A Physicomimetics Control Framework for Swarms of Autonomous Surface Vehicles

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***Abstract*—Teams of autonomous cooperating vehicles are well-suited for meeting the challenges associated with mobile marine sensor networks. Swarms built using a physicomimetics approach exhibit predictable behavior – an important benefit for extended duration deployments of autonomous ocean platforms. By using a decentralized control framework, we minimize energy consumption via short-range communication and self-contained on-board data processing, all without a specified leader. We introduce the task of autonomous surface vehicle (ASV) navigation inside a bioluminescent plume to motivate future study of how the agility and scalability of our physics-based solution can benefit a mobile distributed sensor network.**

I. INTRODUCTION

The capability to carry out an extended-duration ocean surveillance mission brings numerous potential benefits for military, civilian and scientific applications. This research addresses the problem of finding an optimal navigation path through regions of coastal bioluminescence while maintaining covert status of the operation. To accomplish the mission, the ship's navigator must have access to up-to-date information regarding the distribution of the bioluminescent organisms, and such data can be provided in real time by a fleet of small, autonomous vehicles equipped with bioluminescence sensors. Of course, the same vehicles can collect and report other useful measurements, and due to their autonomy, the cost of such *in situ* monitoring missions is expected to be lower than the data-gathering expeditions supervised and supported by human operators. Likewise, data collected by a mobile platform has an increased chance of being more useful in environmental modeling due to the mobile nature of the sensor platform, which gives it the ability to rapidly respond to changes in the environment, as well as the unique option to track the more "interesting" features within its sensor field.

This paper outlines an implementation of a scalable, multi-vehicle sensor network that represents a practical solution to the problems associated with adaptive, wide-area ocean surveillance. The main aspects of our physics-inspired solution are a decentralized control algorithm, minimal requirements for the on-board computation and communication capabilities, and a suite of theoretical analysis methods that predict the long-term behavior of the robotic vehicles in the fleet [1].

II. MOTIVATION

Answers to current issues facing environmental scientists, from human-induced nutrification of coastal waters to increasing industrial pollution, require reliable access to vast amounts of ocean-observation data. Understanding the impact of changes in the world's marine environments requires reliable wide-area adaptive sensing. Because certain environmental phenomena, such as harmful algal blooms (HABs), often occur in unpredictable locations, the sensor platform must be endowed with mobility to enable expeditionary deployment. In addition, because of the large spatial scale of these events, it would be impractical to "blanket" the entire area of interest with sensors – the cost of the ideal "total coverage" solution is simply too great.

A more practical approach is to deploy a moderate-sized collective (i.e., a *swarm*) of autonomous robotic agents, and to program the robots using mapping and tracing algorithms that maximize sensor coverage. Note that our solution does not restrict the type of swarm platforms – the physicomimetics approach that we use as the foundation of our control architecture works equally well for swarms consisting of a few automated boats to a large heterogeneous collection of unmanned surface, underwater and aerial vehicles numbering in the hundreds. This paper will explain how such scalability can be obtained with minimal requirements on the on-board processing and communication hardware, resulting in a low-cost, robust, mobile sea-faring observation platform.

Deployment of automated drones necessitates procedures for dealing with unforeseen events, such as hardware failures or sudden shifts in local wind and ocean current patterns. The reactive aspect of our control framework allows for a "natural" handling of such events, without relying on execution of pre-programmed scripts of complicated rule sets. All members of a physicomimetics swarm are designed to function as "particles" within a virtual physics system, so that we are able to employ standard mathematical analysis techniques to prove long-term stability properties of our implementation. As the end product of our research effort, we envision an intelligent mobile sensor network technology that can meet the demands of maritime civilian and military applications.

We begin with a presentation of the physicomimetics control framework, explaining the basic physics-based control laws that govern the behavior of individual agents. A notable aspect of the physicomimetics approach is the use of mobile robots to emerge structured vehicle formations that can be employed effectively as a distributed sensor and computation network. We describe the utility of such formations through a study of a swarm solution to the problem of mapping and tracing biological marine plumes. Currently, we are evaluating the performance of a simulated physicomimetics swarm tasked with multi-objective navigation of an open region populated with bioluminescent organisms. The simulation work discussed in this paper is part of a comprehensive scientific effort to transition to a hardware-based solution of this plume-navigation problem, and Section V introduces the DRONE platform currently under development by the Harbor Branch Oceanographic Institution (HBOI) with support from the US Office of Naval Research.

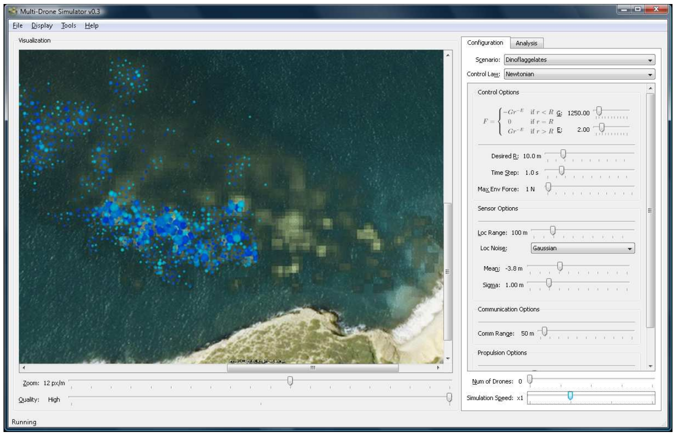
III. BACKGROUND

As we explain in this section, coastal bioluminescence can have adverse effects on stealth navigation. We are developing a distributed surveillance network capable of detecting and predicting distributions of bioluminescent *dinoflagellate* colonies. This section discusses important background information pertinent to the principal components of this paper: the model of bioluminescent plumes, the physicomimetics swarm control framework, and a software simulation engine that provides a virtualized abstraction of the target ASV hardware.

A. Coastal Bioluminescence

Bioluminescence is ubiquitous in the world's oceans, existing primarily in the form of single-celled luminescent phytoplankton, such as *dinoflagellates*. These organisms exhibit what is known as "stimulated luminescence," whereby a mechanical disturbance such as a fish, diver, or ship moving through the water creates a pressure differential which causes the organisms to emit light. In areas of dense concentrations, such luminescent flashes can be very bright, presenting a tactical concern when planning covert night-time naval operations. In coastal environments, the presence and magnitude of these organisms is often higher, influenced by tidal flushing, nutrient enrichment and other forcing factors [2].

Since these factors are not always homogeneous, attempting covert operations, such as night-time beach insertions, can be complicated by the patchwork luminescent "minefield" that emerges just offshore. Previous work has been conducted at Harbor Branch Oceanographic Institution on the design and use of bathyphometers (BPs); devices that measure stimulated luminescence in the water column [3], [4]. These BPs typically operate as shipboard profilers or drifting floats, and are used to actively quantify the bioluminescence potential of an area, as well as provide data used in forecasting future bioluminescence activity. The goal of this project is to explore the potential for a swarm of small autonomous vehicles to be used to actively map an area of interest and find a minimum bioluminescent pathway from an offshore waypoint to a target location. In addition, the tracing of thermo-haline plumes is of interest, both as a better understood, non-biological test case, as well as a means of identifying potential anthropogenic environmental stressors in future applications.



Scenario: Dinoflaggelates

Control Law: Newtonian

$$F = \begin{cases} -Gr^{-E} & \text{if } r < R \\ 0 & \text{if } r = R \\ Gr^{-E} & \text{if } r > R \end{cases}$$

G: 1250.00

E: 2.00

Desired R: 10.0 m

Time Step: 1.0 s

Max Env Force: 1 N

Loc Range: 100 m

Loc Noise: Gaussian

Mean: -3.8 m

Sigma: 1.00 m

Comm Range: 50 m

Num of Drones: 0

Simulation Speed: x1

Zoom: 12 px/m

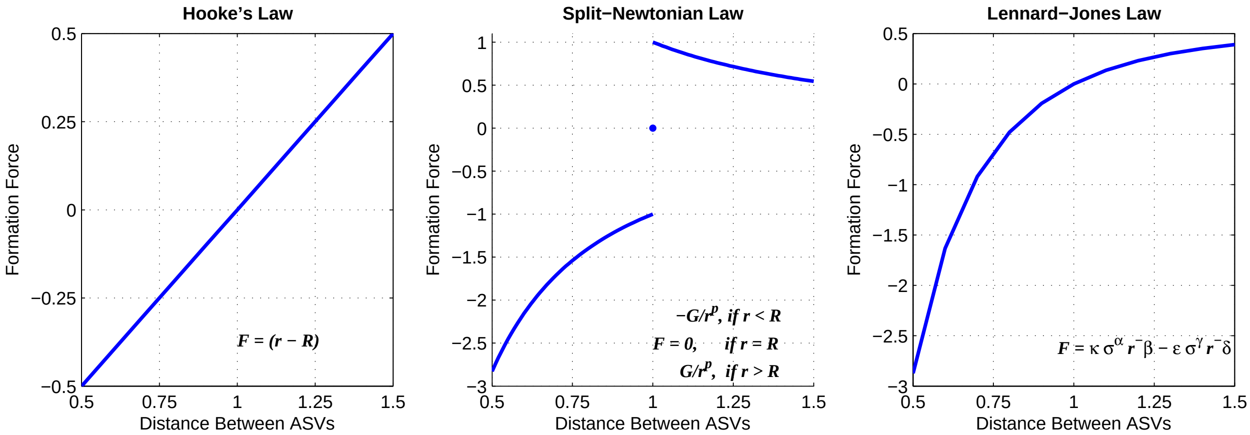
Quality: High

Fig. 1: Simulated nutrient (beige) and bioluminescence (blue) plumes created within the MDS.

To aid in simulation, we created a simplified model of growth and distribution of a luminescent *dinoflagellate* bloom. The fundamental assumption of our model is that the bioluminescent organisms have a small degree of mobility, and that they tend to accumulate in the vicinity of nutrient sources. We also assume that the more abundant the food source, the larger the dinoflagellate colony that forms within this nutrient-rich region. By extension, the amount of bioluminescence generated within a certain area of the biological plume is directly proportional to the size of the colony that occupies the region.

The plume model is based on a computational fluid dynamics (CFD) solver, originally developed by J. Farrell et al. [5]. As the first step in the process, we solve for wind-driven currents over a small, 2 km × 2 km square coastal region. The velocity data is then used to generate a chemical nutrient field, assuming multi-scale transport effects of advection (due to currents), inter-plume mixing (due to turbulence) and temporal dispersion (due to diffusion). Once the nutrient's distribution throughout the environment is established, we introduce a colony of bioluminescent organisms, that have a very limited ability to sense the concentration of the nutrient in their immediate vicinity, and attempt to move toward areas of greater nutrient, while their motion is also subject to random perturbations due to small-scale turbulence in the water. We allow the plume simulation enough time to achieve a stable bioluminescence distribution, and one representative plume configuration is shown in Figure 1.

Note that this CFD-based approach extends well to our physics-driven swarm design, in which we apply the ideas of force and particle interactions to the fleet of drones with the purpose of emerging geometric formations of ASVs. By



(a) (b) (c)

Fig. 2: Three different types of physicomimetics force laws included in our study: (a) Hooke's Law, (b) Split-Newtonian Law, (c) Lennard-Jones Law. Neighbor vehicles repel each other when F is negative, and attract when F is positive. The r denotes the actual distance between the ASVs, and parameter R is the desired separation specified by the algorithm (parameter σ in the Lennard-Jones Law is a function of R). All other parameters control the slope and magnitude of the formation force [6].

arranging the vehicles into a structured lattice, we create a distributed sensor mesh, which we can then use to perform a real-time analysis of the surrounding bioluminescence plume. It is important to note that the stealth navigation task we address in this paper belongs to a larger class of *plume tracing* problems. In our previous work, e.g. [7], we developed a physicomimetics-based solution to the chemical plume tracing (CPT) problem, in which a swarm of inexpensive, mobile robots used simple chemical sensors to search an airborne chemical plume for the source emitter. Here, we extend the methodology to the bioluminescence scenario, in which we require the drones to find a path of minimal bioluminescence between two points separated by an established plume of luminescent organisms. The control framework that manages the operation of the swarm as it navigates within the plume is described next.

B. Physicomimetics Control Framework

To support our experimental studies of the plume-tracing problem, we implemented a physics-based vehicle controller. We call our approach *physicomimetics* because we control the ASVs by mimicking the forces that exist within real-world particle systems (e.g., molecular lattices in solids and electrostatic bonds in liquids). Although these forces are defined only inside the control software, the robots *act* as though the forces are real [8]. Physicomimetics design methodology is minimalistic – there is no need for a global controller, or explicit "leader", or long-range communication [9]. Instead, each drone observes the environment, notes the position of nearby ASVs using an array of RF sensors, and then computes a control force vector that alters the drone's course [10].

The fundamental operational principle of our solution is based on real physical systems, but we also employ a designer's license to alter the system dynamics to better suit the task at hand. For instance, the control method enforces Newton's Laws, such as Conservation of Momentum and the basic $\mathbf{F} = m\mathbf{a}$ equations. However, we can and do change things like universal constants and exponential rates of decrease in the magnitude of the formation force with increasing distance between nearby units [11], [12]. Figure 3 shows seven agents arranged in a hexagonal formation; using a simple geometric construction [8] we can show that the vehicles only need to know the range and bearing (displayed as circles) to their neighbors in order to form such hexagonal lattices. Since hexagonal tiles can tile a planar region (i.e., the hexagonal grids can be connected without spatial gaps), this geometry is particularly well suited for sensor applications.

The reactive nature of the control laws, expressed as functions of the distance between neighboring vehicles (see Fig. 2), allows for straightforward recovery from unexpected events, such as loss of sensor nodes or operation in unstructured environments [1]. Such physicomimetics control forces are mathematically consistent, that is to say that the integral of any virtual control force is actually a measure of a corresponding

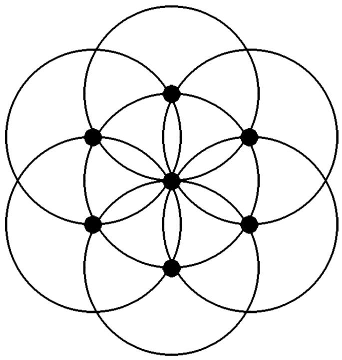


Fig. 3: Hexagonal physicomimetics formation constructed using information about range and bearing to neighbor vehicles.

potential field (which is never explicitly computed by the drones). This level of mathematical accuracy and physical fidelity is what distinguishes the physicomimetics approach from other swarm-control formulations, where concepts of *force* and *energy* lack a rigorous theoretical foundation or are entirely computed by a global controller. Such faithful adherence to a physical consistency of the pairwise interactions between the nodes in the mobile network, endows the system with valuable properties, such as self-organization and self-repair [8].

In order to accomplish tasks other than organizing the fleet into a formation, the physicomimetics framework introduces other types of control forces. It is straightforward, from the standpoint of both theory and practice, to incorporate mission-specific *goal forces* [1]. By balancing the internal cohesion forces and the external goal-directed forces, the group of robots maintains its grid-like sensor arrangement while also moving toward a goal location (see Fig. 4). For instance, when the vehicles are mapping a bioluminescence plume, they periodically share their sensor observations with the neighboring ASVs, and use that data to calculate an additional *goal* force which allows them to achieve mission objectives.

Because of the implicit and strictly-local cooperation within the fleet, the emergent global behavior is that of sensor noise reduction and increased resolution due to the synthetic aperture benefit of multi-drone sensing. Thus, the physicomimetics approach provides two key advantages for mobile marine sensor network design: (1) the formation-keeping swarm exhibits a "consensus building" behavior, so that sensor data from each vehicle influences the fleet's movement without any explicit programming, and (2) the swarm always performs the minimal amount of work to achieve the objectives [1]. Because of these properties, we can build ASVs that require less energy and time to complete the mission, and we do so at a smaller per-ASV cost, since we can use less expensive, limited-range sensors for each individual vehicle [13]. In addition, the physical foundation of the system is subject to standard analysis methods, meaning that we can select control parameters that elicit the needed response ahead of time. Thus a physicomimetics swarm is able to function "out of the box," reducing deployment time and minimizing the need for human oversight during operation [12].

The key ability that makes all of this versatility possible is coordinated multiplicity. In particular, whereas each individual unit relies on short-range sensing and local communication, the emergent behavior of the overall swarm enables it to achieve a task that was impossible for any one vehicle to accomplish on its own.

C. *Multi*-DRONE *Simulation Engine*

The multi-DRONE simulator (MDS) is a comprehensive software tool that provides a configurable test environment for the bioluminescence plume-navigation problem (see Fig. 1). The reason for developing this simulation engine is to provide a high-fidelity emulation of key hardware modules, such as communication, localization and control, for the new DRONE platform (see Section V). The MDS effort represents our attempt to model and identify important elements of hardware design that may impact performance of the ASVs on the bioluminescence navigation task.

Our on-going research effort is focused on the physicomimetics swarm controller. In particular, we want to better understand the operational characteristics of this technique in the context of the BPT problem. Therefore, we intentionally structured the simulator's software architecture to parallel the principal components of the target hardware platform. Thus, the simulation engine virtualizes each hardware component of the DRONE, and provides a separate emulated microcontroller clock for every on-board sub-system, such as sensors, control and propulsion. The hardware abstraction model also includes representative noise sources as part of the localization and sensing sub-systems, enabling an accurate study and evaluation of the units' expected performance under a variety of environmental conditions.

MDS implements physically accurate vehicle behavior via a multithreaded object dynamics engine, and all simulated DRONEs operate based on a decentralized, fully distributed, event-driven model. The simulation of the marine environment is strictly separated from the sensing and control structures within the plume-tracing agents, and this separation is enforced through the use of different spatial and temporal scales for the simulated physics of the world, and the internal operation of the vehicles. In other words, just like in the real world, the environment is always changing, even while the drones acquire sensor readings, communicate with their swarm neighbors, and execute their respective navigation strategy.

The operation of this pseudo real-time system is driven by periodic events, and each agent in the simulation responds to these events according to its current state, available sensor information, and current mission objectives. The DRONE software objects are themselves an aggregate of smaller, sub-system modules. These sub-systems are software models of the the corresponding hardware devices, and they all interact via specific messages, exchanged over an emulated system data bus. Although the resulting software implementation is noticeably more complex than other similar frameworks, e.g. [6], the corresponding increase in the level of simulated detail allows us to control and study the impacts of various hardware constraints on the ability of the physicomimetics controller to overcome limitations of individual drones, and to demonstrate an increase in the navigation performance that we expect from a multiagent solution [14].

IV. CURRENT MDS EXPERIMENTS

In this section, we describe the on-going experimental study of the physicomimetics control algorithms in the context of the bioluminescence navigation problem. We are simulating a fleet of ASVs, arranged in a hexagonal formation (see Fig. 3), navigating through a bioluminescence surface plume, like those shown in Fig. 1. Using the MDS testbed, we are evaluating performance of three different control laws: Hooke's Law (i.e., the Spring Law), a modified version of

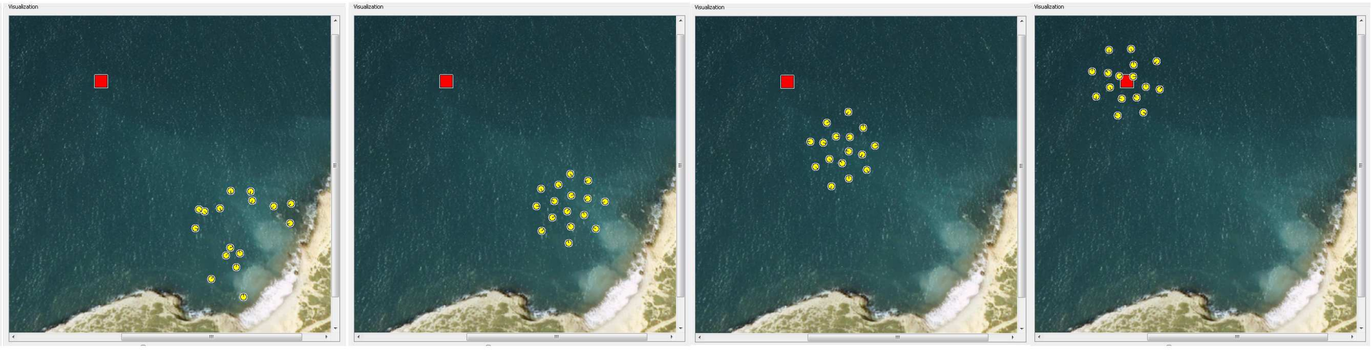


Fig. 4: A team of simulated drones homing in on a goal location. The vehicles (yellow dots) start out in random locations, and then use the physicomimetics control method to self-assemble into a hexagonal lattice formation, which then navigates toward the goal position (red box).

Newton's Universal Law of Gravitation, and the law based on the Lennard-Jones potential (derived from the interactions of van der Walls and Pauli forces), as shown in Fig. 2. We simulate a variable number of drones controlled by each of these different force models performing the BPT task for several plume configurations, with the swarm attempting to cross the plume using a path of *minimal* bioluminescence.

The navigation algorithm used by the drones is a variant of a gradient search algorithm. We selected a naïve gradient-following algorithm for these experiments because it is a simple procedure that uses minimal on-board processing power, and because exchanging small amounts of scalar-valued data does not require large bandwidth [13]. Consistent with our swarm design methodology, we demonstrated in [7] that a multiagent approach can overcome problems that prevent a single-vehicle solution from achieving its goal. For this study, we are looking at the swarm's ability to mitigate intermittent problems in the sensor and localization modules, further strengthening the case for a distributed, multi-vehicle approach to mobile ocean-observing sensor platforms.

During the mission, each simulated drone measures the amount of bioluminescent organisms present in the water surrounding the drone, broadcasts that information to its neighboring ASVs, and then computes two distinct physicomimetics goal forces: the first goal force is in the same direction as the gradient of observed bioluminescence, and the second goal force is an attractive force toward the specified goal location that the swarm must reach. Please note that the goal forces are combined with the physicomimetics formation forces, so that the final direction of a drone's movement is a function of the mission-based objectives, the formation cohesion forces, as well as inertial effects due to its previous navigational actions. Figure 4 shows a time-lapse sequence of screenshots from the MDS application, in which the swarm first assembles into a formation, and then navigates toward a specified goal location. Due to their local nature, the physicomimetics algorithms are highly scalable, and are not restricted by bottlenecks typically associated with "single leader and many followers" approaches [9]. Using the MDS engine, we have simulated swarms of over 120 agents, and these limits are based on the capabilities of our single processor. In the real world, each agent only needs to track its closest neighbors, thus minimizing computational, communication and sensing complexity.

We keep track of three performance metrics: (1) navigation time, (2) amount of bioluminescence measured by the swarm and (3) the quality of the body-centered hexagonal formation during the tracing. For performance metric (2), we normalize the amount of luminescence detected by the drones with respect to the minimal bioluminescence capacity of the region within the sensor range of each vehicle. In evaluating metric (3), we keep track of the angular and radial errors, so that each physicomimetics control law can be evaluated in terms of its suitability for the BPT task. The main goal of these software experiments is to refine the design of the target hardware platform, which we discuss next.

V. HBOI DRONE ASV PLATFORM

The biological plume tracing (BPT) problem provides the context in which we will explore a marine-centered application of our physicomimetics distributed control architecture. To demonstrate the practical benefits of this approach, we are constructing a group of seven simple Autonomous Surface Vehicles (ASVs). Called DRONEs, these units are designed to serve as low-cost prototype test platforms to evaluate swarm formation and plume tracing algorithms in calm open water. By limiting the type and amount of resources committed to a single DRONE, we are able to achieve a cost-effective scale in the number of sensing platforms that can be deployed, and thus improve the spatial and temporal resolution of the DRONE sensor network.

Each vehicle (see Fig. 5) measures approximately 46 cm in diameter, is outfitted with two Voith-Schneider cycloidal propellers (VSPs), and powered by simple, low-cost, SLA batteries. This basic configuration allows the vehicle to move in an omni-directional fashion, accurately replicating the virtual particle motion of the physicomimetics control algorithms. The vehicles contain an on-board ARM9 CPU, and HBOI's RF-based Hyperbolic Localization System (HLS). This system provides passive neighbor localization and data sharing within

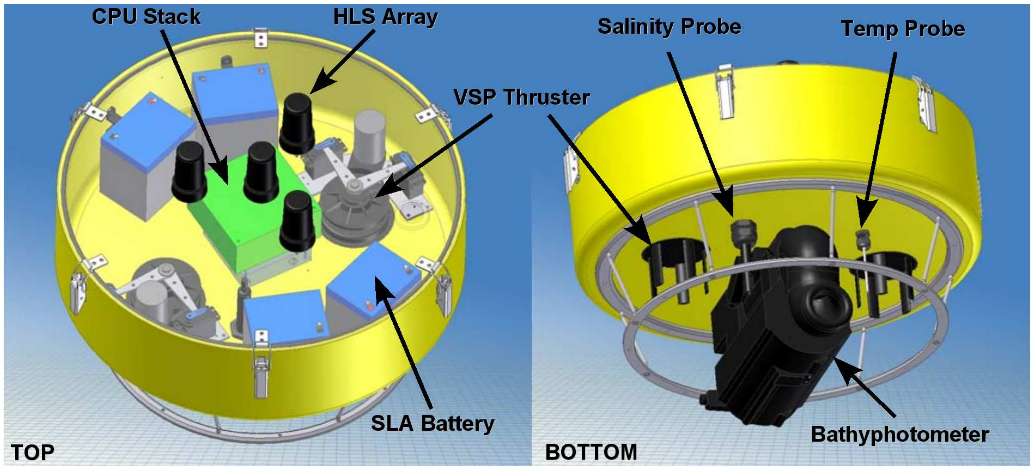


Fig. 5: HBOI DRONE platform equipped for the bioluminescent plume-navigation mission.

the swarm, allowing the group to execute its control scheme using only local information.

While not necessary for group cohesion and plume tracing, a simple GPS and digital compass are also included, for geo-referencing and waypoint navigation. No collision avoidance is included in the prototype design at this time. Finally, each vehicle is equipped with temperature and salinity probes for tracing thermal and saline plumes. Eventually, a small bathyphotometer payload will be added for detecting bioluminescent phytoplankton. Figure 5 shows the inclusion of the compact MBBP, developed by the University of California, Santa Barbara.

VI. SUMMARY AND FUTURE WORK

In this paper, we proposed a novel framework for control of swarms of Autonomous Surface Vehicles, applied to a coastal bioluminescence sensing task. Due to its simple, fully-distributed nature, our physics-based solution is easily computable, relies only on local information, and is scalable to large collections of ASVs, without the need for a specified leader.

We also described a simulation engine which models a virtual ASV swarm, functioning in the same asynchronous, event-driven fashion as the real vehicles. This simulator has demonstrated robust swarm cohesion and successful goal-following with swarms of over a hundred virtual agents. A plume generator has been implemented within the simulation, which generates a “virtual bioluminescence plume.” This generator is now being used in experiments to evaluate the swarm’s performance, applied to the task of seeking the minimum luminescence path to a goal location.

Continuing this work, we intend to use the results of our virtual plume tracing experiments to refine the force law parameters of our physicomimetics control system, and to implement this technology on a swarm of small, low-cost ASV test platforms currently under construction.

ACKNOWLEDGMENT

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