behavior by which moths reacquire the plume after loss of the signal. Moths periodically counterturn during both processes so that the paths produced appear as zigzags. Both simulations and experiment convincingly point to the utility of zigzagging across an odor plume as a strategy well suited to maintaining intermittent contact with the plume [20, 24, 27]. In essence, male moths surge upwind at some angle to the wind upon encountering pheromone above some threshold concentration, but switch to casting about after sufficient time without further stimulus ([26] gives a review).

In comparison, relatively large and slow-moving aquatic creatures such as blue crab and lobster likely use a combination of chemical cues and up-current motion (rheotaxis) to locate odor sources emitted by carrion, prey, or other individuals [20, 23]. Blue crabs and lobsters forage in a turbulent boundary layer over the coastal and estuarine sea floor. Chemical plumes in these habitats are subsequently turbulent themselves and, like atmospheric odor plumes, consist of discrete propagating packets or filaments separated by non-odor-laden fluid [28]. Due to the greater density of water, however, the relevant scales of turbulence are approximately an order of magnitude smaller than in air [29]. Though lobsters and crabs move more slowly than moths, mean flow velocities encountered in their habitats are typically lower than in air, and they too must react to chemical stimulus on the time scales associated with the small scale eddies that cause the intermittent nature of the chemical signal [20, 23, 30, 31]. The influence of larger eddies, at scales sufficient to cause the plume to meander, is relatively unexplored due to the limited sizes of laboratory flumes[30], though it is likely that search behaviors exhibited by crabs and lobsters must also be robust to occasional loss of intermittent contact with the plume [23].

The relatively large size of these arthropods compared to moths is important because it is comparable to the typical near field widths of odor plumes found in their environment. These animals are likely to have evolved to exploit the additional spatial information resolvable in the plume to improve the efficiency of their search [20, 29, 32], for instance to remain closer to the centerline of the plume [23]. Blue crabs and lobsters follow qualitatively similar zigzagging trajectories towards odor sources [20, 23]. Information attained from spatial sampling, such as relative intermittency, peak length, and off-time, or packet-scale properties such as relative concentration peak height and peak slope [28], may improve the ability of these animals to track the outside edge of a plume where the gradients in these properties are steepest and converge rapidly [10, 23], or turn towards the plume centerline thereby increasing the probability of encountering further stimulus [32].

Biologically inspired plume tracing algorithms implemented on an AUV [33] could provide a mechanism to localize chemical sources and trigger high-resolution near-field surveys. Bio-mimetic strategies for the specific task of chemical source localization are attractive alternatives to exhaustive grid surveys because they are robust, efficient, and obviate the need for infrastructure-intensive globally referenced navigation by navigating relative to the chemical plume itself. However, the chemical plumes traced by moths, lobsters, and crabs typically emanate from very small sources and usually do not persist over long time-scales and are hence rather different from persistent plumes of geologic or anthropogenic origin.

VIII. TOWARD AUTONOMOUS DATA DRIVEN MISSION PLANNING

Navigation is a fundamental consideration for autonomous data-driven mission planning. Current in-situ sampling capabilities are dependent on the quality of location estimation to put observations in the proper context. Thus, the precision of the navigation defines the map resolution and hence the quality of the final data product.

An adaptive survey requires the highest quality environmental and navigation sensing and real-time estimation. To match the advances of in-situ chemical sensors an AUV's localization capabilities require a similar incremental increase in quality. A goal of an adaptively survey is to simultaneously make measurements on a variety of scales, so the navigation must be able to concurrently deliver location estimates with uncertainty less than the minimum spatial scale of interest.

The authors' experience thus far has reinforced the necessity of precise real-time and high quality navigation sensors. The results illustrate possible input strategies for an autonomous mission planner, but the re-tasking and adaptation are predicated on a high quality estimate of current and past locations. Two points are important when considering this problem: the importance of making estimates that are both globally referenced and real-time. Many conceivable adaptive search strategies, especially those inspired by biological models, do not seem to require globally referenced localization. For example, if a moth's goal is to find a chemical plume there is no need to locate that plume or it's signature in any consistent coordinate frame, only to develop a set of behaviors that guarantee localizing the target. Our approach to developing such a capability cannot ignore the real scientific need to make a quantifiable map based on observations and externally referenced localization. Moreover, as we experiment with new techniques for adaptive survey we require a globally consistent coordinate frame to compare algorithms and to run data-denial post-processing experiments. The necessity of making navigation estimates in real-time is obvious for making in-situ decisions based on payload and navigation sensors. The requirement challenges the current state-of-the-art because much of the quality in localization estimates in AUV surveys comes from post-processing. In summary, adaptive mission planning in-situ will require new levels of real-time navigation.

In addition to precision navigation, accurate models of sensor response characteristics are necessary to avoid spatial aliasing of data. Response characteristics of sensors can vary orders of magnitude in time, dynamic range, and domain of spatial coverage. Furthermore, distinctions must be understood as to if a sensor behaves as a continuous sampler, or if the sensor is able to make discrete measurements that are truly independent of prior measurements (i.e. issues of baseline drift, saturation, and hysteresis). For example, along with the standard problems of electronic origin, a membrane inlet type detector such as the METS sensor is subject to latency issues associated with membrane permeability. These factors introduce a first-order time delay between actual concentration and resulting observation. Although the membrane associated delay can be characterized [19], it nonetheless acts as a low-pass filter reducing the temporal, and therefore spatial, resolution observable from the moving AUV, presenting an integration challenge – incorporating a continuous time-lag within a feedback loop. Finally, the real-time data processing capabilities must be such that sensor's noise sources can be quickly and reliably identified. Thus, the spatio-temporal precision of the chemical sensor data, like that of vehicle navigation, also defines the map resolution and hence the quality of the final data product.

The authors suggest that several potentially practical avenues exist for advancing the state-of-the-art of chemical oceanography by extending the coverage of instrumentation to appropriate spatial and temporal resolutions. The concepts presented here are not intended to be an exhaustive description of possible techniques for advancement. As the complexity of adaptive data-driven operation grows, new phemonological models will be necessary to effectively develop and rigorously define frameworks for adapting sensing strategies to environmental conditions and to quantify the effectiveness of these new techniques. Furthermore, the authors encourage input from others to develop novel approaches for improving the technical capabilities of this branch of chemical oceanography, particularly those involving AUV operation.

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