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Team formation and steering algorithms for underwater gliders using acoustic communications [☆,☆☆]

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ABSTRACT

In order to take measurements in space and time from the undersampled vast ocean, it is necessary to employ multiple autonomous underwater vehicles, such as gliders, that communicate and coordinate with each other. These vehicles need to form a team in a specific formation, steer through the 3D region of interest, and take application-dependent measurements such as temperature and salinity. In this article, team formation and steering algorithms relying on underwater acoustic communications are proposed in order to enable glider swarming that is robust against ocean currents and acoustic channel impairments (e.g., high propagation and transmission delay, and low communication reliability). Performance of the proposed algorithms is evaluated and compared against existing solutions, which do not rely on underwater communications, using different ocean current models.

1. Introduction

In the recent years, underwater acoustic sensor networks (UW-ASNs) [2,3] have been deployed to study dynamic oceanographic phenomena such as variations of salinity and temperature, fish migration, and phytoplankton growth for environmental and disaster monitoring (e.g., climate change, tsunami and seaquakes, pollution). In order to enable these applications, it is necessary to take measurements in space and time from the undersampled vast ocean in such a way as to monitor the variations of these phenomena. For example, coral reef spatio-temporal variations are studied in [4] to assess the ability of coral reefs to cope with accelerating human impacts.

Current solutions for ocean sampling rely on existing integrated ocean observing infrastructure, which is comprised of static platforms such as subsurface moorings, ocean-bottom sensors, surface moorings, and mobile platforms. Static platforms will connect to the onshore sensing and high-performance computing resources through high-speed undersea cables, while mobile platforms will connect through satellite and terrestrial links from the ocean surface. These solutions are limited with respect to their application domain, their scalability, and their data quality (e.g., the accuracy of sensed data). These limitations can be removed by using multiple autonomous underwater vehicles (AUVs) that communicate and coordinate with each other and that swarm as a team. Moreover, as long-time measurement is generally needed to collect and derive the spatio-temporal distribution of the data, it is necessary that these AUVs operate over prolonged time periods. Hence, in this article we focus on underwater gliders – a class of energy-efficient propeller-less AUVs. These vehicles can operate over months as they use battery-powered hydraulic pumps to change buoyancy, which power their forward gliding along a sawtooth trajectory.

In order to efficiently take the measurements, it is necessary that these vehicles communicate and coordinate with each other to form a team in a specific formation and steer through the 3D region of interest. Specifically, given the number of gliders to form the team and the formation geometry, which depend on the monitoring application, the gliders need to decide and reach their positions in the specified formation; then, once the formation has been formed, they need to move through the region along a predefined trajectory while maintaining the formation. This problem can be split into two subsequent subproblems: *team formation* (Phase I) and *team steering* (Phase II). In this article, we focus on providing robust yet practical solutions to these two subproblems by proposing the use of underwater acoustic communications to facilitate the coordination of the gliders. In this work, *robustness* refers to the ability of the AUVs to maintain the specified formation in the presence of ocean currents and communication errors.

In the underwater environment, because of the high medium absorption, radio frequency (RF) waves can propagate only a few tens of meters and require high transmission power. Also, while optical transmissions do not suffer from such high absorption, they scatter and require precise pointing of the narrow laser beams,

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[☆] A preliminary shorter version of this article is in Proc. of IEEE Sarnoff Symposium, Princeton, NJ, April 2010 [1].

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which makes them impractical for underwater communications. For these reasons, *acoustic technology is used for underwater inter-vehicle communications*. However, acoustic communications suffer from several impairments: they are influenced by path loss, noise, multi-path, Doppler spread, and high propagation delay. All these factors determine the temporal and spatial variability of the acoustic channel, and make the available channel bandwidth and data bit rates limited and dramatically dependent on both range and frequency.

The problem of underwater vehicle coordination is generally difficult due to its distributed nature and to the harsh communication environment. Decentralized algorithms that are robust enough to compensate for the communication errors caused by the acoustic channel impairments need to be designed so that the gliders can self organize into a team and maintain the predefined formation along the assigned trajectory. To support the coordination of multi-agent systems, *swarming intelligence* has been introduced. A swarm is typically made up of a number of agents interacting locally with one another and with their environment. Through swarm intelligence, the fleet of agents would be able to optimize the mission and achieve a mutual goal. Numerous swarming algorithms such as particle swarm optimization (PSO) [5] have been proposed for the coordination and control of the agents. However, many of these algorithms, several of which inspired by the biological swarms of ant colonies, bird flocking, bacterial growth, and fish schooling, assume a large number of agents and do not perform well when the number of agents is small, as is the case with expensive AUVs.

To address this problem, many solutions such as [6–9] have been proposed by underwater robotics researchers to steer a team of autonomous vehicles along a specified path and thus performing a mission such as adaptive sampling. For many of these solutions, inter-vehicle communications are assumed to be ideal (i.e., no packet loss, no delay, etc.) or are based on ideal graph theory models. Therefore, it is not clear how well they perform using real underwater communications. There are also some solutions such as [10] that rely on air communication techniques (e.g., satellite communications) to exchange inter-vehicle information. In this case, these vehicles have to surface, thus wasting more energy and time (not to mention the risk that – as it has happened – the vehicle is stolen by pirates or damaged by vandals).

To overcome the limitation of using theoretical communication models and relying on radio communication techniques, we introduce innovative coordination algorithms using underwater communication techniques to support swarming of a realistically limited number of underwater gliders (less than ten). Specifically, we propose: (1) a *team formation algorithm* to move the gliders into the specified geometry in minimal time and without collisions, and (2) an *attraction and repulsion swarming algorithm* to steer gliders while maintaining the formation. Underwater acoustic communication techniques are combined with these algorithms in order to improve the performance of vehicle coordination. For team formation, a packet type that performs well for long-range communications is used. For team steering, the relative locations of AUVs are estimated from the Doppler shifts extracted from ongoing opportunistic inter-vehicle communications.

The contribution of our solution is the following:

- Our team formation and team steering algorithms use real underwater acoustic modems and are combined with more realistic underwater communication models. Therefore our solution is closely integrated with realistic underwater communications.
- We design novel underwater acoustic communication techniques to improve the performance of inter-vehicle communications. For example, reliable short FSK-modulated packets are used for long-range communication during team formation.
- We propose a hybrid team steering scheme based on the Doppler shifts extracted from ongoing opportunistic inter-vehicle communications. These Doppler shifts are then used to estimate the relative locations of the AUVs, which are then fed back for distributed steering control.

Our communication techniques are biologically inspired in the following aspects: (i) long-range communication technique for team formation is inspired by the low-frequency long-haul vocalization used by kill whales, (ii) team organization consisting of rotating roles of a leader and multiple followers is inspired by migratory bird flocking, and (iii) Doppler-based relative velocity estimation to maintain the geometry by exploiting local communications is inspired by the echolocation adopted by bats.

The remainder of the article is organized as follows. In Section 2, we review the related work for UW-ASNs and AUV team formation and steering. In Section 4, we present the proposed algorithms for team formation and steering, while in Section 5 their performance is evaluated. Conclusions are then drawn in Section 6.

2. Related work

Cooperation of a team of AUVs to efficiently complete underwater missions such as adaptive sampling [11,10] has attracted many researchers. For example, a solution was proposed for cooperative control of multiple vehicles based on virtual bodies and artificial potentials [10]. However, the control is achieved through satellite communication, which is not available underwater. Periodically, these AUVs have to surface to update their global positioning system (GPS) location and mission plan. The control of the AUVs is not in real time, therefore team formation and steering error due to unpredictable events such as variations of ocean currents cannot be fixed in real time.

In [7], research work in the European Union project GREX, which focuses on the coordination and control of cooperating heterogeneous autonomous marine vehicles (AMVs) in uncertain environments, is summarized. A general architecture for cooperative AMV control in the presence of time-varying communication topologies and communication losses is proposed. The simulation results with the networked marine system simulator and the real sea-experiment results are presented and show the efficacy of the algorithms developed for cooperative motion control. Some theoretical and practical implementation issues have, however, been raised.

A leader–follower approach is proposed in [9] for multi-AUV coordination using underwater communications. Specifically, two control algorithms are designed for two scenarios using two AUVs. The effectiveness of both algorithms are verified only in simulations.

In [8], a solution is proposed to address the problem of steering a group of vehicles along given spatial paths while holding a desired geometrical formation pattern (i.e., the path following problem). The solution is built on Lyapunov-based techniques and addresses explicitly the constraints imposed by the topology of the inter-vehicle communications network. By decoupling the path-following and coordinated control system, the dynamics of each AUV can be dealt with by each vehicle controller locally at the path-following control level, while coordination can be achieved using a decentralized control law whereby the exchange of data among the vehicles is kept at a minimum. The effectiveness of the proposed solution is verified by simulations. However, as the communication impairments are based on ideal graph theory models, i.e., the network topology of the AUVs follows an ideal probabilistic graph without considering the performance of underlying acoustic communication techniques or hardware constraints, the proposed solution needs to be extended to handle stringent