

# Using Slocum Gliders for Coordinated Spatial Sampling

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**Abstract**—Buoyancy driven Autonomous Underwater Vehicles (AUVs), such as the Slocum glider, allow for a prolonged presence to study the oceans. They can operate for weeks or even months recording oceanographic data for a fraction of the cost of research vessels. However, the vehicles are limited to the number of sensors that can be carried onboard. Alternatively, a group of AUVs performing formation flight, where AUVs maintain particular positions relative to each other, could be used to observe ocean conditions and phenomena at a high spatiotemporal resolution carrying a variety of sensors. The vehicles can conceptually act as a single science instrument that can be easier and less expensive to deploy than higher cost, large AUVs.

In this paper we propose and evaluate, using simulations, an effective coordination strategy for formation flight which monitors the formation quality using underwater communication. If an AUV drifts out of formation, all vehicles are instructed through underwater communication to resurface in order to reestablish the formation. Overall, this strategy is able to keep a formation of gliders longer than the traditional approach and can gather significantly more data samples, which corresponds to an overall decrease in the per sample energy cost.

## I. INTRODUCTION

Buoyancy driven Autonomous Underwater Vehicles (AUVs) allow for a prolonged presence of scientific sensors in the oceans. They operate for weeks or even months recording oceanographic data for a fraction of the overall cost of research vessels. Formation flight is a form of swarming where AUVs maintain a particular position relative to each other and allows for the observation of ocean conditions and phenomena at a high spatiotemporal resolution [1]. In addition, formation flight enables AUVs with different sensor payloads to conceptually act as a single science instrument allowing enhanced sensing capabilities to be implemented by groups of lower cost, small AUVs instead of higher cost, large AUVs [2].

Maintaining a swarm formation is a difficult challenge. General localization technologies, such as GPS, are unavailable underwater. Various factors may also account for a vehicle to drift out of formation, including environmental conditions, dead reckoning, and even a vehicle's particular ballast configuration to name a few. Current approaches to establish and maintain formation using the Slocum glider, the target vehicle of our research, is through radio and satellite communication during the AUV's periodic surfacings [3], [4]. The vehicles are typically programmed to surface at predetermined time

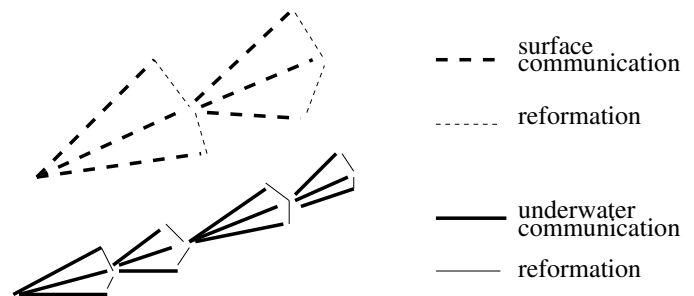


Fig. 1. Illustration of different formation flight tracks of three gliders with surface communication only and with surface and underwater communication for out-of-formation signaling. Both tracks include reformation phases which require some gliders to wait at the surface until all three gliders are back within formation.

intervals where GPS fixes are acquired to determine their new locations. The new positions and a select subset of the acquired data is then transmitted to a shore based control center. At the control station, a new waypoint set is calculated by a flight engineer or a computer algorithm to reform or maintain the group of vehicles. Although functional, alternative approaches should be explored.

This paper proposes and evaluates a simple but effective new coordination strategy for formation flight which monitors the formation quality using underwater communication, and in particular studies the effect of the new strategy on the overall energy consumption across the group of vehicles. If an AUV drifts out of formation while underwater, all vehicles are instructed through the acoustic modem to resurface in order to reestablish the formation. The differences between the two described approaches is depicted in Fig. 1. The new strategy is able to use the ranging capabilities of the WHOI Micro-Modem to determine the distance between the vehicles and signal a break of the formation to the others in the group. Like the surface only model, the proposed strategy also uses a control station to automatically calculate and generate new missions scripts for the vehicle.

Although this strategy may overall increase the frequency of surfacing, it has the advantage of (1) reducing the time needed at the surface to reestablish the formation since AUVs are not allowed to drift significantly out of formation, and

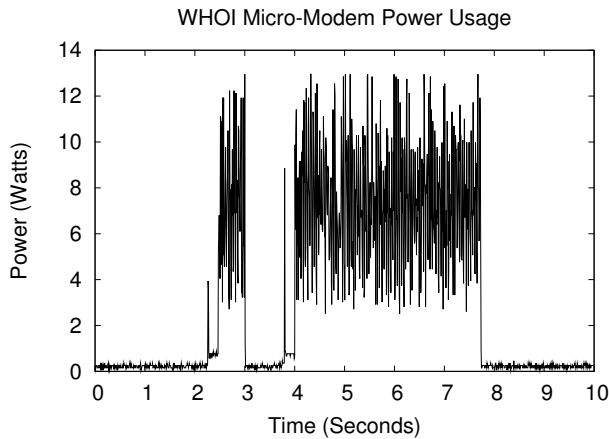


Fig. 2. Trace of the power consumption of a WHOI Micro-Modem in a tank during communications testing and measured by a Tektronics TDS 3014 oscilloscope.

(2) acquiring more scientific data at the desired spatiotemporal resolution since larger portions of the missions are flown as part of the formation. In this paper we will focus on the potential tradeoffs between the two coordination strategies. The main contributions are:

- 1) The development of a detailed simulation model for a leader/follower formation where three Slocum gliders are required to stay within a predefined distance from one another. The model makes use of a Slocum glider simulator and uses energy models derived from power measurements collected during previous deployments.
- 2) A set of simulation results for virtual missions that use the described formation strategies. The missions start off the coast of New Jersey and run to the edge of the continental shelf. The simulations use datasets of surface currents acquired by coastal radar and bathymetric datasets to simulate the ocean floor. Formation diameters of various sizes and surface intervals are investigated.
- 3) The evaluation of the cost and benefit tradeoffs between two coordination strategies, one with and one without underwater communication capabilities. The results of the simulations show that on average, vehicles that are able to communicate underwater can stay in formation longer compared to those that cannot.

Based on the results of our evaluations, we show that acoustic underwater communication can be beneficial in improving the swarming behavior over the existing surface only strategy. Although we share concepts from other initiatives that perform coordination using underwater communication, such as the GREX project [2], [5], [6], [7], the focus of this paper is instead the energy impact it may have to the fleet of gliders and the samples they are deployed to collect. In particular we show that for formations with smaller diameters, which are also more prone to break, the per sample energy cost can be decreased. For larger formation sizes the energy cost overhead may however not be justifiable.

## II. BACKGROUND

The AUV coordination strategy is implemented and evaluated on the infrastructure described in our previous work [8], [9], [10]. This section will briefly describe the WHOI Micro-Modem, which is the essential technology required to perform the formation among the vehicles. A summary of the implementation platform, the Slocum glider, will also be given along with the energy models and simulation framework used to fulfill the evaluation of the proposed approach.

### A. WHOI Micro-Modem

The Woods Hole Oceanographic Institution (WHOI) Micro-Modem [11] is an underwater acoustic communication device designed for low-power systems. The modem is capable of sending signals with a low-rate, low-power frequency-shift keying (FSK) or with a faster, but more power intensive, phase-coherent keying (PSK). When transmitting using FSK, the WHOI Micro-Modem sends out 32 byte packets at a rate of 80 bits per second after overhead from error-correction is taken into account. In addition to the normal packets, the WHOI Micro-Modem also has the ability to send out minipackets (21 bits). These minipackets are used for a variety of tasks such as pinging, range-finding, and data acknowledgment [11]. The transmission of packets requires 10-50W depending on transmission mode and the distance that the packet is being sent. Listening for and receiving FSK encoded packets requires 80-158mW [12], [13]. Based on the modems success in other AUVs, [11], [14], it was chosen to be integrated into the Slocum glider.

To gain an additional perspective on the possible power consumption that could be observed during deployments, a set of simple communication tests were carried out using the modem and a tow-fish. The power consumption measured from a Tektronics TDS 3014 oscilloscope is depicted in Fig. 2 and is the basis for the acoustic cost model used in the evaluation of the coordination strategies. It does not include the cost of the Linux Gumstix computer used to interface with the modem. In Fig. 2, the modem is initially in a listening and receiving state. It then transmits a header followed nearly immediately with transmission of the data payload. Further tests will be performed in the future to ensure that the most accurate model can be produced for the modem. Sea trials will also help us to experiment with the exact configurations of the modem that are necessary for various deployment scenarios.

### B. Slocum Glider

The Slocum Electric Glider is a commercially available Autonomous Underwater Vehicle produced by Teledyne Webb Research (TWR) [15]. Unlike propeller driven vehicles, for example [16], [17], the glider belongs to a class of buoyancy driven AUVs [15], [18], [19], [20]. Its buoyancy is altered through the motion of a piston at the front of the vehicle. This change in buoyancy allows the AUV to move vertically in the water column. Its pitch can be refined by adjusting the glider's center of gravity through the movement of an internal battery pack. With its wings, the vehicle is able



Fig. 3. Two Slocum Electric Gliders equipped with WHOI acoustic Micro-Modems. The modem's transducer is the protruding cylinder on one of the science bays.

to achieve forward motion and creates a sawtooth flight profile as it makes inflections near the surface and at deeper depths [1]. A controllable fin allows the vehicle to change its bearing and navigate to designated waypoints at approximately 35 cm/sec [21]. Satellite and radio communication allows for the transmission of newly collected data, and if required, new mission instructions. Typical missions last four to six weeks depending on the AUV's sensor configuration and environmental conditions.

We currently have two gliders equipped with WHOI Micro-Modems as depicted in Fig. 3. These vehicles have been customized to support two payload bays. One of the bays in each glider houses a Linux Single Board Computer (SBC) and the hardware necessary for acoustic communication. This includes the WHOI Micro-Modem, its co-processor, as well as an amplifier. The transducers for the modems protrude out from the top of the payload bays in Fig. 3.

The second payload bay in the vehicles is dedicated solely to scientific instruments. One of the gliders in Fig. 3 is outfitted with WET LABS' optical backscatter and fluorometer sensors. The other vehicle's science bay is modular so that it can be equipped with a Fluorescence, Induction and Relations (FIRE) System, or a Doppler Velocity Log (DVL) sensor. This allows the vehicles to be specialized for specific missions, and with formation flight, can collect samples in the same space and time, thus emulating a single science instrument.

The Linux SBCs in the vehicles have a 200MHz ARM processor with 64MB of RAM and 2GB of storage space. It is a lower power alternative to the SBCs installed in our previous prototype system [8]. The prototype consists of customized software for both of the glider's standard onboard computing systems (two 16MHz Persistor CF1s) and the Linux SBC. This infrastructure provides the ground work for the AUV to perform more complex tasks, such as dynamic feature tracking, and has been deployed to track a thermocline off the coast of New Jersey. It will also be used to support future collaborative sensing missions using acoustic communication and the formation strategy described in this paper.

### C. Measurement Infrastructure

In our previous work, [9], a power measurement infrastructure is described that records the power required of a subset of the glider's components. This infrastructure consists of a measurement board populated with Hall effect sensors to gather readings of the current draw of the devices. The readings are transmitted to the science payload bay computer which records the data onto a compact flash card. Voltages logged from the glider are used with the current readings to provide the estimated power of the devices.

A glider equipped with a more optimized power measurement infrastructure was deployed in August 2010 for one month off the coast of New Jersey. The sole objective of the deployment was to obtain the energy required for the buoyancy engine to perform inflections at depths of up to 100 meters. Thus, all but four Hall effect sensors were removed to reduce the power required by the board to enable a prolonged deployment that could reach the continental shelf off the coast. With this change, the clock frequency of the science bay computer was also lowered since it was no longer responsible for logging a full dataset. Overall, these modifications reduced the overhead of the measurement infrastructure by nearly 40%.

The buoyancy engine of the Slocum Electric Glider is one of the most energy expensive components on the vehicle [1]. A more precise cost was investigated in the August 2010 sea trials because previous deployments, [9], did not achieve the full depth range capable of the 100 meter coastal version of the AUV. A new energy model for the buoyancy engine, derived from measurements recorded by the infrastructure during the deployment, is depicted in Fig. 4(a). The overall trend is similar to the previous measurements but is no longer best described by a linear model as a slight bow can be observed. Because the buoyancy engine is such a critical device it is crucial to have the most accurate energy model possible when evaluating energy costs of the glider.

During a deployment, the vehicle must periodically surface to gain a GPS fix and to send a subset of its gathered data back to shore via an Iridium satellite modem. On the completion of the transfer of the logged data, the glider may be given new instructions or told to continue its current mission. Like the buoyancy engine, this can be an expensive operation. To accomplish a surfacing, a glider must increase the vacuum in the hull to inflate an air bladder that keeps the tail fin, which contains the antenna necessary for the communication, above the waves.

Fig. 4(b) contains the measured energy required for the vehicle to surface during the August 2010 deployment. The data represents whole vehicle measurements and quantifies how much energy is required to keep the vehicle at the surface. Like the buoyancy engine, it is an important metric to incorporate during the evaluation of the coordinated sampling approach proposed since the vehicles are instructed to surface when the formation falls apart and stay at the surface during reformation.

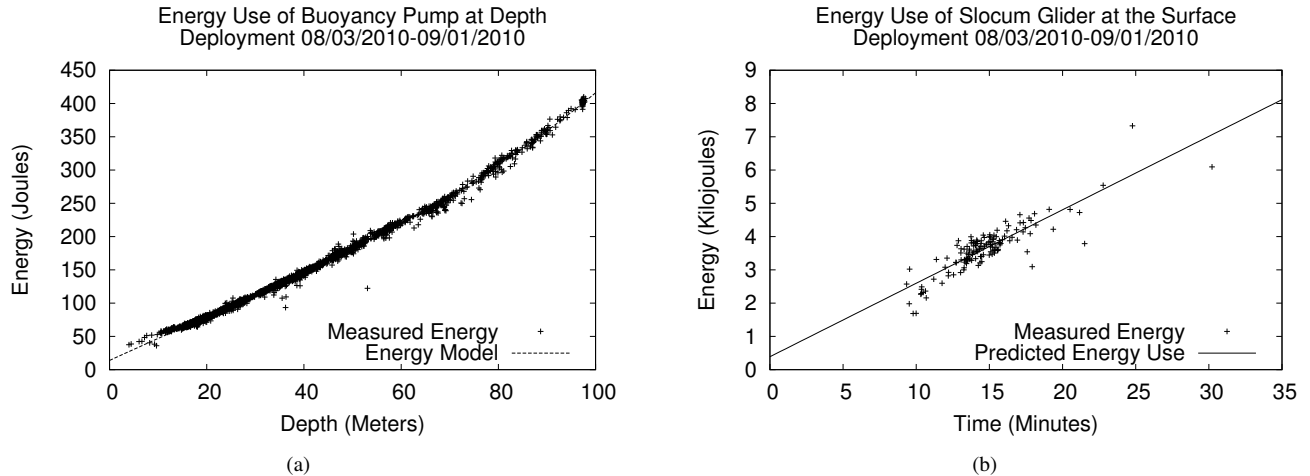


Fig. 4. Energy models derived from measurements obtained from the measurement infrastructure in [9] during a deployment in August 2010. (a) Energy use of the buoyancy engine as a function of depth produced. Inflections at deeper depths require more energy as the pump must work against the additional water pressure. (b) The time and energy used by a glider at the surface. At the surface, a glider communicates a subset of its acquired data to a shore based field station.

#### D. Simulation Environment

The effectiveness of the formation strategies described are evaluated using a Slocum glider simulator first presented in [9]. The simulation framework is capable of using multiple speed models. One is similar to the one used in TWR’s Shoebox simulator. The Shoebox simulator contains the essential electronics of the glider that are necessary to run simulated missions in real-time and named after the shoebox sized container it is housed in. The other speed model that is used as part of our simulation infrastructure is a speed distribution that was empirically derived from several years of glider flight data off the coast of New Jersey. Distributions were made for  $25^\circ$  and  $26^\circ$  as these are the most common angles flown by the vehicle.

As discussed in the previous subsection, the buoyancy engine is an expensive device and can have an effect on mission endurance. To more accurately estimate the energy required by the engine, the simulator incorporates the bathymetric dataset from NOAA’s National Geophysical Data Center’s ETOPO1 model [22]. Like a real vehicle, the simulated virtual glider makes inflections near the surface and at deeper depths. The depths of the ocean floor are interpolated using the AUV’s position and the dataset to make for more realistic inflections at depth as it will be instructed to inflect several meters before hitting the bottom.

A Slocum glider’s flight is also heavily influenced by the currents it experiences during its deployment because of its slow forward speed. To add another metric of realism, Coastal Radar (CODAR) [23] from Rutgers, and Hybrid Coordinate Ocean Model (HYCOM) [24] have been incorporated into the simulator. CODAR provides hourly surface current information measured from sites along the coast line at a resolution of 6km. HYCOM not only supplies nowcasts, but also forecasts of current vectors at predefined depths at a

more coarse resolution. Although resolution is an issue with either approach, the simulator can be used to produce missions similar to what may be expected in real deployments [9].

Furthermore, the simulation framework makes use of energy models recorded using the measurement infrastructure described in Section II-C and [9]. It is a versatile tool that allows for the specification of a virtual environment for the simulated AUVs to interact with. It is generally used to perform energy usage estimates on simulated vehicles on multi-day missions and is used to evaluate the coordinated flight strategies described in this paper.

### III. EVALUATION

As mentioned above, the proposed coordination strategy uses the WHOI Micro-Modem to improve formation quality to increase the number of samples gathered collectively by a swarm of vehicles. The quality of the formation is measured by the percentage of time, relative to the whole deployment length, the AUVs are within the formation distance. Samples collected when any of the vehicles break the formation are discarded and do not count towards correlatable data since it is assumed the vehicles will carry heterogeneous sensor payloads whose data can only be merged if measured within the specified time and space constraints.

The effectiveness of the approaches are evaluated using the Slocum glider simulation infrastructure described in the previous section. The speed distribution model of  $26^\circ$  is used as it is derived from over 3.5 years of glider flight time data. The simulator has been updated with the new energy models from the August 2010 deployment including the surface and buoyancy engine models. Energy costs for acoustic communication among the vehicles are constructed from the oscilloscope measurements shown in Fig. 2. While underwater, AUVs equipped with the modem are in a low power listening/receiving state when not transmitting.

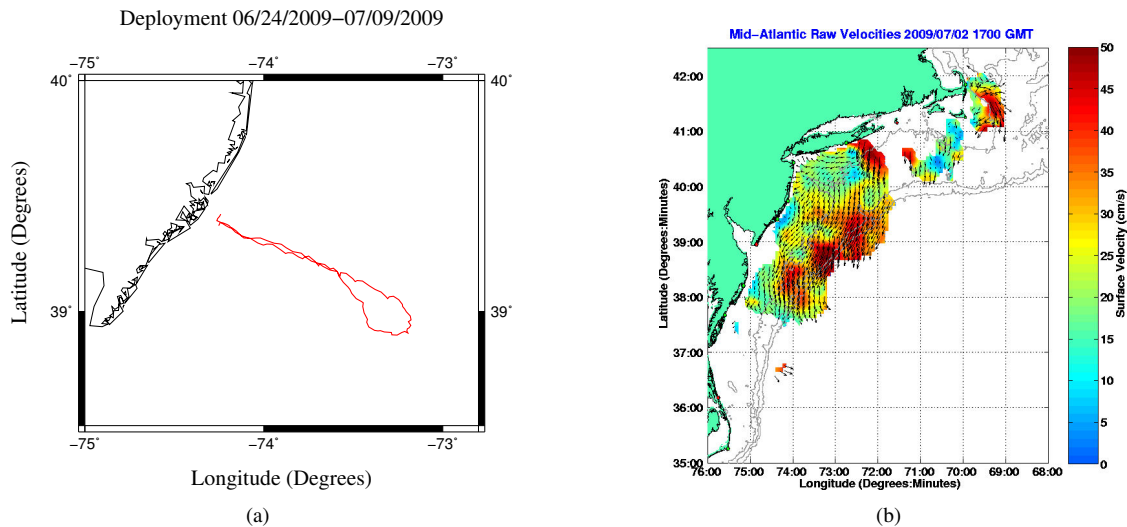


Fig. 5. (a) The flight path of the glider deployment used as the basis of the simulated missions. (b) An hourly average of the surface currents measured using CODAR during the deployment.

The simulation involves a virtual deployment of three Slocum gliders flying a multi-day mission in a leader/follower formation. One vehicle is designated the leader and will remain so throughout the mission. If any of the followers are detected to not be within the formation, the leader and any followers still in the formation will remain at the surface while waiting for trailing gliders to rejoin the group.

The simulated mission is inspired by a 15 day glider deployment from late June to early July of 2009 off the coast of New Jersey. The flight path of the vehicle during the mission is depicted in Fig. 5(a). The AUV was at times exposed to significant currents which caused it to drift south as it made its journey to the continental shelf.

Surface currents measured throughout the deployment, using CODAR, are used for all simulations. Overall, the CODAR coverage of the deployment area was satisfactory throughout the whole mission and was one of the reasons this specific deployment was chosen. An hourly average of the surface currents measured using CODAR during the deployment is shown in Fig. 5(b). The current vectors, in Fig. 5(b), off the coast of New Jersey are quite strong and are likely partially responsible for the southward drift of the vehicle in Fig. 5(a).

The virtual AUVs in the simulations are deployed at the same time and place the real vehicle was and are instructed to target a similar waypoint near the continental shelf. To reduce simulation time, only the flight leg from shore to the shelf is considered. This flight typically takes the glider five to ten days to complete depending on the season and other environmental conditions.

The baseline formation strategy used for comparison does not use acoustic underwater communication. Gliders using this strategy will surface at predetermined time intervals where they can obtain and communicate their positions to the others in the swarm through a proxy, shore based, control station. Followers out of formation are given new instructions to fly near the leader's most current position; the remaining vehicles

wait with the leader at the surface. The swarm only continues its mission when all vehicles have again flocked together.

The alternative approach, which uses the WHOI Micro-Modem, also performs predetermined vehicle surfacings. Like the baseline, the AUVs can use satellite communication with the base station to organize the formation. In addition, the vehicles are able to use the modem's ranging capabilities, using minipackets, to approximate their distance from one another while underwater [14]. This is performed in 15 minute intervals in our simulations. Then, if it is determined that the followers are out of the formation range, the leader will send an immediate surface request to the group using the modem. A two minute transmission cost is charged to perform this task. Any recoordination is again determined at the surface and accomplished through the control center.

The simulations for both strategies rely on two important parameters, namely the surface interval time and the formation distance. The surface interval describes the interval of time in hours the gliders should resurface; the formation distance parameter specifies the size of the radius the following gliders have to be in from the leader to be considered within the formation. Simulations were performed for the two approaches with formation distances ranging from 0.5–5km and surface intervals from 1–6 hours. When a glider surfaces, it remains at the surface for a minimum of 15 minutes to communicate with the field station and to obtain accurate GPS fixes. AUVs may stay at the surface longer if they are waiting for the swarm to reorganize. At the start of a particular simulation instance, small random noise factors are created such as compass errors for each glider and perturbations applied to interpolated current vectors. For each of the formation size and surface interval parameter pairs, 50 simulations were performed so that their overall trend on the two strategies can be determined. All 3,600 simulations were performed with a runtime of several days on a six node, 80 processor, computing cluster with 256GB of RAM.

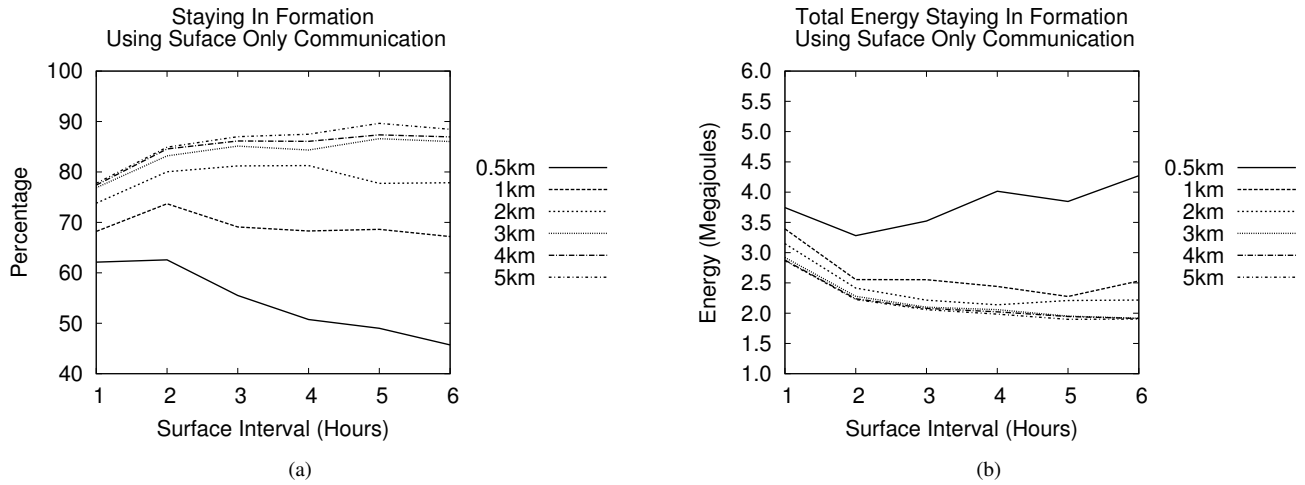


Fig. 6. Coordination strategy with surface communication only. (a) Quality of formation as percentage of mission time where formation was maintained. (b) Overall energy usage across all gliders in the swarm.

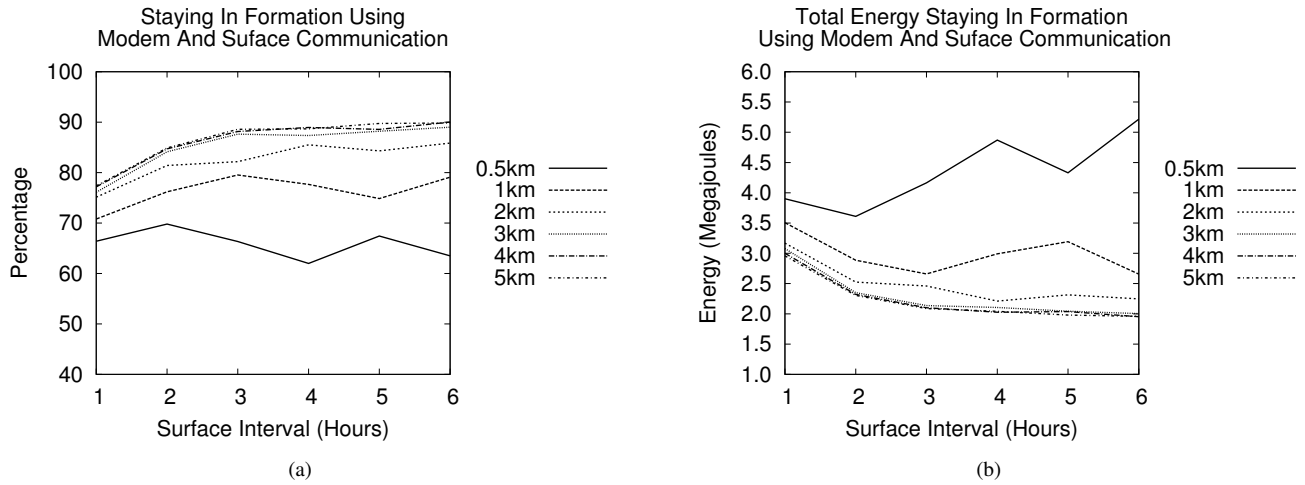


Fig. 7. Coordination strategy with surface and underwater communication. (a) Quality of formation as percentage of mission time where formation was maintained. (b) Overall energy usage across all gliders in the swarm.

Fig. 6 and Fig. 7 respectively show the simulation results for the surface only and the acoustic modem and surface communication strategies. Fig. 6(a) and Fig. 7(a) depict the quality of the formation as a percentage of mission time the formation was maintained. It should be noted that a perfect formation quality is not achievable because the vehicles are required to surface periodically; the time spent at the surface does not contribute to the formation time even if all of the followers are within range of the leader. Fig.6(b) and Fig. 7(b) present the energy consumed across the fleet of gliders at the end of the simulations.

In Fig. 6(a), we observe that if the formation distance is broadened, formation quality improves because the followers are less likely to fall out of range of the leader. Prolonging the time between surfacings decreases collaborative sampling among the vehicles with small formation sizes. Not only are

they likely to break the formation by the virtue of the small formation requirement, but they also may not realize they have fallen out of the group for quite some time. Once it has been realized, a follower may be quite distant from the leader and so the whole group's progress is delayed. For larger formation sizes it is however beneficial to increase the surface interval as it does not waste time at the surface since the swarm is likely to remain true in form.

The energy of the surface only communication approach is presented in Fig. 6(b). Tighter formations require more energy, since they, as just described, are likely to break formation and require recoordination. A decrease of the fleet's energy is observed at the two hour surface interval mark because hourly surfacings may be wasteful since much of the time is spent above the water rather than making any flight progress.

Significant improvement in the formation quality can be

achieved using the proposed approach as shown in Fig. 7(a). For small formation sizes with large surface intervals the difference is the most dramatic because the vehicles in the group have the ability to surface and re-coordinate when necessary. So it may be the case that during a simulation with six hour surface intervals, the AUVs resurface every few hours if the environmental conditions caused the formation to break. In the same simulation, conditions could have been such that the group did not need to surface at all for the entire six hours. Larger formation sizes do not benefit as much with use of the modem. Again, large formation sizes cause the vehicles to not fall out of place very often which translates into fewer rendezvous.

In Fig. 7(b), all of the simulations experience an energy overhead. Even if the AUVs do not surface based on a surface request by the leader, they carry the overhead of constantly listening to hear for those requests. They must also periodically reply to the leader's range finding packets. Short formation sizes are the most difficult to achieve and maintain, and so they require the most energy regardless of the coordination strategy used.

Overall, the new strategy is able to keep a glider formation longer, but at the cost of an additional energy overhead. For small formation granularities the tradeoff is clearly in our favor, in the best case increasing the flight time within formation by 49% while requiring only 13% more energy. This corresponds to a 25% decrease in the energy cost per collaborative data sample collected in the formation compared to surface only communication. For larger formations this is not the case since maintaining the formation and the corresponding energy budget are comparable across the two strategies.

#### IV. CONCLUSION

In this paper we show that low-bandwidth underwater communication can be effectively used to maintain an AUV formation in addition to surface communication. An overview of the WHOI Micro-Modem and its measured power consumption using an oscilloscope were provided. A summary of the power measurement infrastructure, energy models derived from a deployment equipped with the infrastructure, and the simulation framework used in the evaluation were also described.

The evaluation of the baseline surface only communication and surface in addition to underwater communication formation strategies were performed and subsequently discussed. Across nearly all simulations with varying formation distances and surface times, the new strategy was able to stay in formation longer. However, it also comes with an increase in energy consumption for the entire swarm as compared to the surface only communication approach.

Our formation strategy was especially effective for formations with small formation distances between the leader and follower AUVs in the swarm and is the likely configuration to be used in real deployments. For larger formation sizes, some improvement in formation quality could still be achieved,

but the slight increase in energy costs may not be justifiable as both strategies perform nearly the same. In the best case, our strategy was able to achieve a 49% longer flight within formation, costing only 13% more energy, but reducing the overall data sample energy cost by 25%.

#### V. FUTURE WORK

The integration of the WHOI Micro-Modem stack into the Slocum Glider is still in progress. Most of the hardware installation of the modem has been accomplished, however the software infrastructure needed to integrate the modem into the rest of the glider's systems must still be put in place. Depending on the processing capabilities needed by the applications during deployment, the software interface to the modem could be either implemented on the vehicle's science bay computer or on the Linux SBCs we have installed as part of our previous work [8]. The science bay computer provides a lower power alternative but cannot support complex tasks while also interacting with sensors.

We have kept the described formation algorithm very simple to make it easier to implement in real sea trials. In the future, we do not plan to keep the gliders within the formation at the surface waiting for the rendezvous to complete as it can be very dangerous at the surface. We may also not restrict that a glider is designated as a leader for the entire duration of the mission. For example, it may be advantageous to demote the leader and promote a follower that is closer to a target waypoint.

When the software infrastructure is in place, initial testing will occur in a controlled environment such as a lake or swimming pool. This should allow for basic communication tests between gliders and a tow-fish lowered from a research vessel. Once communication is established, gaining correct range information between gliders is also required for our formation strategy.

Another key component that must be in place is a communication protocol that allows the vehicles to interact with one another. One such option is the Compact Control Language (CCL) [25]. This would allow the Slocum glider to interoperate with other vehicles in the future to create heterogeneous swarms. More importantly, it will also be used to debug the vehicles from topside during sea trials. Dynamic Compact Control Language (DCCL) [26], inspired by CCL, is an alternative option that produces more compact messages and has support for data compression and encryption.

When the needed components are achieved individually, the final hurdle is to ensure that communication, ranging, and control all succeed together. Having a glider automatically surface when it is out of range of a tow-fish lowered from a vessel would mark an important stepping stone in realizing the proposed formation strategy. Because all of these components are extremely critical, they must all be tested extensively to ensure long term formation deployments are possible.

We would also like to continue to perform more power measurements to gain a better understanding of the power requirements of the glider's components including the acoustic

modem stack. For example, it would be useful to have a more crisp model of the idle, receive, and transmit costs of the modem during deployments so that in the future communication can be planned accordingly. A cost model may, for example, determine that certain messages are not worthwhile sending given the remaining energy budget of the mission.

The measurements will be made by the next generation of the power measurement infrastructure. It is designed to be more adaptable, so it can be easily altered for the sensor set equipped for the mission. Any newly collected readings will be used to build and improve the energy models for the simulation framework [9]. This will more accurately determine any trade-offs that coordination or swarming algorithms may provide.

Finally, we are planning to investigate other forms of coordination. We may, for instance, have vehicles perform adaptive data sampling across the group. Thus, a vehicle may trigger another to start collecting readings because it has detected something of interest using its own sensors. The behaviors needed for plume detection and tracking would also be an ideal application for a group of AUVs and should also be explored.

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