NIMS-AQ: A novel system for autonomous sensing of aquatic environments

Michael J. Stealey*, Amarjeet Singh*, Maxim A. Batalin*, Brett Jordan†, and William J. Kaiser*
*Department of Electrical Engineering, University of California, Los Angeles
†Department of Mechanical Engineering, University of California, Los Angeles
Email: stealey@ucla.edu

Abstract— **As concern for water resource availability increases, so does the need for intelligent aquatic sensing applications. The requirements, and complexity of such applications has also increased due to demands for: 1) broad spatial coverage and high spatial resolution monitoring, 2) capability for resolving fine scale spatiotemporal dynamics and 3) the need for rapid system deployment with semi-autonomous operation. With these criteria in mind, we present the Aquatic Networked InfoMechanical System (NIMS-AQ). NIMS-AQ was developed based on experience gained from engineering research and collaboration with aquatic scientists and environmental engineers during several in-field measurement campaigns [1], [2], [3]. In this paper we demonstrate the effectiveness of NIMS-AQ through two experimental sensing campaigns encompassing both river and lake environments. Each campaign is centered around critical water resource monitoring objectives such as temperature, flow and contaminant levels. Experimental results for autonomous depth profiling using a submersible sonar system as well as adaptive sampling algorithms guided by phenomena models are presented herein. The found results conform with our objectives for rapid and systematic operation. Preliminary studies also indicate the systems viability for use with an Autonomous Iterative experiment Design for Environmental Applications (A-IDEA) methodology that is currently under development. The IDEA methodology [1] provides effective characterization of spatiotemporal dynamics in aquatic environments. A-IDEA, as it is to be implemented on the NIMS-AQ platform, is also described.**

I. INTRODUCTION

Water quality degradation is a primary concern for populated and agricultural regions due to the impacts of several sources of pollution including urban runoff and agricultural drainage, among others [4], [5]. A broad class of aquatic monitoring applications require sensing an environment that displays significant heterogeneity in both space and time. As an example, river observations are useful for answering the questions pertaining to the spatiotemporal variability of velocity and water quality dynamics resulting from pollutant inputs, hydrodynamic mixing regimes, and biogeochemical cycling processes that are themselves distributed in time and space. Observations will require an increased resolution above periodic point sampling if we are to understand processes well enough to predict conditions and manage water quality at arbitrarily large scales [6]. As another example, the growth of planktonic microorganisms, that form much of the base of the food webs in freshwater and marine ecosystems, is dependent on the availability of dissolved nutrients and light. These parameters display highly dynamic spatiotemporal distributions [7] often due to interdependence with other physical and chemical parameters such as temperature, pH and solar radiation.

A variety of remotely administered and autonomous systems exist for transporting water quality sensors through aquatic environments. Buoyed or moored deployment platforms provide one dimensional vertical profiling capabilities over long time periods at key locations [8], [9], [10]. Autonomous underwater vehicles (AUVs) have been used extensively by the oceanographic community, and more recently in lakes and river systems [11], [12]. Robotic boats [13] and Autonomous Surface Vehicles (ASVs) [14], [15] have now been used for several important aquatic applications, including monitoring the phytoplankton growth and tracking thermal plumes. Tethered systems, such as Riverboat[1] and the Rapidly Deployable Networked InfoMechanical System (NIMS-RD) [16] have been introduced recently to provide ease of deployment and accurate localization respectively.

In spite of the recent advancements in technology and commercial viability, currently available systems have many constraints that preclude long-term, remote, autonomous, high-resolution monitoring in the real environment. These constraints include limited availability of energy, precise autonomous actuation and highly accurate localization, among others. In addition, a large team effort, involving experts from diverse domains including biology, statistics and engineering, is often required for successful completion of many complicated field campaigns in aquatic domain [2]. Limited campaign time along with the high associated resource cost (team effort and the cost of robotic and sensing systems) demand for optimized utilization of the available time in the field.

In this paper, we introduce a new tethered robotic system for obtaining high-resolution observations of dynamic spatiotemporal phenomena in aquatic environments. This new system, Aquatic Networked InfoMechanical System (hereafter referred to as NIMS-AQ), was conceived based on the increasing requirements of aquatic applications following the success of several field campaigns achieved using the Rapidly Deployable Networked InfoMechanical System [16] (hereafter referred to as NIMS-RD). We describe the system design and development and demonstrate the usefulness of the system through two field sensing campaigns carried out in diverse environmental conditions. First, in the Merced River (California) with flowing water and second, sampling

[1]Developed by Oceanscience

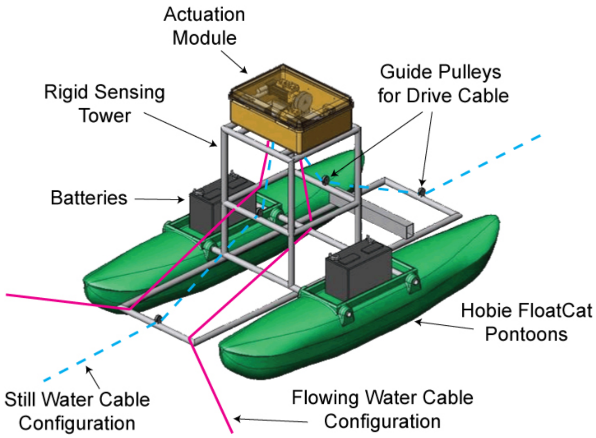


Fig. 1: Aquatic Networked InfoMechanical Systems (NIMS-AQ) prototype craft

a cross-section of a lake (Merced, California) with near zero-flow conditions. Based on the successful deployment of this new system in diverse environments, we propose a foundation for an autonomous selection of iteratively improved experimental design [1], Autonomous Iterative experimental Design for Environmental Applications (hereafter called A-IDEA). The application of the A-IDEA methodology, as described in this paper, can be used to optimize the limited campaign time and acquire data to characterize the spatiotemporal dynamics of the observed phenomena with high fidelity in an autonomous fashion.

II. Related Work

Over the past decade, several prototype robotic systems have been developed and tested in-field for sensing aquatic systems at different scales. Preliminary approaches used in limnology and oceanography involved using individual sensors for spot measurements of phenomena such as dissolved oxygen, temperature, electrical conductivity and pH, among others [17]. Such an approach is suitable only for an environment with small spatial coverage and uniform phenomena distribution. Buoyed or moored deployment platforms with static distribution of sensors have been used in river environments and provide vertical profiling capabilities over long time periods at key locations [8]. Several such platform, such as Lake Diagnostic System (LDS)[2], are commercially available and hence are also commonly used for sampling and verification of the vertical stratification commonly observed in temperate lake environments [10].

The Remote Underwater Sampling Station (RUSS) is a robotic buoy platform[3] consisting of a floating platform containing solar panels and sensor package that floats freely below the platform with the capability to sample at user-specified intervals up to 100 meters with a precision down to 0.2 meters of the target depth. This system has been used in several studies for characterizing the metabolic rate activities in lake environments [9], [18], [19]. This provides additional capability of one dimensional characterization (along the depth) at high spatial resolution. Such systems provide the required frequent profiles of hydrographic, chemical and biological parameters measured in-situ. These systems, even though fill in the gap for time sampling continuum in ways that were not feasible earlier, still lack the capability to characterize the ecological variability in space across the complete three-dimensional environment.

Autonomous underwater vehicles (AUVs) have been used extensively by the oceanographic community, and more recently in lakes and large rivers [11], [12]. These are primarily suited for environments with very large spatial coverage and for observing phenomena where repeated sampling at densities less than a few meters is not required. As an example, Tantan, an AUV developed by [12] is 2.0 meters long, 0.75 meters wide and 0.75 meters high and weighs 180 kilograms. It is used for monitoring a lake with surface area of 670 kilometers^2 and depth of 41 meters. Additionally AUVs often provide very little control of the system to the user as it performs its task. With minimal real-time control over the system it becomes difficult to implement any autonomous sensing algorithm involving adaptive sampling of the observed environment. In our experience it has been necessary to obtain repeatable sampling locations at densities in the sub-meter range in order to develop sufficient models, as observed during the study of planktonic migration [2].

Tethered robotic systems have been used to provide detailed characterization of the cross-section of the aquatic environments. NIMS-RD [16] was used succesfully during several aquatic campaigns [2], [20], however, the setup time of the system and its dependence on a strong support infrastructure make it unsuitable for certain aquatic applications that require high spatiotemporal resolution. A small and lightweight system, Riverboat[1], provides an ability to perform river discharge measurements. Measuring 1.2 meters in length and weighing around 16 kilograms with the complete accessory installation the platform is highly portable. However, this system is limited to manual operation and hence is limited in its ability to perform any autonomous sampling, typically required in aquatic applications.

Robotic boats [13] and Autonomous Surface Vehicles (ASVs) [14], [15] have also been used for aquatic campaigns. Several of such systems, such as Q-Boat[1], are also commercially available. Such systems, highly depend on Global Positioning System (GPS) for their localization, thus limiting their ability to perform accurate sensing at a fine spatial scale on the order of few centimeters. In the next section, we describe the design and development of a new system that combines the advantages of a surface vehicle (reducing the dependence on support infrastructure and making the system easy to deploy) and advantages of a tethered operation (providing accurate localization at a very fine spatial scale), in addition to providing an ability to perform autonomous operation.

III. NIMS-AQ: System Design and Development

The Aquatic Networked InfoMechanical System (NIMS-AQ) is the latest in the family of NIMS systems[16], [21],

[2]Developed by Precision Measurement Engineering Inc.
[3]Developed by Apprise Technologies

(a) NIMS-AQ on the little lake at UCM's campus

(b) NIMS-AQ on the Merced River

Fig. 2: Images taken in the field using the different configurations of NIMS-AQ: in still water (lake) and in flowing water (river) environments

[22], developed specifically for aquatic applications. Fig. 1 displays a schematic view of the prototype NIMS-AQ system. It is comprised of a rigid sensing tower supported by two Hobie FloatCat pontoons[4] in a catamaran configuration. An actuation module resides on top of the sensing tower that drives the horizontal cable and vertical payload cable (horizontal and vertical motion respectively) across a cross-section of the aquatic environment. Power for the system is provided by two deep cycle marine batteries housed on top of the pontoons. The horizontal drive cable is kept center-aligned to the craft by using guide pulleys that can be repositioned based on the type of aquatic environment in which NIMS-AQ is sampling (flowing or still water conditions).

TABLE I: NIMS-AQ Specifications

Length:	2.2 m
Beam:	1.25 m
Draft:	0.2 m
Displacement:	100 kg
Velocity:	0.1 - 3.0 m/s
Range/Endurance:	1 km / 12-24 hrs (based on duty cycle)
Navigation:	< 0.1 m
Power/Propulsion:	Sealed Lead Acid Batteries / DC Servo Motors
Experiments:	Hydrographic survey, Mass Balance, Contaminant Flow

A. Design Improvements

NIMS-AQ was conceived after the success of NIMS-RD [16] to satisfy the increasing demands of aquatic applications. NIMS-RD is a robotic cableway analogous to the cableways used by US Geological Survey (USGS) teams. NIMS-RD is a portable system, however it requires anchoring on either side of the transect capable of supporting up to a 4500 N load. The power and actuation hardware of NIMS-RD reside on one side of the transect and use high strength aircraft cable to actuate a sensor platform across the cableway. The sensor platform is capable of both horizontal and vertical actuation via a system of pulleys with centimeter accuracy. Aquatic campaigns, using NIMS-RD have included stream flow monitoring and solute mass balance measurements [23], biological studies for understanding the growth patterns of phytoplankton in lake environment [2] and urban runoff onto urban watersheds [23]. Terrestrial NIMS-RD campaigns include the study of alpine plant dynamics as well as rain forest fragmentation. The increasing demands of aquatic applications and specific constraints associated with the NIMS-RD system make it unsuitable for many aquatic applications currently of scientific interest. Demands including sampling cross-sections of aquatic environments larger than NIMS-RD can safely accommodate or requiring increased spatial coverage through multiple cross-sections in a timeframe less than the breakdown and re-setup time of the NIMS-RD platform would allow.

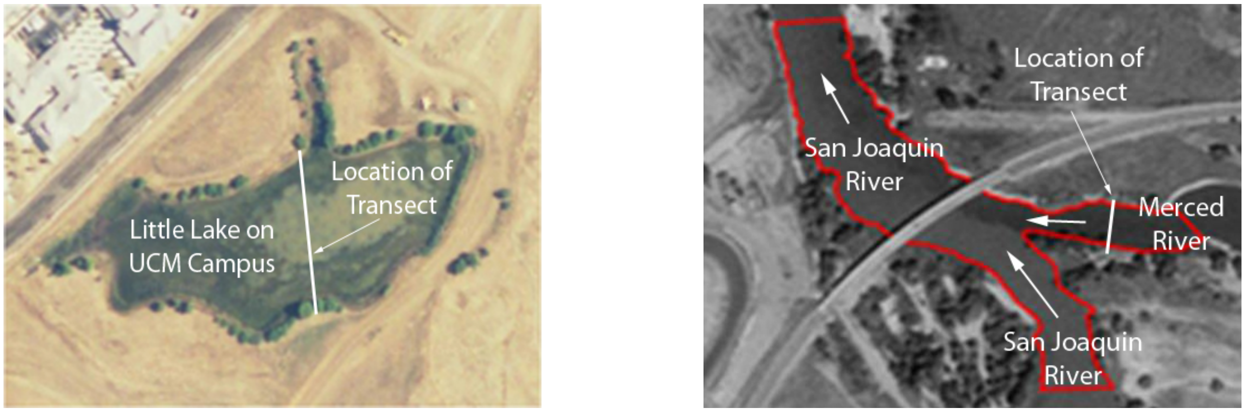
[4]Developed by Hobie Cat Company

B. Design Adaptation

The prototype NIMS-AQ platform is designed to use a tethered drive cable in two possible configurations, as displayed in Fig. 2. The first configuration, as captured in Fig. 2a is suitable for environments with near zero-flow and routes the drive cable center-aligned along the length of the craft. The second configuration, as captured in Fig. 2b is for the environments with flowing water and routes the drive cable into the front of the craft over the left pontoon, then center-aligned into the actuation module, and finally out of the front of the craft over the right pontoon. The second configuration allows the pontoons to stay in line with the flow of the water at all times, thus minimizing the drag on the craft. Each of these configurations are also marked in the schematic in Fig. 1. In either configuration the observed tension on the drive cable was between 90-180 N, a significant reduction when compared to the NIMS-RD tension requirements.

C. System Reuse

Development time of NIMS-AQ was reduced considerably by leveraging the existing field-proven hardware and software from the NIMS-RD platform. The NIMS-RD actuation module was modified to allow the module to reside on top of the NIMS-AQ rigid sensing tower. Center placement of



(a) Little lake on UCM's campus

(b) Confluence of San Joaquin and Merced River

Fig. 3: Satellite view of the two deployment sites used for testing the prototype NIMS-AQ system

the module on top of the sensing tower provides easy access to the actuation spools for cable management, allows the payload to be raised entirely out of the water and helps maintain overall balance of the craft. Similar adaptation of the NIMS-RD control software was achieved while developing the actuation software for NIMS-AQ prototype platform. Only minimal code changes were required due to the orientation of the actuation module (it was oriented vertically in NIMS-RD compared to horizontally in NIMS-AQ), physical dimensions of the drive components and the new cable setup.

The algorithms and software used for calibration, localization and control by NIMS-AQ remained nearly identical those found on the NIMS-RD system. For the sake of completeness we briefly explain these here. The NIMS-AQ system is calibrated by creating a relational set of physical position to motor encoder values at each demarcation across the transect. During our preliminary deployments demarcations were aligned visually, however embedded demarcations (RFID or magnets) are used on the NIMS-RD platform, a method that will be adopted by the NIMS-AQ platform in the future. Localization is accomplished by using the relational set created during calibration to compute new position relationships between physical coordinates and motor encoder values. Encoder values that fall between the known demarcations (typical case) are computed using ordinary least squares regression. The relational set (and localization) can be verified (or updated) by re-visiting a known position (demarcation) on the cable and refreshing the encoder value accordingly. The NIMS-AQ prototype is currently operated using a file-based protocol. Once the NIMS-AQ has been calibrated it will react (move, sample, etc.) to changes made in it's control files. The control files are modified by the on-shore user or sampling script over the wireless field network. A socket based control method exists on the NIMS-RD platform and will be adopted for future versions of NIMS-AQ. For more details, please refer to [24].

D. *Infrastructure Requirements*

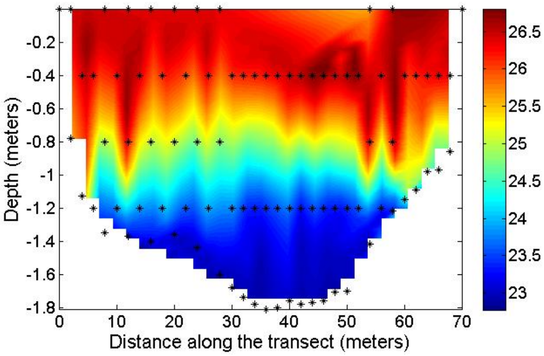
A horizontal drive cable runs through the center of the the rigid sensing tower of NIMS-AQ and into the actuation module. The drive cable is anchored on both sides of the transect and is made from 1200 newton break strength nylon coated wirerope (pre-stretched). It is kept between 90 - 180 newtons of continuous tension using a ratchet strap. It contains color coded demarcations at intervals of 5 meters for calibration, synchronization and ease of visual positioning or verification. The vertical payload cable is constructed from the same wirerope as the horizontal drive cable providing up to 20 meters of depth sampling for the attached sensors.

Power is provided to NIMS-AQ prototype system using two deep cycle marine batteries. Depending on the density and duty cycle of sampling the craft can remain in operation for 12 - 24 hours without having to recharge the power cells. Each pontoon holds one battery in a water resistant housing and helps maintain the stability of the craft by keeping the weight of the batteries as close to the water surface as possible. The pontoons used in the construction of NIMS-AQ are rated to support up to 159 kilograms. The weight of the prototype craft with all components, batteries and sensors weighs approximately 100 kilograms. See Table I for system specifications.

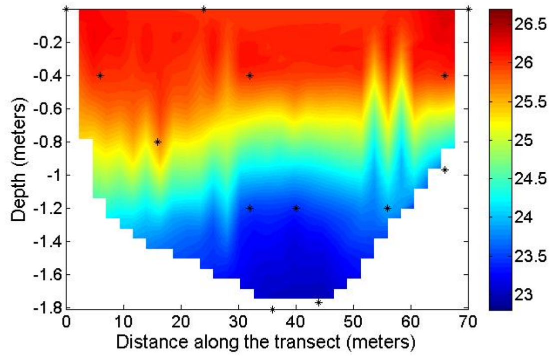
The craft is self contained in terms of having all the required sensors, processor, radio and power requirements on board thereby eliminating the need for any cabled festooning back to shore. All inter-system communication is performed using an in-field 802.11 network. The field network is comprised of a wireless access point and wireless bridge to support the coverage beyond the reach of the single access point. System information and observed data can be collected in real time using this network. We hosted the access point directly on the NIMS-AQ prototype during our test deployment at little lake at University of California, Merced campus. This was done for performing range experiments and can be observed as the white box on the left side of NIMS-AQ in Fig. 2a

IV. Field experiments

Two field campaigns were performed in August, 2007 at Merced, California to test the functionality of the prototype NIMS-AQ in diverse aquatic environments. These diverse environments include a river with water flowing at approximately 1.5 m/s and a lake with near zero-flow. Several experiments were executed to verify the calibration and



(a) Surface distribution of temperature (^oC) as observed during one of the raster scans



(b) Predicted surface distribution of temperature (^oC) using path planning algorithm and learned GP model

Fig. 4: Temperature distribution as observed using NIMS-AQ during experiments performed at UC Merced lake. Points in the figure represent observation locations

localization approaches used, perform model driven adaptive sampling and to test the sonar for autonomous depth profiling and hydrographic survey. Typically NIMS-AQ would carry a full compliment of water quality sensors: temperature, pH, specific conductivity, nitrate and chlorophyll-a, among others. Our initial experiments were limited to real-time monitoring of temperature and depth using hydrolab and sonar measurements for localization and depth profiling. However pH, specific conductivity and luminescent dissolved oxygen (LDO) were also recorded for post deployment analysis.

Fig. 3 displays a satellite view of both the deployment sites. The scientific objective at the confluence zone, displayed in Fig. 3b, was to characterize the transport and mixing phenomena at the confluence of two distinct rivers - Merced river (relatively low salinity) and the agricultural drainage-impacted San Joaquin River (relatively high salinity) by observing several parameters that may control the mixing behavior of the two streams. The primary objective of the experiments at the small lake on the University of California Merced (UCM) campus, displayed in Fig. 3a, was to test out the system and other components in a near zero-flow aquatic environment. We plan to use this system at other locations where biologists are interested in studying the growth patterns of phytoplankton in a lake environment.

A. River Deployment

The prototype NIMS-AQ system was deployed in the Merced River near the confluence region of the San Joaquin and Merced rivers. This deployment was used to profile the behavior of craft in an environment with water flow. Total length of the transect across the river was 25 meters with the maximum depth of 1.5 meters along the transect. The flow of the river was approximately 1.5 m/s. Using the flowing water configuration, with the pontoons staying in line with the flow of the water at all times as displayed in Fig. 2b, the horizontal drive cable was tensioned to approximately 90 newtons. The system was tested for operation at low (0.1 m/s) to moderate (0.5 m/s) speeds. Post calibration, the localization of the system was found to be highly accurate with less than 2 centimeter deviation over the course of a complete test run. Each test run was comprised of moving to pre-defined locations along the cross-section of the transect. Precise localization was also verified by comparing the bathymetry data with the depth measurements using sonar. A short video captured during the field operation of NIMS-AQ at this deployment site can be downloaded at http://www.ascent.cens.ucla.edu/research/nims/nimsaq/videos/NIMS_AQ_Merced_River.avi.

B. UC Merced Small Lake Deployment

The second deployment was performed at a small lake on the UC Merced campus. This site was selected based on the convenience and its similarity to another lake environment where biologists are interested in understanding the growth patterns of phytoplankton. Total length of the transect was approximately 80 meters across the cross-section of the lake. The system was used in the still-water configuration with the drive cable being center-aligned along the length of the craft, as displayed in Fig. 2a. The behavior of the craft was tested at low (0.1 m/s) and high (2.0 m/s) speeds again yielding high accuracy with minimal deviations due to slip on the order of 2-3 centimeters. In addition to calibration and localization testing, adaptive sampling experiments were performed in conjunction with the sonar for the depth profiling. A short video captured during the field operation of NIMS-AQ at this deployment site can be downloaded at http://www.ascent.cens.ucla.edu/research/nims/nimsaq/videos/NIMS_AQ_Little_Lake.avi.

C. Adaptive Sampling using Gaussian Processes

A common approach in statistical methods for addressing a spatially distributed phenomena is to use a rich class of probabilistic models called Gaussian Processes (GPs) [25]. Using such models, one can quantify the informativeness of a particular location, in terms of the uncertainty about our prediction of the phenomena, given the measurements made at already visited locations. To quantify this uncertainty, we used the mutual information (MI) criterion [26]. If the phenomenon is discretized into finitely many sensing locations $\mathcal{V}$, then for a set of locations $\mathcal{P}$, visited by the mobile robot, the MI criterion is defined as:

$$\mathrm{MI}(\mathcal{P}) \equiv H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}}) - H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}} \mid \mathcal{X}_{\mathcal{P}}), \tag{1}$$

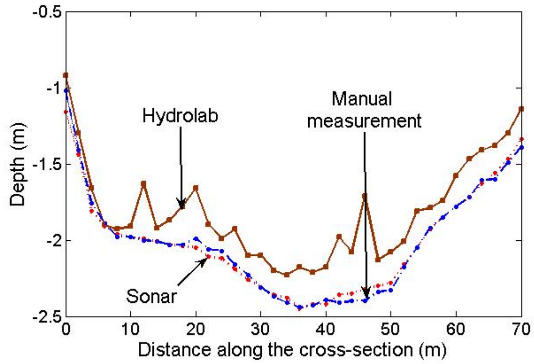


Fig. 5: Comparison of depth profile of a cross-section of the lake at UC Merced as observed using Sonar, hydrolab depth sensor and manual measurements

where $H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}})$ is the entropy of the unobserved locations, and $H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}} \mid \mathcal{X}_{\mathcal{P}})$ is the conditional entropy after observing at locations $\mathcal{P}$. Hence mutual information measures the reduction in uncertainty at the unobserved locations.

In particular, we first learned a non-stationary GP model, (using an extension of [26]), by maximizing the marginal likelihood [25] using the temperature data from one of the raster scans (deterministic scans with uniform sampling density). This non-stationary process was learned by dividing the complete region into smaller sub-regions and combining the locally-stationary GPs from each of these sub regions. We then ran the path planning algorithm as proposed in[27] with the starting location and ending location at either end of the transect. Fig. 4a displays the temperature distribution as observed during one of the raster scans. Points in the figure represent the observation locations. A total of 89 locations were observed during the raster scan. Bilinear interpolation is used to create the surface distribution from the temperature observed at these locations. The output of path planning algorithm was a set of 13 locations. Fig. 4b displays the temperature distribution as predicted using the temperature data from these 13 locations observed during the path planning experiment and the learned model from the raster scan. Root Mean Square (RMS) error between the predicted values and the values as observed during a raster scan performed just prior to the path planning experiment was only approximately 0.59 ^{o}C.

D. System Results

In both the flowing and the still water environments a drift of approximately 2 centimeters was observed following the test raster scans. The accumulated drift falls within the tolerable error bounds for the system and can be resolved by frequently synchronizing the system with the nearest demarcation on the horizontal drive cable. In both the environments, the setup time of NIMS-AQ was less than an hour. The ability to set up, calibrate and operate the system in such a short time frame facilitates the use of several sampling approaches for investigating the dynamic spatiotemporal phenomena. Several experiments were conducted to perform autonomous depth profiling using sonar.

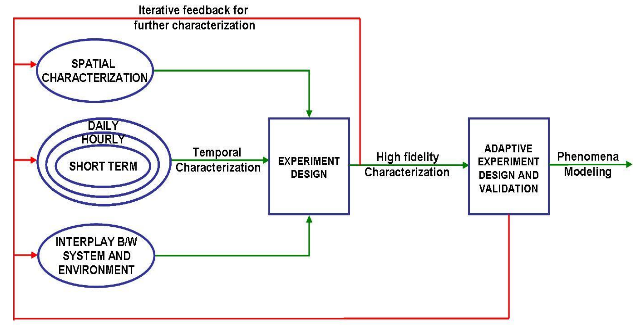


Fig. 6: Schematic view of IDEA Methodology as presented in [1]

Fig. 5 displays the comparison of depths as reported by the sonar [28], the hydrolab depth sensor [29] and manual depth measurements. Sonar and hydrolab measurements were chosen based on a steady state reading once NIMS-AQ reached the desired position. Manual measurements were then taken using a weighted surveyors tape from a boat at a point on the NIMS-AQ approximately 20 centimeters away from the sensor nodes. As is clearly indicated by the Fig. 5, depth measurements as reported by the sonar were highly accurate in spite of high turbidity of the water in the lake.

V. Autonomous experiment design using NIMS-AQ

Successful completion of adaptive sampling experiments, autonomous depth profiling using sonar and accurate localization using NIMS-AQ displays the utility of the system for autonomous operation in real environments. Aquatic environments, displaying large spatiotemporal dynamics in the phenomena distribution, require such systems to iteratively adapt the experimental design for characterizing these dynamics with high fidelity. An iterative experiment design methodology was proposed in [1]. The capabilities of NIMS-AQ make it a desired system for implementing such a methodology in an autonomous fashion. For the sake of completeness, we will now briefly explain the iterative experiment design methodology as proposed in [1], before proposing an extension with autonomous selection of experimental design.

A. IDEA (Iterative experimental Design for Environmental Applications) Methodology

IDEA provides a methodology for in-field adaptation of experimental design to perform detailed characterization of the spatiotemporal distribution of the observed environment. This involves an in-field adaptation in the experiment design to capture phenomena dynamics exploiting observations from prior models, iteratively executed experiments and the behavior of the underlying control processes (if known). Experiments are designed iteratively to characterize the spatial and temporal distribution of the observed environment. It also involves designing experiments to characterize the interference caused by the sampling system such that the

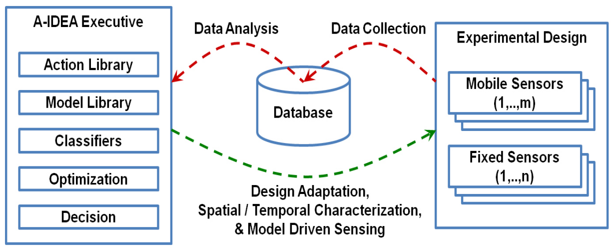


Fig. 7: Conceptual schematic for implementing Autonomous IDEA (A-IDEA)

integrity of the collected data can be relied upon. Such an approach can optimize the limited campaign time and acquire data that characterizes the spatiotemporal distribution of the observed phenomena with high fidelity. Once the detailed spatial and temporal characterization is performed, this methodology involves designing experiments to adaptively sample the observed environment, while validating the earlier learned models for the phenomena distribution in the observed environment. Fig. 6 provides a schematic representation of IDEA methodology. For more details, please refer to [1]

B. Extending IDEA methodology for autonomous operation

Conceptually Autonomous IDEA (hereafter called A-IDEA) is a collection of conjunctive networked applications designed to autonomously apply and execute the IDEA methodology for the characterization of an unknown environment. Ultimately A-IDEA will implement the IDEA methodology as illustrated in Fig. 7.

- A-IDEA Executive: Collection of libraries, classifiers, optimization and decision modules used for spatiotemporal characterization. Each of these modules (or a combination) will perform decision making for design adaptation and model driven sensing of the environment.
- Database: Local data repository used for the real-time collection and retrieval of the data observed using the mobile and fixed sensors in the experimental design.
- Experimental Design: The utilization of the mobile and the fixed sensors governed by the field-science experts and the IDEA design adaptation.

A-IDEA under it's current development would operate as follows. An experimental design would be proposed utilizing the available mobile (1,. . . ,m) and static (1,. . . ,n) sensing resources as per the given experimental design methodology. An preliminary offline model would guide the initial placement of static nodes at the desired point locations and initialize the path planning for the mobile robots. Each of these sensing devices (both the mobile and the static devices) once loaded and launched by the A-IDEA system would relay the observed data (and position for the mobile robots) in real-time using a field agent. Field agent(s) will collect the raw data relayed from the sensors and then aggregate and relay it to a local database over a wireless field network. The A-IDEA Executive module periodically queries the local database to extract sensor data for analysis. The frequency at which the A-IDEA Executive queries the database is a function of sensor sampling frequency, modeling requirements, and the rate at which the field agents are collecting the data from the sensors. concurrently data analysis using preexisting IDEA algorithms is used to generate models and classifiers for the phenomena being characterized. Then based upon the models and classifications discovered, decisions can then be made for actions to be taken by the A-IDEA system for the next round of sampling. This would include autonomous scheduling of the new positions to sense by the mobile robots as well as suggested new positions for the static nodes to be relocated to if need be. This process iteratively continues until a spatiotemporal convergence is achieved that sufficiently characterizes the phenomena, or the application determines it requires further intervention to achieve the desired characterization goals.

As of the writing of this paper, several of the A-IDEA components exist as modular pieces of software that are currently manually invoked in the field. The field agents employed in our deployments relay raw data to a specific end user and are modified to interface with the proposed local database [30], [31]. A manual implementation of the IDEA methodology as displayed using two field deployments in [1] will constitute the primary composition of what will be performed by the A-IDEA executive module. Currently, IDEA requires input from field-science experts to determine limits for the convergence of the spatiotemporal characterization of a given phenomena. The greatest foreseen challenge to successfully complete development of A-IDEA is the ability to quantify field-expert knowledge in a form usable by an autonomous system. Based on our experience in using the manual IDEA methodology, an autonomous implementation would increase the utilization of deployment time as well as reduce the number of field-experts required during a deployment.

VI. Conclusions and Future Work

The results of the preliminary NIMS-AQ deployments in diverse environments, including a lake with near zero-flow of water and river with flowing water, demonstrate the ability of the system to be a flexible tool for aquatic field research. Reduced setup and calibration time, verified through these field deployments, makes it suitable platform to perform sensing over multiple cross-sections, providing large spatial coverage. Being a tethered system, it provides accurate localization over high spatial resolution, that is important for several aquatic applications. Additionally, reduced dependence on specific infrastructure for system support makes it an ideal tethered platform that can be deployed in areas not possible with other tethered systems.

Experiments performed with sonar indicate its applicability for autonomous depth profiling, further reducing the setup time for the system and making the system autonomous. Results from the adaptive sampling experiments indicate the applicability of NIMS-AQ for such experiments, thus providing an opportunity to further improve the spatial coverage by making observations adaptively at only a few locations. These results motivated the extension of iterative experiment design methodology, successfully demonstrated earlier for effective characterization of environmental phenomena [1], to autonomous IDEA methodology. Such an approach will enable autonomous characterization of complex aquatic phenomena with high fidelity.

In the future, we plan to extend NIMS-AQ to a multi-cabled version based on three dimensional NIMS platform [22]. This will provide the system with a capability to span the surface of aquatic environments using three or four cables. With an ability for vertical actuation of the sensor payload, it will make the system ideal for detailed three dimensional characterization of the aquatic environments. We are also planning on implementing autonomous calibration using RFID (and magnetic) tags attached with the horizontal cable. This will make the system setup completely autonomous thus providing an ideal platform for testing the autonomous IDEA approach. We plan to integrate the modules of A-IDEA into a single package and test it out with the proposed system changes in the upcoming deployments, that cater toward several imperative aquatic applications.

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References

[1] A. Singh, M. A. Batalin, M. J. Stealey, V. Chen, Y. Lam, M. Hansen, T. Harmon, G. Sukhatme, and W. J. Kaiser, "Mobile robot sensing for environmental applications," in *6th International Conference on Field and Service Robotics*, Chamonix, France, June 2007.

[2] A. Singh, M. A. Batalin, M. J. Stealey, B. Zhang, A. Dhariwal, B. Stauffer, S. Moorthi, C. Oberg, A. Pereira, V. Chen, Y. Lam, D. Caron, M. Hansen, W. J. Kaiser, and G. Sukhatme, "Human assisted robotic team campaigns for aquatic monitoring," *Journal of Field Robotics, Special Issue on Teamwork in Field Robotics*, p. to appear, 2007.

[3] T. Harmon, R. Ambrose, R. Gilbert, J. Fisher, M. Stealey, and W. Kaiser, "High-resolution river hydraulic and water quality characterization using rapidly deployable networked infomechanical systems (nims rd)," *Environmental Engineering Science*, vol. 24, p. 2, 2007.

[4] A. Laroche, J. Gallichand, R. Lagace, and A. Pesant, "Simulating atrazine transport with hspf in an agricultural watershed," *Jornal of Environmental Engineering ASCE*, vol. 122, pp. 622–630, 1996.

[5] C. Walsh, A. Roy, J. Feminella, P. Cottingham, P. Groffman, and R. Morgan, "The urban stream syndrome: Current knowledge and the search for a cure," *Journal of North American Benthic Society*, vol. 24, pp. 706–723, 2005.

[6] N. Quinn, K. Jacobs, C. Chen, and W. Stringfellow, "Elements of a decision support system for real-time management of dissolved oxygen in the san joaquin river deep water ship channel," *Evironmental Modelling and Software*, vol. 20, pp. 1495–1504, 2005.

[7] T. Kratz, L. Deegan, M. Harmon, and W. Lauenroth, "Ecological variability in space and time: Insights gained from the us lter program," *BioScience*, vol. 53, pp. 57–67(11), 1 January 2003.

[8] J. V. Reynolds-Fleming, J. G. Fleming, and J. Richard A. Luettich, "Portable autonomous vertical profiler for estuarine applications," *Estuaries*, vol. 25, pp. 142–147, 2004.

[9] R. Gelda and S. Effler, "Metabolic rate estimates for a eutrophic lake from diel dissolved oxygen signals," *Hydrobiologia*, vol. 485, pp. 51–66(16), October 2002.

[10] S. MacIntyre, J. R. Romero, and G. W. Kling, "Spatial-temporal variability in surface layer deepening and lateral advection in an embayment of lake victoria, east africa," *Limnology and Oceanography*, vol. 47, no. 3, pp. 656–671, 2002.

[11] D. R. Blidberg, "The development of autonomous underwater vehicles (auvs); a brief summary,," in *IEEE International Conference on Robotics and Automation*, Seoul, Korea, May, 2001.

[12] M. Kumagai, T. Ura, Y. Kuroda, and R. Walker, "A new autonomous underwater vehicle designed for lake environment monitoring," *Advanced Robotics*, vol. 16, pp. 17–26, January 2002.

[13] G. S. Sukhatme, A. Dhariwal, B. Zhang, C. Oberg, B. Stauffer, , and D. A. Caron, "The design and development of a wireless robotic networked aquatic microbial observing system," *Environmental Engineering Science*, vol. 24, no. 2, pp. 205–215, 2006.

[14] C. Cannell, A. Gadre, and D. Stilwell, "Boundary tracking and rapid mapping of a thermal plume using an autonomous vehicle," *Proceedings IEEE/MTS OCEANS*, pp. 1–6, 2006.

[15] M. J.E., M. A., C. W., and W. C., "Evolution of the autonomous surface craft autocat," in *OCEANS 2000 MTS/IEEE Conference and Exhibition*, vol. 1, pp. 403–408.

[16] B. L. Jordan, M. A. Batalin, and W. J. Kaiser, "NIMS RD: A rapidly deployable cable based robot," in *IEEE International Conference on Robotics and Automation (ICRA)*, Rome, Italy, April 2007.

[17] A. Lopez-Archilla, S. Molla, M. Coleto, M. Guerrero, and C. Montes, "Ecosystem metabolism in a mediterranean shallow lake (Laguna de Santa Olalla, Doanna national park, SW Spain)." *Wetlands*, vol. 24, no. 4, pp. 848–858, 2004.

[18] R. Gelda and S. Effler, "Estimating oxygen exchange across the airwater interface of a hypereutrophic lake," *Hydrobiologia*, vol. 487, pp. 243–254, November 2002.

[19] D. Popa, A. Sanderson, R. Komerska, S. Mupparapu, D. Blidberg, and S. Chappel, "Adaptive sampling algorithms for multiple autonomous underwater vehicles," in *Autonomous Underwater Vehicles, 2004 IEEE/OES*, 17-18 June 2004, pp. 108–118.

[20] A. Singh, M. A. Batalin, V. Chen, M. J. Stealey, B. Jordan, J. Fisher, T. Harmon, M. Hansen, and W. J. Kaiser, "Autonomous robotic sensing experiments at san joaquin river," in *IEEE International Conference on Robotics and Automation (ICRA)*, Rome, Italy, April 2007, pp. 4987–4993.

[21] R. Pon, M. Batalin, J. Gordon, M. Rahimi, W. Kaiser, G. Sukhatme, M. Srivastava, and D. Estrin, "Networked infomechanical systems: A mobile wireless sensor network platform," in *IPSN'05*, pp. 376–381.

[22] P. H. Borgstrom, M. J. Stealey, M. A. Batalin, and W. J. Kaiser, "NIMS3D: A novel rapidly deployable robot for 3-dimensional applications," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China, 2006.

[23] T. C. Harmon, R. F. Ambrose, R. M. Gilbert, J. C. Fisher, M. Stealey, and W. J. Kaiser, "High-resolution river hydraulic and water quality characterization using rapidly deployable networked infomechanical systems (NIMS RD)," *Environmental Engineering Science*, vol. 24, no. 2, pp. 151–159, 2007.

[24] M. J. Stealey, "The networked infomechanical systems rapidly deployable (NIMS-RD) platform," Master's thesis, University of California, Los Angeles (UCLA), 2007.

[25] M. Seeger, "Gaussian processes for machine learning," *Int. Jour. of Neural Systems*, vol. 14, no. 2, pp. 69–106, 2004.

[26] A. Krause, A. Singh, and C. Guestrin, "Near-optimal sensor placements in gaussian processes: Theory, efficient algorithms and empirical studies," *Journal of Machine Learning Research (submitted)*.

[27] A. Singh, A. Krause, C. Guestrin, W. J. Kaiser, and M. A. Batalin, "Efficient planning of informative paths for multiple robots," in *International Joint Conference on Artificial Intelligence(IJCAI)*, Hyderabad, India, January 2007, pp. 2204–2211.

[28] "Imagenex 852 scanning sonar," 2007. [Online]. Available: http://www.imagenex.com/Downloads/What_s_New/852 _Ultra-Miniature/852_ultra-miniature.html

[29] "Hydrolab minisonde 5," 2007. [Online]. Available: http://www.hydrolab.com/products/hydrolabms5.asp

[30] K. Chang, N. Yau, M. Hansen, and D. Estrin, "Sensorbase.org - a centralized repository to slog sensor network data," June 2006.

[31] G. Chen, N. Yau, M. Hansen, and D. Estrin, "Sharing sensor network data," CENS Technical Report 71, March 2007.