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Distributed Computing Framework for Underwater Acoustic Sensor Networks

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***Abstract*—The goal of this paper is to enable near-real-time acquisition and processing of high resolution, high-quality, heterogeneous data from mobile and static sensing platforms to advance ocean exploration by providing infrastructure for a distributed computing framework. Reaching this goal will improve the efficiency of monitoring dynamic oceanographic phenomena such as phytoplankton growth and rate of photosynthesis, salinity and temperature gradient, and concentration of pollutants. resource provisioning framework for organizing the heterogeneous sensing, computing, and communication capabilities of static and mobile devices in the vicinity in order to form an elastic resource pool a hybrid static/mobile computing grid is presented. This local computing grid can be harnessed to enable innovative data- and compute-intensive mobile applications such as onshore near-real-time data processing, analysis and visualization, mission planning and online ocean adaptive sampling.**

I. INTRODUCTION

The goal of this paper is to enable near-real-time acquisition and processing of high-resolution, high quality, heterogeneous data from mobile and static sensing platforms to advance ocean exploration. Reaching this goal will improve the efficiency of monitoring dynamic oceanographic phenomena such as phytoplankton growth and rate of photosynthesis, salinity and temperature gradient, and concentration of pollutants. Toward this end, this paper will provide infrastructure for distributive computing framework to enhance the capabilities of the NSF's Ocean Observatories Initiative (OOI) cyberinfrastructure [1]. This enhanced cyberinfrastructure, which spans over multiple environments (underwater, ocean surface, and terrestrial), will ensure continuous acquisition of oceanographic data through seamless integration of static and mobile sensing, computation, and communication resources [2], [3].

To ensure sufficient coverage of the vast undersampled 3D aquatic volume, intelligent adaptive sampling strategies involving teams of Autonomous Underwater Vehicles (AUVs) with underwater wireless communication capabilities become essential. These autonomous vehicles should coordinate and steer through the region of interest, and cooperatively sense and transmit multimedia data to onshore stations for real-time data processing and analysis. This paper utilizes a resource provisioning framework [4] for organizing the heterogeneous sensing, computing, and communication capabilities of static and mobile nodes (AUVs) in the vicinity in order to form an *elastic resource pool* - a hybrid static/mobile computing grid. This local computing grid can be harnessed to enable innovative data- and compute-intensive mobile applications.

The direct impact of the proposed research on marine science will be demonstrated with the following research areas as application scenarios: onshore near-real-time data processing, analysis and visualization, and mission planning. In addition, the framework will help in online ocean adaptive sampling, team strategy, formation geometry and team path, and individual underwater vehicle control. The response time, quality, and relevance of such mobile applications, which rely on real-time in-the-field processing of locally generated data, can be drastically improved using our envisioned framework. Currently, the primary impediments to real-time in-the-field data processing are insufficient sensing and computing capabilities on individual mobile sensors, which prevents them from producing meaningful results within realistic time bounds in isolation, and the prohibitive communication cost and response time involved in enabling such data-intensive applications.

Hence, this work will help us achieve the following goals 1) Create an autonomic cyberinfrastructure which will leverage online data service from existing infrastructure and will determine when, what, and how to offload computation from in-network to remote infrastructure 2) Enable near-real-time acquisition and processing of high-resolution, high quality heterogeneous oceanic data, online adaptive sampling and improving forecasting of data by merging observations with advanced ocean models.

II. ROLE-BASED ARCHITECTURAL FRAMEWORK

The self-organization capability (for handling service discovery and service request arrivals as well as for task distribution and management) is imparted by the role-based architectural framework. It also facilitates interactions among the mobile entities for coordination and seamless switching among the three logical roles: i) service requester, which places requests for workloads that require additional data and/or computing resources from other devices, ii) service provider, which can be a data provider, resource provider, or both, and iii) arbitrator (also typically known as broker), which processes the requests from the requesters, determines the set of service providers that will provide or process data, and distributes the workload tasks among them. Data providers provide scalar or multimedia data while resource providers lend their computational (CPU cycles), storage and communication resources for processing data. Our framework applies to applications exhibiting data parallelism (in which data is distributed across different parallel computing nodes

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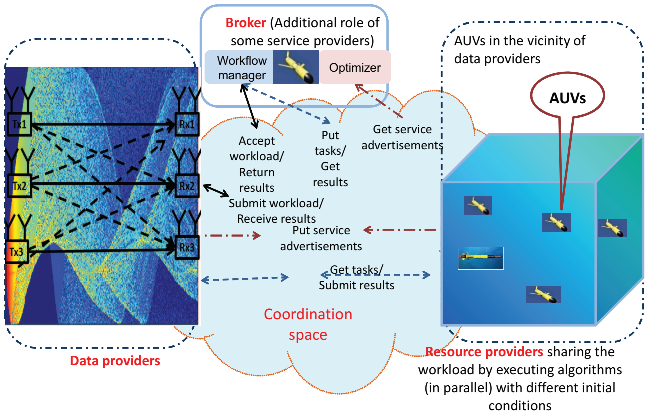

Fig. 1. An overview of the envisioned distributed computing framework for near-real-time data processing and analysis. The right hand side of the figure shows an underwater channel with Tx and Rx nodes (in our case AUVs) communicating with each other.

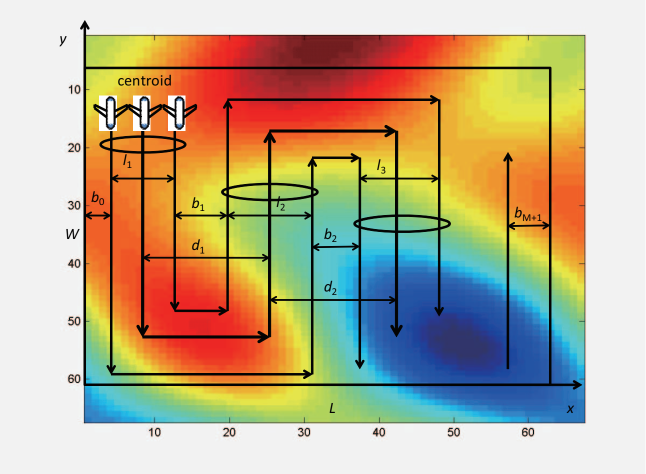

Fig. 2. Trajectory planning for multiple vehicles for one micro-round (here $V = 3$).

that perform the same task) as well as to applications exhibiting task parallelism (in which parallel computing nodes may perform different tasks on the same or different data). The different tasks of a workload may be distributed among the available service providers based on a policy that aims at minimizing battery drain.

In [5] we introduced the concept of external uncertainty which is the position uncertainty associated with a particular underwater entity/node as seen by others. Knowledge of ocean currents is essential to reduce not only the energy spent by AUVs for navigation but also the external uncertainty. An AUV may be able to measure the velocity of the ocean current affecting itself using expensive on-board current profilers. However, an AUV has no knowledge of the ocean currents affecting other AUVs in the network (that may be far apart) and, therefore, their impact on the external uncertainty. Data from ocean observing systems such as the National Oceanic and Atmospheric Administration (NOAA) can be propagated from onshore stations to the UW-ASN to improve uncertainty estimates. Conventionally, data from underwater sensors is first sent to onshore stations for assimilation into ocean models, analysis, and decision making on future sensing strategies. Then, mission-specific commands and queries are sent back to individual AUVs. The distributed framework will forward the data directly to a subset of AUVs. This pool of AUVs will share resources to enable this estimation in-situ rather than sending it to an onshore location and hence, saving time and energy.

In order to achieve efficient and cost-effective sensing coverage of the vast under-sampled 3D aquatic volume, intelligent adaptive sampling strategies involving a team of Autonomous Underwater Vehicles (AUVs) endowed with underwater wireless communication capabilities become essential. Given a field of interest to sample, the AUVs should coordinate to take measurements using minimal resources (time or energy) in order to reconstruct the field at an onshore station with admissible error. This paper will enable advanced ocean adaptive sampling by enhancing the OOI cyberinfrastructure with robust distributed computing framework which will leverage the computation resources of local nodes (AUVs, buoys). This will enable 1) immediate availability of high-resolution, high-quality, heterogeneous sensor data from mobile platforms for near-real-time processing and analysis, 2) autonomic decision of the appropriate communication strategy for efficient aggregation and dissemination of information that ensures short turnaround time from mission planning to team formation, and 3) reliable real-time coordination among AUVs for distributed control (maintaining team formation geometry and team path). These capabilities have broad and significant impacts on several areas of marine science and technology.

III. PROPOSED WORK

In our adaptive solution we capture the spatial distribution of the field of any oceanic phenomenon (such as variation in temperature, salinity or dissolved oxygen) and also track its temporal variations (in space and time) using a team of AUVs. To take samples the AUV moves across a field by following a certain trajectory and takes samples as it moves (as shown in Fig. 2). Our solution operates in two phase, Phase I captures the spatial distribution of a manifestation (say salinity, temperature, chlorophyll concentration) in the field of interest while Phase II tracks the temporal variations of the manifestation. Both the phases together form a round, which is repeated over time. The two phases are shown in the timing diagram in Fig. 3(c). In Phase I, the field is scanned randomly to obtain a preliminary estimate of the spatial distribution of the manifestation in the field by using the technique of compressive sensing (CS); and in Phase II, the field is scanned adaptively, in multiple micro-rounds to capture the temporal variations. Once the sampling locations are determined the trajectories of each AUV is estimated by solving multiple travellers salesman (mTSP) problem. All AUVs start and end at the same location, such that each intermediate sampling

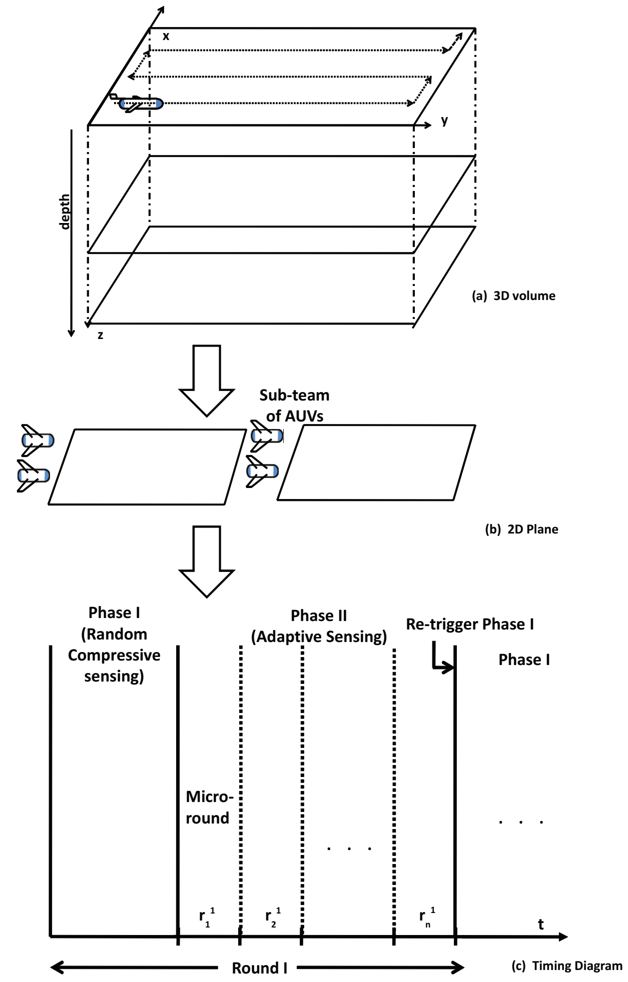

Fig. 3. Block (a) shows ocean as a 3D volume, (b) The 3D volume is divided into multiple 2D planes. Each 2D plane is represented by a parallelogram constructed with solid black line, (c) Timing Diagram of phase 1 and 2 that occur while sampling a 2D plane.

location is visited exactly once and the total cost of visiting all nodes is minimized.

To distribute the computation load to vehicles in the team of AUVs, we envision that the computing and storage capabilities of the AUVs in the vicinity can be utilized to form an elastic resource pool that can process massive amounts of locally generated data in parallel. We propose a ubiquitous computing solution that is aimed at organizing AUVs in the vicinity into a wirelessly connected local distributed computing grid. The collective computational capability of this distributed grid can be exploited to perform distributed computation. In our distributed computing grid the leader AUV is called broker and other AUVs are the service providers. In the above adaptive sampling solution we have considered only 2D field. For this we have divided the 3D volume of ocean (as shown in Fig. 3). This helps to reduce the control complexity of changing the buoyancy or vertical thruster to move up or down. For a 3D volume we are faced with another problem, i.e., how to optimally partition a team of AUVs in to sub-teams that can adaptively scan the individual 2D planes. This is a compute intensive resource allocation problem and can be handled by the distributed framework.

The adaptive sampling solution which estimates the sampling locations also involves solving compute intensive optimization problem. These locations are obtained by minimizing energy while keeping the error bounded and vice versa. The compressive sensing as well as solutions to mTSP problem are compute intensive. Currently, once the samples (temperature, salinity or oxygen) have been measured by team of AUVs, they are sent to an onshore locations for reconstruction of the phenomenon from the observations (using CS technique) as the AUVs do not have sufficient computational capabilities. These CS techniques involve multiple matrix multiplication and matrix inverse calculations which can be performed in parallel by AUVs in the team. The broker will be responsible for dividing these tasks and aggregating the results. Solutions to mTSP problems are also compute intensive. The distributed computing framework provides us with the infrastructure to distribute these compute intensive tasks in-network.

IV. CONCLUSION AND FUTURE WORK

Enabling applications that require real-time in-the-field data collection and processing using mobile sensor nodes such as AUVs is challenging due to i) the insufficient computing capabilities and unavailability of complete data on individual mobile nodes and ii) the prohibitive communication cost and response time involved in offloading data to remote computing resources such as on-shore location for centralized computation. The infrastructure for resource-provisioning framework for organizing the heterogeneous sensing, computing, and communication capabilities of static and mobile sensors in the vicinity in order to form an elastic resource pool - a hybrid static/mobile computing grid is presented. As a future work we will integrate UW-ASNs with the OOI cyberinfrastructure. This involves integration of data obtained from remote sensing, data from online ocean systems, and computation resources of existing observation systems.

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