Bio-inspired Communications for Coordination among Autonomous Underwater Vehicles

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***Abstract*—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 paper, bio-inspired underwater acoustic communication and coordination algorithms are proposed to enable glider swarming that is robust against acoustic channel impairments. Performance of the proposed algorithms is evaluated when i) number of vehicles, ii) team formation geometry, and iii) team target trajectory are provided.**

I. Introduction

In the recent years, UnderWater Acoustic Sensor Networks (UW-ASNs) [1], [2] 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). 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 [3] to assess the ability of coral reefs to cope with accelerating human impacts.

While there have been several promising approaches to enable underwater adaptive sampling, current solutions are limited with respect to their application domain, their scalability, and their consistency. 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 paper 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 powers 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 paper, we focus on providing practical solutions to these two subproblems by proposing bio-inspired communication techniques to facilitate the coordination of the gliders.

In the underwater environment, because of the high medium absorption, Radio Frequency (RF) waves can propagate only 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. 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. Numerous swarming algorithms such as Particle Swarm Optimization (PSO) [4] 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.

Hence, we introduce innovative bio-inspired communication and coordination techniques to support swarming of a realistically limited number of underwater gliders (less the 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. Our communication techniques are biologically

inspired in the follows 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 paper is organized as follows. In Sect. II, we present the proposed bio-inspired solutions for team formation and steering, while in Sect. III their performance is evaluated. Conclusions are then drawn in Sect. IV.

II. Proposed Solution

Solutions for both phases (team formation and steering) are designed considering practical constraints and limitations of state-of-the-art underwater acoustic modems.

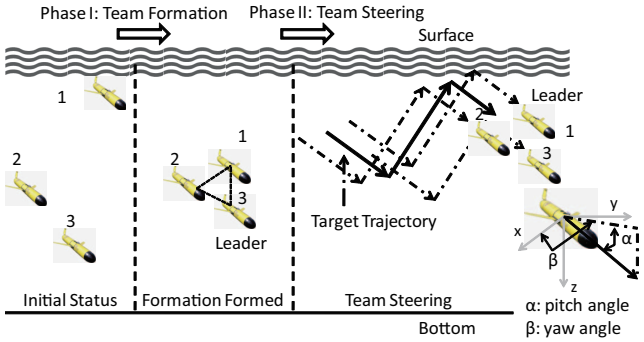


Fig. 1. Overview of the proposed solution for team formation and steering.

A. Overview

In this paper, we focus on how to form the team according to the given formation geometry when randomly scattered gliders are selected and on how to steer them along the trajectory while maintaining the formation. We assume that the gliders in the team have been selected from a pool of vehicles using a task allocation algorithm (e.g., [5]). As in Fig. 1, given i) the number of scattered gliders, ii) the corresponding geometry formation, and iii) the target trajectory, two phases of operations are required to perform the monitoring mission: 1) the selected gliders need to be mapped into a specified geometry formation making sure that no collisions occur (Phase I); 2) after the first phase, the team needs to steer through the 3D region of interest along the predefined trajectory while maintaining the formation (Phase II). Note that, swarming using a specified geometry formation is necessary not only in coordinated monitoring missions, but also in many applications such as surveillance/tracking and collision avoidance in critical navigation missions.

In our solution, a glider is selected to play the role of *leader* to guide the other gliders, which will then act as *followers*. These are *logical roles* that do not depend on the physical position within the formation, i.e., the leader is not necessary ahead of the followers at all times.

TABLE I
4 Types of Packets used by WHOI Acoustic Micro-Modem

Type[1]	Modulation	Coding Scheme	bps	Max. Frames	Frame Bytes
0	FH-FSK		80	1	32
2	PSK	1/15 spding[2]	500	3	64
3	PSK	1/7 spding	1200	2	256
5	PSK	9/17 RBC[3]	5300	8	256

[1] Type 1 and 4 are unimplemented; [2] i.e., "spreading"; [3] i.e., "Rate Block Code".

As the Global Position System (GPS) does not work underwater, gliders can only receive GPS signals when at the surface; therefore, to calculate their positions while underwater they can only rely on localization algorithms. Moreover, accuracy of the location information decreases as the time in the water increases due to the accumulation of localization errors. Consequently, in order to take advantage of the GPS information, the last surfaced glider is chosen to be the *leader*. The aim of the leader is to let the team be on track along the target trajectory, while the aim of the other gliders, the so-called *followers*, is to maintain the formation according to the predefined geometry. When surfaced, a glider advertises itself as the *'new'* leader by broadcasting a message. Upon receiving this message, the *'old'* leader sends a confirmation to the new leader using an acknowledgement packet (ACK), whereas the other gliders just update their leader information without sending any ACK to avoid message implosion. The ACK packet from the 'old' leader serves also as communication redundancy to echo the message from the new leader; by leveraging spatial diversity, the probability of reaching all the gliders is thus increased.

Our solution controls the *pitch angle* α and *yaw angle* β (see Fig. 1) to steer each glider and keep the team formation. The pitch α for a glider ranges in $[\alpha_{min}, \alpha_{max}]$ and determines the velocity of the vehicle (in fact the horizontal velocity can be considered constant in the absence of ocean currents).

B. Team Formation

To enable the communications between the scattered gliders, we adopt a communication technique that emulates the vocalizations used by killer whales. These whales use low frequency whistles ranging from 0.5 to 40 kHz (with peak energy in $6-12$ kHz) to communicate with each other. These low frequencies make long-range communication possible, as explained by the underwater communication theory: low-frequency tones undergo a lower medium attenuation and achieve a higher Signal-to-Noise Ratio (SNR) [6] at the receiver. Moreover, the whistles are usually short, which is advantageous as they are less affected by multipath. This effect is similar to what happens in wireless communications: shorter packets experience a lower Packet Error Rate (PER).

We incorporated these characteristics in our acoustic communication framework, to understand which we show in Figs. 2 and 3 the WHOI Micro-Modem's PER performance as measured in our testbed emulation. As presented in Table I, there are four types of packets used by these underwater acoustic modems, each adopting a different combination of modulation

and coding scheme, and a specific number of frames. By comparing Figs. 2 and 3, it is clear that type 0 packets have the lowest PER when the SNR is low, which means that they performs the best for long-range communications. This is because type 0 is the shortest packet and the modulation it uses (FSK) is very robust; this comes, however, at the price of low bit rates (80 bps). For these reasons, this packet type is a proper choice for long-range control message exchange to resemble long-haul whale vocalizations.

The communication protocol for team formation is depicted in Fig. 4. To calculate the 'best' formation position for each glider - with the objective of minimizing the formation time while avoiding collisions -, the leader broadcasts a packet to collect the positions from the followers. Upon receiving the position packet from all the followers, the leader runs the formation mapping algorithm to find the best mapping (glider $\rightarrow$ vertex in the geometry); then, the leader informs each follower about their assigned formation position. The followers then acknowledge the reception of the message from the leader, and all the gliders start moving towards their assigned positions. All these control messages use short type 0 packets as their aim is to reach far apart gliders that are scattered in a wide region.

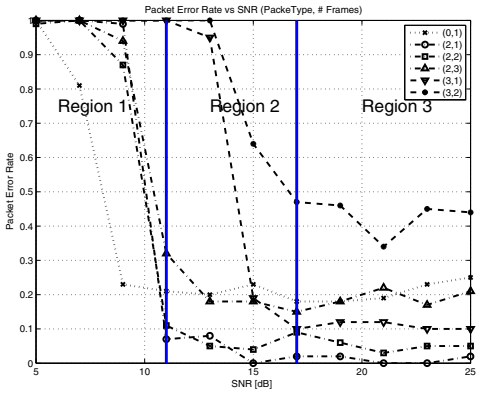


Fig. 2. Packet Error Rate (PER) for Type 0, 2, 3 packet.

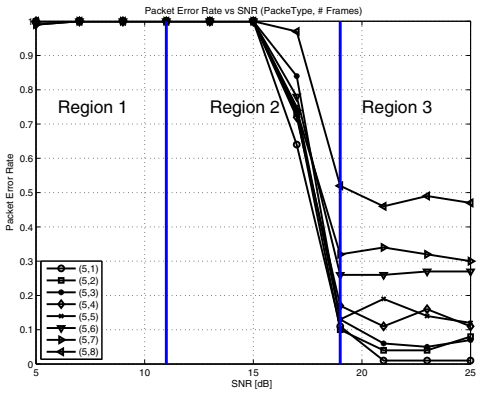


Fig. 3. Packet Error Rate (PER) for Type 5 packet.

The gliders can move in regular formations as shown in Fig. 5. Different formation geometries can be used depending

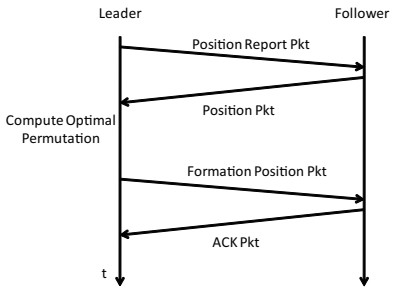


Fig. 4. Protocol for Team Formation (Type 0 packets).

upon the number of gliders and the type of mission. Given the number of gliders to form the team and the corresponding geometry formation, the problem that we face is to map every glider to its position in the formation.

Selecting a position in the formation for a glider depends upon factors such as the time for that glider to reach this position, the possibility of collision with other gliders, and the permutation of the gliders with the formation positions. We have to determine the optimum to minimize both, *the time* and *energy* spent to attain the formation. We first optimize on time to find the mapping, and then on energy consumption, while deciding on the exact trajectory for the selected mapping.

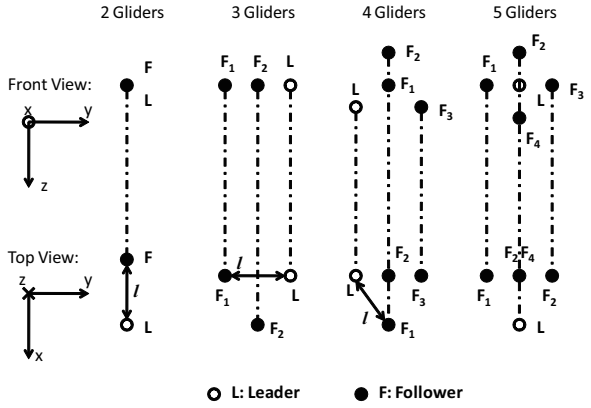


Fig. 5. Formation geometries for 2 - 5 gliders in Front and Top Views, where the mission-specific inter-glider distance is l and the last surfaced glider is chosen as leader.

The formation optimization problem, which aims at mapping the gliders to formation positions, finds - out of all the permutations that avoid collisions (the so-called *feasible solutions*) - the best permutation that minimizes the time to form the team formation. Specifically, given N gliders $1, 2, \ldots, N$, and the corresponding formation points $G_1, G_2, \ldots, G_N$, we need to find a permutation $\pi \in \Pi$ such that the time spent by the gliders to form the formation is minimized while no collision occurs. Here, Π is the set of all $N!$ permutations.

For simplicity and because of the large inter-vehicle distances, in this paper a glider is considered to be a single mass point. Note, however, that our solutions can be straightforwardly extended to account for the real dimensions of the gliders by adding marginal spaces between the points. To ensure no collision among gliders, the *sufficient and necessary*

condition is that two or more gliders of the team do not meet at the same point *and* at the same time as they move along their trajectories. However, solving this problem in the 3D space is complex; also, the solution would be affected by the uncertainty of the velocities of the gliders caused by ocean currents. Therefore, we adopt a simpler conservative approach that relies on a *sufficient condition* to avoid collisions. Note that the fastest way for a glider to move to a point is to follow the sawtooth trajectory laying in the vertical plane containing the current glider position and the destination point. Hence, a sufficient condition to ensure no collision is that the projections of the glider trajectories on the x-y plane - segments describing the horizontal advance of the gliders - do not intersect (Fig. 6).

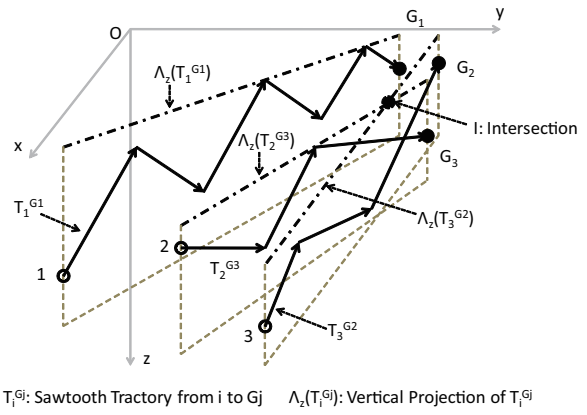


Fig. 6. Mapping gliders 1, 2, and 3 to geometry vertexes G_1, G_3, and G_2, respectively. Note that gliders 2 and 3 may collide as $\Lambda_z(T_2^{G_3})$ and $\Lambda_z(T_3^{G_2})$ intersect at point I.

If we denote the initial position of glider i and formation point G_i as $\mathbf{P}_i^0 = (x_i^0, y_i^0, z_i^0)$ and $\mathbf{P}_{G_i} = (x_{G_i}, y_{G_i}, z_{G_i})$, respectively, given the constant horizontal speed s_H of the gliders, the formation mapping problem can be formulated as,

Given: $\mathbf{P}_i^0, \mathbf{P}_{G_i}, s_H (\forall i = 1, \ldots, N)$

Find: $\pi^* \in \Pi$

Minimize: $\max\left(\sqrt{(x_i^0 - x_{G_j})^2 + (y_i^0 - y_{G_j})^2}/s_H\right)$

Subject to:

$$G_j = \pi(i); \tag{1}$$

$$\pi \in \{\pi : \forall i, m, i \neq m, \Lambda_z(T_i^{\pi(i)}) \cap \Lambda_z(T_m^{\pi(m)}) \equiv \emptyset\}; \tag{2}$$

where $T_i^{\pi(i)}$ is the vertical trajectory from i to its mapped point $\pi(i)$ and $\Lambda_z()$ is the vertical projection to the x-y plane. Here, (1) is the mapping of glider i to G_j, and (2) ensures that the permutations incurring intersections of vertical trajectory projection, i.e., those unfeasible, not be considered.

C. Team Steering

The team steering problem can be divided into two subproblems: 1) steering the team to follow the planned team trajectory, and 2) maintaining the formation. As the leader (the last glider that has surfaced) has the most accurate position information, it is selected to estimate the *team dislocation*, i.e., the deviation from the target trajectory. The leader calculates the adjusted sawtooth trajectory to steer the team back to the target trajectory. Depending on the application requirements, the leader can decide to either move back to the closest point on the target trajectory, or to head towards the final destination of the target trajectory; while the former strategy is more conservative as it minimizes the time to go back to the target trajectory, the latter is more energy efficient when the goal is to reach the final destination. The other gliders, i.e., the followers, will then focus on maintaining the geometry of the formation, which also implies following the leader's path. Due to space limitation, in the following we focus only on this second subproblem.

We use a hybrid approach to keep the team formation depending on whether the position information is *absolute* or *relative*. Specifically, *Absolute Formation Adjustment (AFA)* is used when absolute information such as gliders' position is available; whereas *Relative Formation Adjustment (RFA)* is used when relative information such as inter-vehicle velocity is available. The reason for this hybrid approach is to reduce the communication overhead for position information dissemination. Using absolute positions, in fact, requires the exchange of location information, which introduces overhead. On the other hand, relative inter-glider velocity information can be estimated by each glider by measuring the Doppler shift of ongoing inter-vehicle communications. These relative velocities can then be used to control the trajectory of each glider in such a way as to keep the inter-distance between gliders constant. While this 'opportunistic' approach does not guarantee that the absolute geometry be maintained (e.g., rotations can occur), it does not introduce additional overhead as it may exploit ongoing communications. Consequently, in order to compensate for the errors due to formation rotations, the team periodically goes back to AFA to readjust the geometry using absolute positions.

The communication protocol for hybrid steering is presented in Fig. 7. Periodically, each glider runs AFA using the position information obtained from the localization algorithm. Then, RFA is run using relative information extracted from inter-vehicle packets. Glider i's relative velocity is estimated by j when an inter-vehicle packet is received. This information is then embedded into the reverse direction packet and fed back to i. At this point, the gliders are able to make adjustments according to their relative velocity. Finally, if the leader (or any other follower) assesses that the geometry is seriously compromised (i.e., if the team dislocation is greater than the dislocation associated with a new permutation), the leader can rerun the formation optimization problem and find the new best permutation (often involving only a subset of the vehicles) to reconstruct the geometry.

Intuitively, in order to keep the formation, two gliders need to move closer if the distance between them is larger than the initial specified distance, i.e., the equilibrium distance in the formation geometry. Conversely, they need to move farther if their distance is smaller than the equilibrium distance. In such a scenario, an *Attraction and Repulsion Model (ARM)* is appropriate to implement the swarming behavior using local controls. Bio-inspired algorithms based on the ARM have been

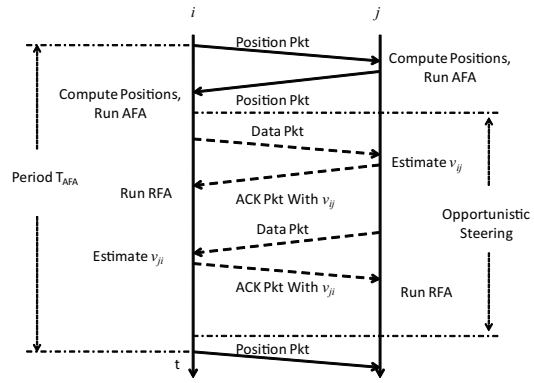


Fig. 7. Hybrid steering using bio-inspired communications.

proposed and analyzed in [7], [8]. In this paper, we account for the physical constraints characterizing SLOCUM gliders and their energy-efficient acoustic WHOI Micro-Modems, and propose a novel distributed attraction and repulsion swarming solution integrated with the communication mechanisms. As ARM is similar to a spring system in physics, we treat the team as such a system and we define a metric between i and j called virtual potential energy, $E_{ij} = \frac{1}{2}k_{ij}\Delta x_{ij}^2$, where k_{ij} is the virtual spring constant and Δx_{ij} is the displacement from the expected formation equilibrium between i and j.

When glider i is in its equilibrium formation position, the total virtual potential energy between i and its neighbors, $E_i = \sum_{j\in\mathcal{N}_i} E_{ij}$, will be zero; otherwise, it will be greater than zero, where $\mathcal{N}_i$ is the set of neighbors of i. To keep the specified formation, i should adjust its pitch (α_i) and yaw (β_i) angles so that E_i can be minimized. For AFA, given the team glider positions $\mathbf{P}_j$ and directions α_j and β_j, with $j = 1, 2, \ldots, N$, which are obtained by exchanging control packets, in a given interval δ [s] glider i will adjust its pitch and yaw by solving,

$$\begin{aligned}
\textbf{Given: } & \mathbf{P}_i, d_{ij}, s_H, \delta, \alpha_j, \beta_j (\forall j \in \mathcal{N}_i) \\
\textbf{Find: } & \alpha_i^* \in [\alpha_{min}, \alpha_{max}], \beta_i^* \\
\textbf{Minimize: } & E_i = \frac{1}{2}\sum_{j\in\mathcal{N}_i} k_{ij}\Delta x_{ij}^2 \\
\textbf{Subject to:} & \\
& \Delta x_{ij} = \|\overrightarrow{\mathbf{P}_i\mathbf{P}_j} + (\vec{\mathbf{v}}_j - \vec{\mathbf{v}}_i)\delta\| - d_{ij}; \quad (3) \\
& \|\vec{\mathbf{v}}_i\| \cdot \sin\alpha_i = s_H; \quad (4)
\end{aligned}$$

where d_{ij} is the equilibrium distance between i and j in the formation, $\overrightarrow{\mathbf{P}_i\mathbf{P}_j}$ is the location vector from i to j, $\vec{\mathbf{v}}_i$ is i's velocity, and $\|\cdot\|$ is the vector length. Note that the velocity of each glider $j \in \mathcal{N}_i$ can be computed at i as $\vec{\mathbf{v}}_j = (s_H \cdot \cos\beta_j, s_H \cdot \sin\beta_j, s_H \cdot \tan\alpha_j)$.

For RFA, we adopt a bio-inspired communication technique that imitates the echolocation mechanism of the bat. A bat estimates the distance to an object by shouting and then measuring the acoustic echoing time from the object. Also, a bat relies on the Doppler effect, i.e., the frequency shift caused by the relative velocity, to sense an object's direction. Specifically, if the object is moving away from the bat, the returning echo will have a lower frequency than the original sound; conversely, the echo from an object moving towards the bat will have a higher frequency. When we do not rely to absolute position information, we use a similar technique to keep the swarm formation. The WHOI Micro-Modem can estimate the relative speed of the transmitter exploiting the frequency shift caused by the Doppler effect. Suppose that during steering glider i obtains its relative speed s_{ij} (*a scalar*) with respect to another glider j. This can be extracted from ongoing inter-vehicle communications without additional overhead: upon receiving i's packet, j can estimate the Doppler frequency shift Δf_{ij}; the relative speed s_{ij} of glider i to j along the line connecting the two gliders is then calculated from $\Delta f_{ij} = -s_{ij}\cdot f_0/c$, where f_0 is the current acoustic communication central frequency and c is the average underwater acoustic wave speed (1500 $\mathrm{m/s}$). Glider j then sends s_{ij} back to i with its own location $\mathbf{P}_j$, which can be estimated using the leader's GPS position, and relative location and velocity. Both s_{ij} and $\mathbf{P}_j$ can be embedded in the ongoing communication packets to avoid additional overhead. In this way, i computes its relative speed vector with respect to j as $\vec{\mathbf{v}}_{ij} = s_{ij} \cdot \frac{\overrightarrow{\mathbf{P}_i\mathbf{P}_j}}{\|\overrightarrow{\mathbf{P}_i\mathbf{P}_j}\|}$.

Consequently, the expected virtual potential energy E_i after time δ can be estimated as $E_i = \frac{1}{2}\sum_{j\in\mathcal{N}_i} k_{ij}\|\vec{\mathbf{v}}_{ij}\delta\|^2$. Hence, the problem of steering i back into formation becomes the search for the optimal pitch and yaw to obtain a correction velocity $\vec{\mathbf{v}}_i$ such that E_i can be minimized,

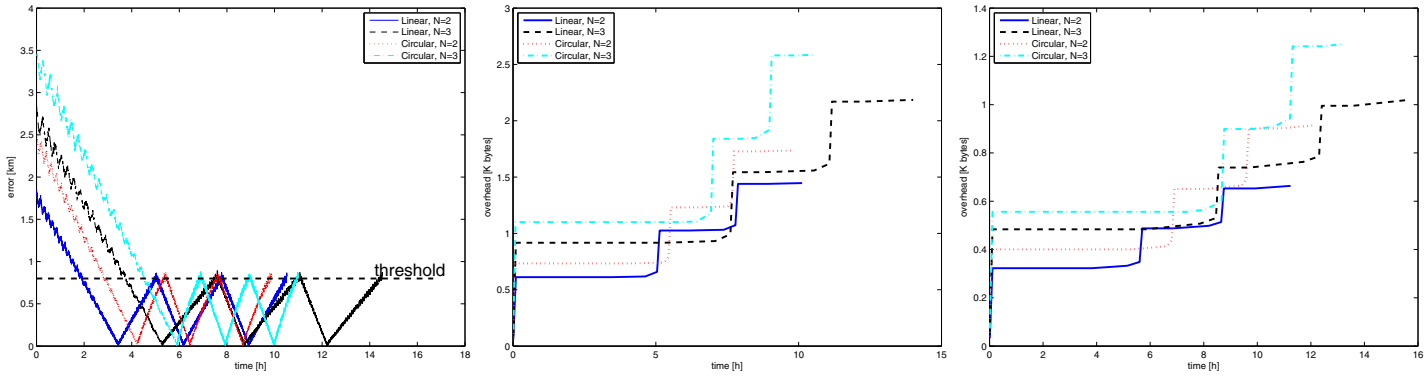
$$\begin{aligned}
\textbf{Given: } & \vec{\mathbf{v}}_{ij}, s_H (\forall j \in \mathcal{N}_i) \\
\textbf{Find: } & \alpha_i^* \in [\alpha_{min}, \alpha_{max}], \beta_i^* \\
\textbf{Minimize: } & E_i = \frac{1}{2}\sum_{j\in\mathcal{N}_i} k_{ij}\|(\vec{\mathbf{v}}_{ij} + \vec{\mathbf{v}}_i)\delta\|^2; \\
\textbf{Subject to:} & \\
& \|\vec{\mathbf{v}}_i\| \cdot \sin\alpha_i = s_H. \quad (5)
\end{aligned}$$

By solving this problem, glider i is able to fix its own steering so that the formation error, i.e., the virtual potential energy, can be minimized. Note that this is a distributed solution as only local information from i's neighbors is needed.

III. Performance Evaluation

In this section, we show the robustness of our algorithms for Phase I (team formation) and Phase II (team steering) against acoustic channel impairments (high propagation and transmission delay, and low communication reliability). Performance of the proposed techniques is evaluated when number of gliders, team formation geometry, and team target trajectory are provided. Specifically, we simulate four different input combinations: i) 2 and ii) 3 gliders with *linear* surface projection of the team target trajectory; and iii) 2 and iv) 3 gliders with *circular* projection of the team target trajectory. Note that the lengths of these projected curves (linear or circular) are both set to 20 Km. In the beginning, gliders are randomly deployed in a 3D region of $4000(L) \times 4000(W) \times 100(H)$ m^3. These gliders move at horizontal speed of 0.25 $\mathrm{m/s}$ with depth ranging in $[0, 100]$ m, while maintaining the corresponding formation, as depicted in Fig. 5. The equilibrium distance between gliders is set to 1.6 Km.

We compare the performance of these four combinations in terms of *displacement error* and *communication overhead* using underwater and terrestrial communications. In this way, the



(a) Displacement using Underwater Communications. (b) Overhead using Underwater Communications. (c) Overhead using Terrestrial Communications.

Fig. 8. Displacement error and overhead for coordination of gliders using underwater acoustic (real case) and terrestrial RF communications (ideal case).

impact of the acoustic channel impairments on team coordination can be evaluated. The displacement error is defined as the average of the displacement distance, i.e., $\frac{1}{N}\sum_{i=1}^{N}\|\mathbf{P}_i - \hat{\mathbf{P}}_i\|$, where $\hat{\mathbf{P}}_i$ is glider i's expected location. If the displacement error is found to be greater than a threshold (0.8 Km here), Phase II (team steering) is interrupted and Phase I (team formation) is triggered to recreate the geometry.

Simulation results are plotted and compared in Fig. 8. As the results after initial team formation are periodic, we only plot results until the third phase. Due to space limitation, displacement errors when terrestrial RF communications are used (*ideal case*) are not presented as these errors have similar magnitude and trend to those associated with the underwater acoustic communication (*real case*), which are showed in Fig. 8(a). The time for the displacement error to reach the threshold when terrestrial communications are used is around 1.5 times larger than that associated with underwater communications, which is due to the high transmission and propagation delay and packet error rate underwater.

The simulation results lead to the following conclusions:

- Our bio-inspired communication and coordination algorithms are effective in the harsh underwater environment. Communication overhead for coordination is low (about 2 KBytes for 10 h of mission) by using communication techniques inspired by killer whales and bats.
- Glider coordination overhead is affected by the the impairments caused by underwater acoustic communications. From the results of the same input combination in Figs. 8(b) and 8(c), the overhead underwater is around 2 times higher than for terrestrial coordination. This is because underwater channels are less reliable than terrestrial wireless channels; hence, a higher number of packet retransmissions is needed. Moreover, the large underwater transmission and propagation delays make it more challenging for medium access control protocols to fairly and efficiently share the bandwidth among multiple vehicles, which leads to a higher probability of packet collisions.
- The displacement error for $N = 3$ increases faster than that for $N = 2$ as controlling a higher number of gliders is more difficult. A higher overhead associated with the coordination task in each phase is also incurred when the number of gliders increases.
- The displacement error along the circular surface trajectory increases faster than that along the linear trajectory. Glider movement would need more frequent adjustments to follow the circular trajectory than for the linear one. Therefore, the error for circular trajectory increases faster as control adjustment is not made in a timely manner. This also results in more overhead.

IV. Conclusion

We proposed bio-inspired underwater acoustic communication and coordination algorithms to enable swarming of a team of gliders, a class of energy-efficient propeller-less autonomous underwater vehicles. These algorithms were shown to be robust against acoustic channel impairments such as high propagation and transmission delay, and low communication reliability.

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