Coordination of Autonomous Underwater Vehicles for Acoustic Image Acquisition

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ABSTRACT

Underwater Acoustic Sensor Networks (UW-ASNs) consist of stationary sensors or Autonomous Underwater Vehicles (AUVs) like propeller-driven vehicles and gliders that are equipped with sensors for performing collaborative monitoring tasks. In this paper, a task optimization framework for image acquisition using a fleet of underwater gliders and AUVs is proposed. The objective of the framework is to form the best possible team and to find the optimal trajectory to reach the selected target object. In this paper, the use of a team of underwater gliders and AUVs for acquiring still images of underwater objects is envisaged. Research specific to this area has been limited. Hence, a framework based on energy minimization for a team of gliders to complete the mission in given time bound is proposed. Further, performance of propeller-driven AUVs and gliders is compared to prove the energy efficiency of the gliders over AUVs for missions with large time bound.

Categories and Subject Descriptors:
C.2.1 [Computer-Communication Networks]: Network Architecture and Design-*Distributed networks*

General Terms: Algorithms, Design, Performance.

Keywords: Underwater Acoustic Sensor Networks, Autonomous Vehicles, Task Allocation.

1. INTRODUCTION

Underwater Acoustic Sensor Networks (UW-ASNs) [1] consist of stationary sensor devices and Autonomous Underwater Vehicles (AUVs), such as propeller-driven vehicles and gliders, equipped with sensors performing collaborative monitoring tasks. UW-ASNs are envisioned for applications like oceanographic data collection, ocean sampling, offshore exploration, disaster prevention, tsunami and seaquake warning, assisted navigation, distributed tactical surveillance, and mine reconnaissance. AUVs are propeller-driven, battery operated vehicles that can operate without external control once assigned a task. Conversely, underwater gliders [2][5] are buoyancy-driven vehicles that alternately reduce and expand displaced volume to dive and climb through the ocean. Gliders are designed to glide from the ocean surface to its bottom and back while measuring different parameters along a sawtooth trajectory through water. A glider is also a type of autonomous underwater vehicle; however, in this paper, we will refer only to a propeller-driven autonomous vehicle as an AUV to avoid confusion. Underwater gliders offer a solution for exploring the ocean with much higher resolution in space and time than is possible with techniques reliant on ships and moorings. In addition to AUVs and underwater gliders, Remotely Operated Vehicles (ROVs) are used to explore oceans. ROVs are highly maneuverable underwater robots connected to surface vessel by umbilical cable and operated by a person aboard it. *The length of the cable confines the scope of operation of ROVs and human limitations of the operator limit the mission length.* AUVs are efficient means of ocean exploration but have a mission length limited to a few days. For these reasons, although gliders are in general slower than propelled vehicles like AUVs and ROVs, they offer an energy-efficient solution for exploring the ocean in prolonged-time monitoring missions.

A substantial amount of research has been done for task optimization of terrestrial robots, but research done for underwater glider and AUV task optimization is very limited. While research has been done on the use of *single* gliders and AUVs for underwater exploration *in isolation*, there has not been substantial research done for a *team* of gliders or AUVs for acoustic image acquisition underwater.

In [1], the applications of UW-ASNs for ocean exploration and research challenges in design of UW-ASNs consisting of AUVs and fixed sensors are described. To overcome the disadvantages affecting UW-ASNs with fixed sensors, UW-ASNs consisting of mobile vehicles carrying sensors are envisaged. The gliders and AUVs act as mobile sensor nodes. Gliders and AUVs, deployed in groups for missions, act independently of each other as they are preprogrammed individually for the mission and have to rise to the surface every time for acquiring new data or information. The disadvantages of this method are: i) no real time monitoring, ii) no online system reconfiguration, iii) no failure detection, and iv) limited data storage capacity. To overcome these disadvantages, UW-ASNs consisting of mobile AUVs serve as a solution. Hence, in this paper, a framework is proposed that will prove that with task optimization among a team of gliders or AUVs, highly energy efficient solutions to many underwater exploration problems can be devised.

This paper envisages the use of a team underwater vehicles that cooperate to complete a specific mission, e.g., *acquire still images and videos* of an unknown underwater object, within an application-dependent delay bound [10][11]. For this application, underwater vehicles rely on *computer vision techniques and algorithms* to reduce the redundancy of the acquired data.

WUWNet'08, September 15, 2008, San Francisco, California, USA.

The paper is organized as follows. In Sect. 2, we describe the acoustic imaging technique the work focuses on. In Sect. 3, we describe the basic assumptions our mathematical framework is based on. In Sect. 4, we cast the problem formulation for gliders and AUVs, while in Sect. 5, we present performance evaluation based on comparison of results of the models developed for gliders and propeller-driven AUVs. Finally, in Sect. 6, we conclude the paper.

2. UNDERWATER ACOUSTIC IMAGING

Underwater imaging technique envisioned in this work is acoustic imaging [4], which produces two dimensional images of underwater objects by transmitting sound waves and detecting reflected waves from the object, as shown in Fig. 1. The main advantage of underwater acoustic imaging over optical imaging is the distance of the object from which the images can be obtained. In deep murky sea waters the visibility of optical imaging system decreases drastically. It is in the range of 1 to 3 m, which limits its use. Acoustic energy penetrates the mud and silt that cause optical turbidity in murky waters because the wavelengths of acoustic waves are longer than optical wavelengths [6]. A side scan sonar is a type of acoustic imaging technique that this paper is focusing on [9]. An example of side scan sonar image is illustrated in Fig. 1, which indicates the superiority of underwater acoustic imaging over optical imaging.

Figure 1: Image of an aeroplane wreck obtained using side scan sonar released by National Oceanic and Atmospheric Administration (NOAA).

Side scan sonar is the technology in which the acoustic wave generating source is placed at one of the side of the glider or the AUV. The side scan sonar is commonly used for imaging objects at the bottom of the sea but it can also be used to image objects that are suspended in the middle of the water body. The acoustic spectrum in which the side scan sonar operates is 0.1 to 1 MHz [6]. The wavelength of the acoustic spectrum is of the order of 0.075 to 1.5 cm. The resolution of an acoustic imaging system is defined as its ability to resolve multiple targets as distinct and separate [7]. It is a function of sonar pulse width, beam spreading, speed of the glider and distance of the glider from the object to be imaged. There are two types of resolution in acoustic imaging systems: 1) *azimuth resolution* (also known as transverse resolution or along track resolution) and 2) *range resolution* (also known as across track resolution).

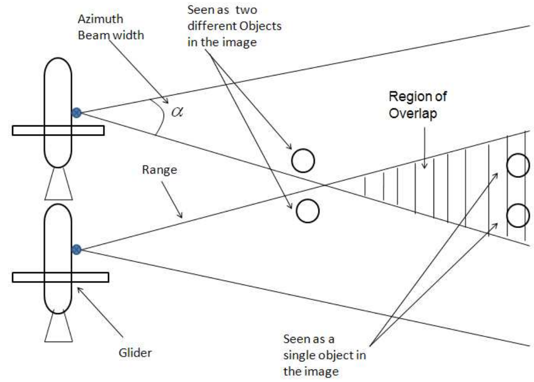

Figure 2: Azimuth resolution or transverse resolution is the power to resolve the objects that lie in a line parallel to the path of the glider or the AUV.

1. The *azimuth resolution* is the ability of resolving similar objects that lie in a line parallel to the path of the glider or the AUV. It is the minimum distance between two objects parallel to the line of travel that will be displayed on the sonar as separate objects in the image. This minimum distance is equivalent to the beamwidth (which widens with its distance from the source) at any particular point, as shown in Fig. 2. The ability to resolve between objects goes on decreasing as the distance of the glider or AUV from the object goes on increasing [9]. Azimuth resolution ρ is given as,

$$\rho = \frac{k \cdot R \cdot \lambda}{L}, \tag{1}$$

   where, k is a constant that depends on shape and size of the receiver, λ [km] is the wavelength of the sonar beam used, L [km] is the length of transmitter/receiver aperture, and R [km] is the radius of the constellation sphere constructed around the target object, as shown in Fig. 3. From (1), it is observed that the radius R of the *constellation sphere* is limited only by the azimuth resolution required for the mission. The azimuth resolution value, in fact, puts a lower limit R_{min} $[km]$ and upper limit R_{max} $[km]$ on the value R. R_{min} is determined by the near/far (NF) field limit or the NF limit of the underwater acoustic imaging system and all conventional side scan sonar systems operate in the far field. Far field limit is a condition where the acoustic wave front arriving at the aperture can be considered as a plane wave. R_{max} is determined by many factors like the absorption of sound in water, salinity, and temperature. The value of R_{max} is provided by the acoustic imaging system manufacturer, and it limits the distance from the target object at which the gliders or AUVs can be positioned for imaging.

2. The *range resolution* is the minimum distance between two objects that lie perpendicular to the line of travel that will be

displayed as separate objects. The range resolution is given by the width of the radar pulse width. If the width of the transmitted pulse is τ [s], then the range resolution Δ [m] is given as,

$$\Delta = \frac{c \cdot \tau}{2}, \quad (2)$$

where, c is the speed of sound in water, which is approximately 1500 m/s [9].

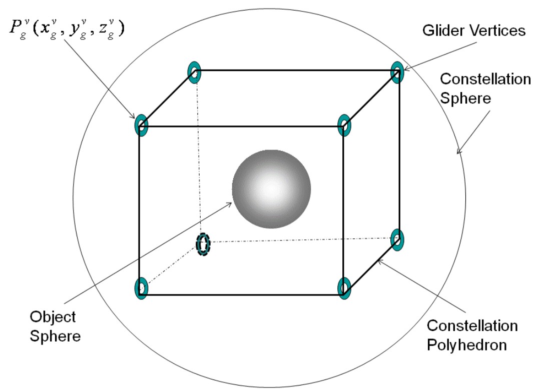

Figure 3: Vertices of constellation polyhedron on the constellation sphere.

3. BASIC MODEL ASSUMPTIONS

The mathematical model is defined in accordance with the following assumptions: 1) a virtual sphere known as the *object sphere* of radius r [m], as shown in Figs. 3 and 4, is assumed around the target object; 2) for the formation of constellation of gliders or AUVs a concentric virtual sphere known as *constellation sphere* of radius R is assumed around the object such that $R > r$; 3) the radius of the constellation sphere is a function of resolution of the acoustic imaging system used, which provides us with the minimum and maximum value of R; 4) all the gliders or AUVs in the constellation form a symmetric polyhedral structure known as *constellation polyhedron*, as shown in Fig. 4, such that all the points of the polyhedron lie on the constellation sphere and the sum of total energy of the constellation is minimum; 5) each glider is assigned a unique point *optimum position* on the constellation sphere so as to avoid collision between two gliders or AUVs.

The *optimum position* is the position from which the glider starts scanning the object. The gliders are constantly moving as side scan sonar imaging can be done only when in motion. Therefore, vehicles move in fixed pattern in which they occupy the *optimum position* alternately to form a rotating polyhedron, as shown in Fig. 4.

- Surface area of the *object sphere*. Let $S_o[m^2]$ represent the surface area of the *virtual sphere* around the target object of radius r, as depicted in Fig. 5, such that it just exactly covers the whole target object, where r is equal to the longest edge of the object. Hecne, the surface area of the abject sphere is given by,

$$S_o = 4\pi r^2. \quad (3)$$

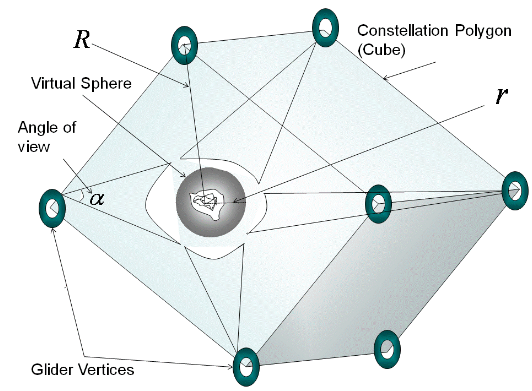

Figure 4: Constellation formation to capture object images.

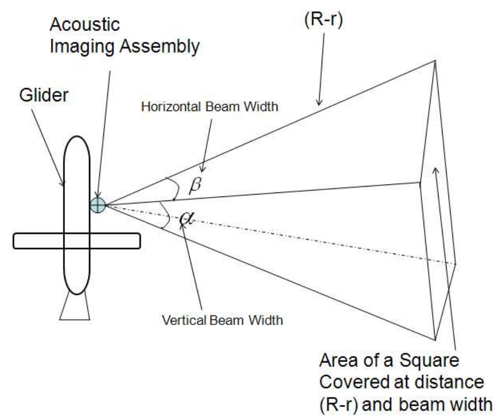

Figure 5: Area covered by side scan sonar at a distance (R-r).

- The area covered S_c at slant range R is determined by the solid angle Υ of the cone that intercepts the half power band width points of the side scan sonar, as shown in Fig. 5,

$$S_c = R^2 \cdot \Upsilon, \quad (4)$$

with

$$\Upsilon = Q \cdot \alpha \cdot \beta, \quad (5)$$

where α and β are the vertical and horizontal beamwidths in radians, respectively, while Q depends on the shape of area covered ($Q = 1$ for rectangular area, $Q = \pi/4$ for circular or elliptical area).

4. PROBLEM FORMULATION

In this section, we formulate a mathematical model for formation of optimal team of gliders and AUVs to complete the given mission with minimum energy respecting the time bound. First, we formulate the problem for gliders and then modify it for AUVs, and from the results obtained we compare their energy efficiency.

4.1 Buoyancy-driven Gliders

The problem of inter-glider task optimization is defined according to the following assumptions: i) gliders are already deployed in a 3D ocean region, ii) gliders receive the mission details from the surface station or they already have information due to classification and ranging done before the mission using SONAR, which includes the three dimensional coordinates of the target object, iii) each glider has information about the approximate relative positions of gliders in neighborhood, and iv) gliders know their approximate distance from the target object. The solution proposed has the objective of selecting the optimum number of gliders based on minimum energy required by the team of gliders to travel towards the target object respecting the time bound for the mission δ [s].

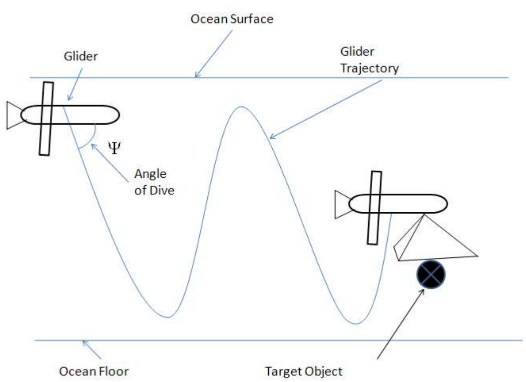

Figure 6: Sawtooth trajectory of the glider.

Gliders move in a sawtooth trajectory as sketched in Fig. 6. The energy model for the glider consists of power required by the glider to operate the buoyancy engine and time for which the buoyancy engine is in the 'on' state. The total energy depends on the angle of dive of the glider, which determines the number of times the glider will climb and descend to cover a predetermined distance. The power consumed by the glider to move is determined by the velocity of the glider. The velocity determines the force required by the piston of the buoyancy engine to pump out the water at a specific rate to achieve the desired velocity [8]. The force is also dependent on the depth at which the glider is present. The external pressure is directly proportional to the depth and is given by $\rho \cdot g \cdot h$, where ρ $[\mathrm{Kg/km^3}]$ is the density of water, g $[\mathrm{km/hr^2}]$ is the gravitational force, and h [km] is the depth. As the depth increases, the force required to pump out the water increases and in turn the power consumption. The power to move is given as,

$$P^M = \frac{1}{2} \cdot F \cdot V_g, \tag{6}$$

where the force F, which is directly dependent on the depth, is

$$F = C \cdot \rho \cdot g \cdot h, \tag{7}$$

with C being a constant that depends on the parameter of the buoyancy engine. Depending on the angle of dive, the distance traveled by the glider in one climb and descent is calculated from lab experiments, simulations, and glider data sheet. From this data, we can calculate the number of climbs C_n required to cover an horizontal distance of 1 km.

We introduce the following notation for construction of our mathematical models:
- $Pos_g^i(x_g^i, y_g^i, z_g^i)$ is the *initial position* of glider g in the deployment region.
- $Pos_g^f(x_g^f, y_g^f, z_g^f)$ is the optimum position f on the *constellation sphere* of glider g around the target object.
- P^M is the power required to run the buoyancy engine.
- $C_o(x_o, y_o, z_o)$ is the center of the *object sphere* with radius r.
- $\mathcal{G}$ is the set of gliders deployed in the region and every glider g is its element.
- X_g is a binary set determining, which gliders are selected in the team for the mission.
- $Z = |(z_g^f - z_g^i)|$ [km] is the depth that glider needs to achieve.
- T_g^M [hr] is the time glider g requires to move a certain distance at horizontal velocity V_g [km/hr].
- T_g^Ω [hr] is the time required to scan the target object by the respective glider.
- E_g^M [J] is the energy required by the glider g to move from initial position to the optimum position.
- E_g^Ω [J] is the energy required by the glider to scan the whole target object alone.
- P_g^Ω [W] is the power required by the glider to capture images of the object.
- δ [hr] is the total time allotted to complete the mission.
- T^{Total} [hr] is the time the team of gliders will take to complete the mission.
- T_{on} [hr] is the time for which the buoyancy engine pump is on and it is determined by the velocity V_g of the glider.

Now, we introduce a specific framework that presents a mathematical model that takes into consideration the initial position of the set of gliders, optimum position of the gliders in the constellation, size of the object, resolution of the acoustic imaging system, area of coverage of the acoustic imaging system, time allotted for the mission, energy of the glider team. The velocity of glider has a very limited range of variation as compared to the AUVs; hence, in the mathematical model we consider the velocity of all gliders to be constant.

The problem is formulated as a *Mixed Integer Non Linear Program (MINLP)*. The objective of the problem is to minimize the energy to reach the optimum positions on the constellation sphere to capture the images respecting the time bound δ.

Multi-Glider Task Optimization Problem

Given : $Pos_g^i, C_o, \mathcal{G}, r, P^M, P_g^\Omega, R_{min}, R_{max}, \delta, V_g, T_{on}, C_n$

Find : $Pos_g^{f*}, X_g^*, R^* \epsilon [R_{min}, R_{max}]$

Minimize : $\sum_{g \epsilon \mathcal{G}} [E_g^M + E_g^\Omega] \cdot X_g$

Subject to :

$$E_g^M = C_n \cdot \sqrt{(x_g^f - x_o)^2 + (y_g^f - y_o)^2} \cdot P^M \cdot T_{on}; \tag{8}$$

$$E_g^\Omega = P_g^\Omega \cdot T_g^\Omega; \tag{9}$$

$$T_g^M = \frac{\sqrt{(x_g^f - x_o)^2 + (y_g^f - y_o)^2}}{V_g}; \tag{10}$$

$$T_g^\Omega = \frac{2 \cdot \pi \cdot R}{V_g}; \tag{11}$$

$$T^{Total} = \frac{1 + \sum_{g=1}^{|\mathcal{G}|}(\frac{T_g^M}{T_g^\Omega}) \cdot X_g}{\sum_{g=1}^{|\mathcal{G}|} \frac{X_g}{T_g^\Omega}} \leq \delta; \quad (12)$$

$$[(x_g^f - x_o)^2 + (y_g^f - y_o)^2 + (z_g^f - z_o)^2] \cdot X_g = R^2; \quad (13)$$

$$\sum_{g \epsilon \mathcal{G}} X_g \geq 1; \quad (14)$$

$$\sum_{g \epsilon \mathcal{G}} X_g \leq |\mathcal{G}|. \quad (15)$$

Constraint (8) determines the energy the glider requires to operate its buoyancy engine while pumping out the water for an ascent and the energy required by the glider to travel a certain horizontal distance at velocity V_g, which is assumed to be constant as it does not vary over a wide range as compared to AUVs. Constraint (9) determines the energy required to capture images of the whole object if the glider were alone on the mission. Constraint (10) determines the time the glider will take to reach the target object traveling at a horizontal velocity V_g. Constraint (11) determines the time one glider would take to acquire the images of the whole object if it were alone. This is the time the glider would need to acquire the images as it will hop from one *optimum position* to another on the *constellation polyhedron*. Constraint (12) determines the total time the team of gliders will take to complete the mission and assures that this time be less than or equal to the given time bound δ. This is a very important constraint as it is a modification of the assumption that all gliders start imaging the object simultaneously. In this work, we consider that if a glider arrives at the object it will start capturing its images until the other gliders in the team arrive, hence the work to be done for the joining gliders is less than what they would have shared if they had arrived simultaneously.

Constraint (12) can be derived as follows. Let T_1^Ω [hr] be the time required by the first glider to complete the mission and having rate of work of κ_1^Ω [MJ/hr], Λ [MJ] be the total work done to complete the mission. Similarly, let T_2^Ω, T_3^Ω, $\cdots$, T_n^Ω be the time required by n gliders and let κ_2^Ω, κ_3^Ω, $\cdots$, κ_n^Ω be their respective rate of work. Hence, we have,

$$T_1^\Omega \cdot \kappa_1^\Omega = \Lambda,$$
$$\vdots$$
$$T_n^\Omega \cdot \kappa_n^\Omega = \Lambda.$$

Let T^{Total} be the total time required to complete the mission. Hence,

$$\kappa_1^\Omega \cdot T^{Total} = \Lambda_1,$$
$$\vdots$$
$$\kappa_n^\Omega \cdot T^{Total} = \Lambda_n,$$

$$T^{Total} \leq \delta$$

$$\Lambda = \Lambda_1 + \Lambda_2 + \cdots + \Lambda_n,$$

$$\Lambda = \tfrac{\Lambda}{T_1^\Omega} \cdot (T^{Total} - T_1^M) + \tfrac{\Lambda}{T_2^\Omega} \cdot (T^{Total} - T_2^M) +$$
$$\cdots + \tfrac{\Lambda}{T_n^\Omega} \cdot (T^{Total} - T_n^M),$$

where T_1^M is the time to reach the target object, $T^{Total} - T_1^M$ is the time the first glider will work alone on the mission until the second glider arrives. Similarly, $T^{Total} - T_2^M$ is the time for which first and the second glider will work until the third glider arrives.

$$\Lambda = \Lambda[(\tfrac{1}{T_1^\Omega} \cdot (T^{Total} - T_1^M)) + (\tfrac{1}{T_2^\Omega} \cdot (T^{Total} - T_2^M)) +$$
$$+ \cdots + (\tfrac{1}{T_n^\Omega} \cdot (T^{Total} - T_n^M))],$$

$$[1 + \tfrac{T_1^M}{T_1^\Omega} + \tfrac{T_2^M}{T_2^\Omega} + \cdots + \tfrac{T_n^M}{T_n^\Omega}] = T^{Total}[\frac{1}{T_1^\Omega} + \frac{1}{T_2^\Omega} +$$
$$+ \cdots + \tfrac{1}{T_n^\Omega}],$$

$$\frac{1}{T^{Total}}(1 + \sum_{i=1}^{N} \frac{T_i^M}{T_i^\Omega}) = \sum_{i=1}^{N} \frac{1}{T_i^\Omega},$$

$$T^{Total} = \frac{1 + \sum_{i=1}^{N} \frac{T_i^M}{T_i^\Omega}}{\sum_{i=1}^{N} \frac{1}{T_i^\Omega}} \leq \delta.$$

Constraint (12) imposes that the total time the team of gliders will take to complete the mission be smaller that the time bound δ. This time is calculated such that, as soon as the first glider reaches the object, it is starts scanning it and other gliders join in the mission as they arrive. Constraint (13) puts bounds on the distance between center of the *object sphere* and the *optimum position* of the gliders selected in the team such that all gliders lie on the *constellation sphere*. It assures that all the gliders be placed on the constellation sphere. Constraint (14) assures that at least one glider be always selected for the mission. Constraint (15) assures that the total number of gliders selected for the mission do not exceed the available set $\mathcal{G}$.

4.2 Propeller-driven AUVs

The problem formulation for AUV is similar to that of the gliders. The only difference is that AUVs are able to change their velocity according to the time bound of the mission but at the cost of some extra energy. The only equation that changes for the AUV case is,

$$E_a^M = [\zeta \cdot V_a^\gamma + P_{min}^M] \cdot T_a^M, \quad (16)$$

where E_a^M $[J]$ is the energy required by AUV a to move from initial position to the optimum position. This constraint is very different from the glider case as AUV needs energy throughout the time it travels to keep its rotors on unlike gliders, which require energy only at the time of climb. Also, the velocity of AUVs can be adjusted in much larger range than with gliders. The energy model of the AUV has two components, the velocity and time to move and the energy required to operate the onboard electronics. Note that the energy is non linearly dependent on velocity as it varies with time and linearly dependent on the constant component of energy required to drive the electronics.

5. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed framework. In Sect. 5.1, we compare the energy efficiency of a team of gliders with a team of AUVs for a given mission length, in Sect. 5.2, we show how the energy of a team of gliders and a team of AUVs varies with the size of the team, and, in Sect. 5.3, we analyze how localized the problem of optimal task allocation is.

We consider a $10 \times 10 \times 0.2$ km^3 3D underwater region for the deployment of the gliders and AUVs, which is similar to the region off the coast of New Jersey. The object is placed in the center of the region whose coordinates are $(5, 5, 0.1)$ km and has diameter of 0.08 km.

5.1 Energy comparison based on the time bound δ for the mission

In this section, we compare the output of the mathematical models developed for a team of AUVs and a team of gliders implemented using AMPL and solved with MINOS optimization server. The results are plotted using MATLAB. The gliders are initially randomly deployed in the 3D underwater region. The parameter values for the glider are set as, the power to operate the buoyancy engine of the glider is 90 W, the power required for acoustic imaging assembly is 45 W, velocity of the gliders is 1.4 km/hr, C_n has a value of 4, the time for which the buoyancy engine needs to be on to move at a horizontal velocity of 1.4 km/hr is 0.015 hr. The parameter values for the AUV [3] are set as the power to operate the propeller engine is 900 W, the power required for acoustic imaging assembly is 45 W, velocity of scanning is 1.4 km/hr. The velocity of AUVs is dependent on various non-linear factors like drag force, friction of the motor, etc., hence the non-linear component values of ζ is set as 0.005 and that of γ to 1.5.

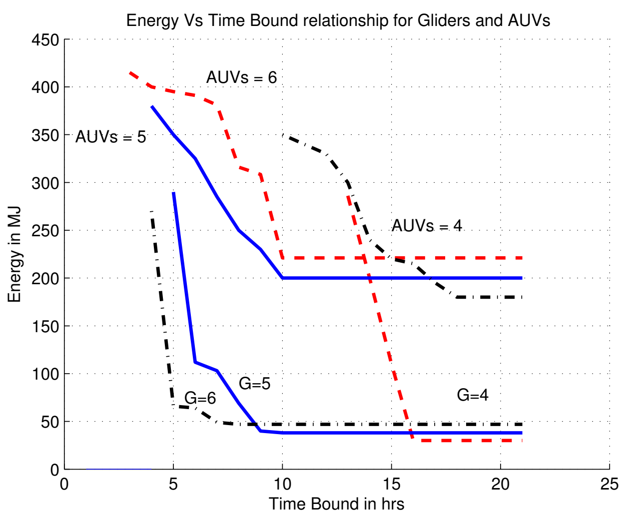

Figure 7: Comparison between the energy in MJ of gliders and AUVs vs. the time bound for the mission δ.

In Fig. 7, we observe that as the length of the mission goes on increasing (time bound) the energy required by the gliders and AUVs for the same mission differs. The energy of team of gliders is comparatively much less than that required by the team of AUVs. AUVs are time efficient as compared to the gliders as we can see from the graph the *infeasible region* for team of AUVs is much smaller than the infeasible region for team of gliders. As the time bound goes on increasing and approaches the feasible region of gliders, the energy difference between the glider team and AUV team is drastic. As seen from the graph, the energy required by the team of 4 AUVs is about 100 MJ more than that for a team of 4 gliders. Also, a team of 5 AUVs can perform the same work as a team of 6 gliders in less time, but it consumes much higher amount of energy - around 100 MJ - than the team of 6 gliders. Hence, we can infer from the plot that as a mission length increases, the team of gliders becomes much more energy efficient than the team of AUVs.

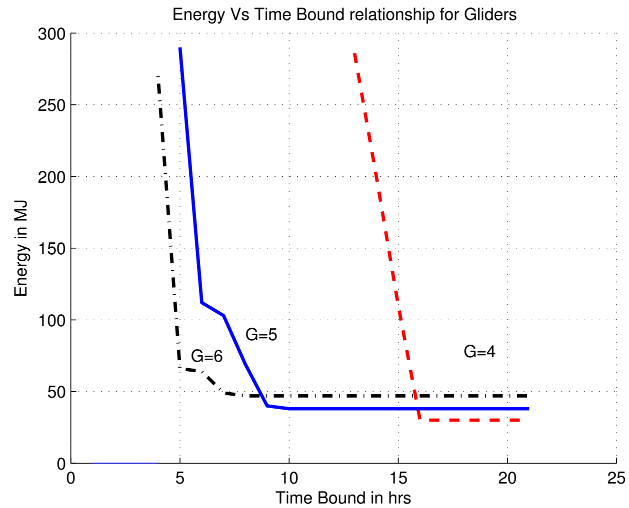

Figure 8: Relationship between the energy in MJ of gliders vs. the time bound for the mission δ.

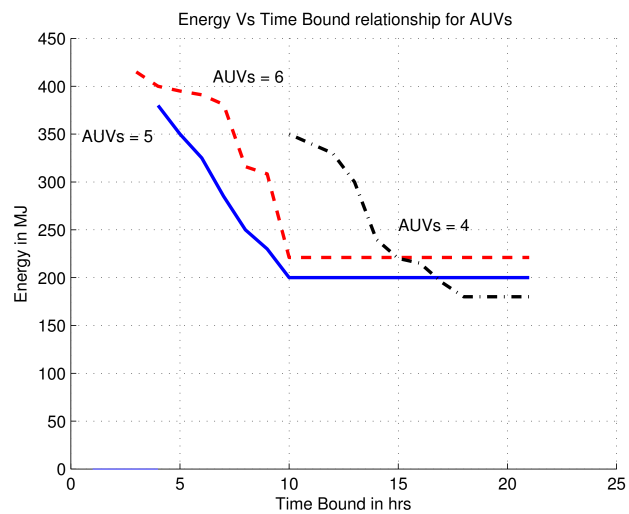

Figure 9: Relationship between the energy in MJ of AUVs vs. the time bound for the mission δ.

From Figs. 8 and 9, it is observed that as the mission length increases the number of gliders or AUVs selected for the mission decreases. The energy of team of AUVs or gliders also decreases with increase in time bound. Ideally for a infinite time bound only a single glider or a AUV will be selected, so that the energy of team is minimum. The optimization algorithm is run centrally on the computer of one of the glider or a AUV. As the time bound goes on increasing, the solution of the optimization problem involves more and more vehicles in the proximity of the target object. *Hence, while a distributed solution of the problem involving only localized vehicles would be suboptimal, for a very large time bound the difference between this suboptimal and the optimal solutions would become negligible.* Hence, we can conclude that the problem is localized for large time bound.

5.2 Energy comparison based on the number of gliders or AUVs present in the team

In this section, we show how the total energy of a team of gliders and a team of AUVs varies with the team size. From Figs. 10 and 11 we observe that as the value of δ goes on decreasing, more and more gliders are required to form the team. From Fig. 11 we conclude that, as δ goes below a certain value, the mission becomes impossible to complete using a single glider and at least two gliders are required to complete the mission in the given time bound. A similar scenario for AUVs is indicated in Fig. 13. AUVs are fast compared to the gliders, but as the value of δ goes below a certain value it becomes impossible for a single AUV to complete the mission. From Fig. 10 and Fig.11, we also observe that the total energy of team as the team size varies from 1 to 5 gliders is in the range of 200 to 250 MJ.

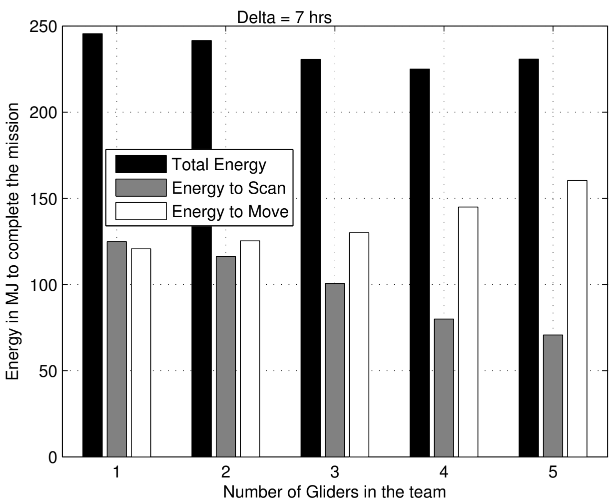

Figure 10: Total energy of team of gliders in MJ against the number of gliders in the team when time bound δ is 7 hr.

The energy for same variation in number of AUVs in the team is 1800 to 2000 MJ, as can be seen from Figs. 12 and 13. We can observe that the energy for same size team of AUVs and gliders differ by around 1600 to 1750 MJ. Also, the energy to travel for AUVs from the initial position to the optimum position, as shown in Figs. 12 and 13, is more dominant than the energy to scan, which is in contrast to that of team of gliders where energy to scan is very dominant, as can be seen from Figs. 10 and 11. This implies that the AUVs as a team consume a very large amount of energy as compared to a team of gliders to travel towards the object. This is where the energy efficiency of gliders has its advantage over AUVs in saving energy and cost. For mission with longer distance and longer mission lengths, a team of gliders is preferred over a team of AUVs.

5.3 Localized nature of the task allocation

From Figs. 14 and 15 we observe that the value of the maximum distance from which a glider is selected to form a optimal team is almost constant as the size of the team goes on increasing. This implies that the optimization problem is very localized and it considers only the gliders present within a certain range (in this case maximum of 6.8 km) every time for selecting a optimal team. In contrast to this, we can observe in Figs. 14 and 15 that, in case of

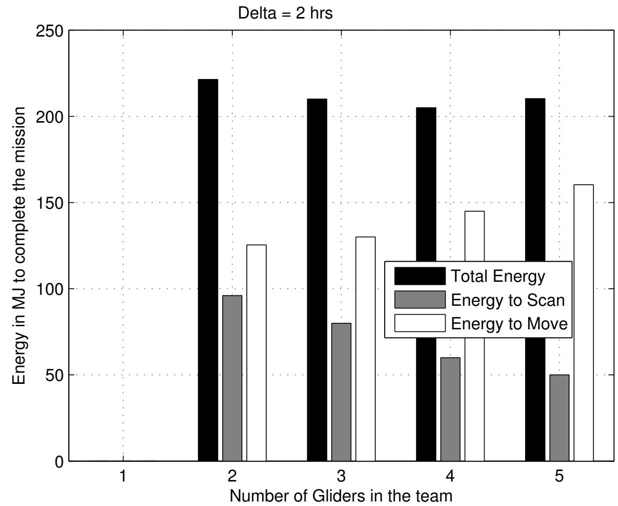

Figure 11: Total energy of team of gliders in MJ against the number of gliders in the team when time bound δ is 2 hr.

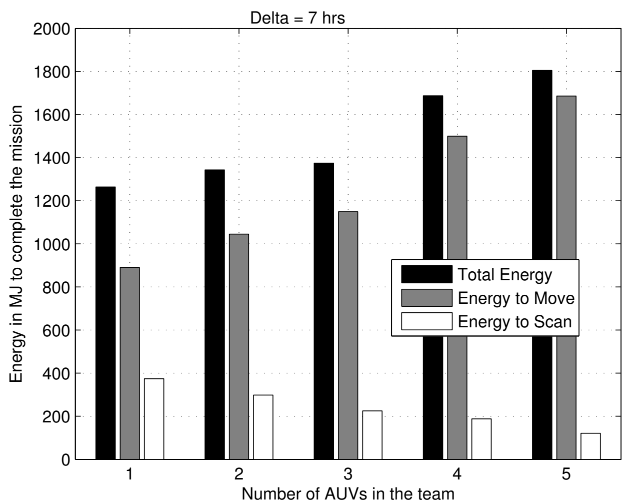

Figure 12: Total energy of team of AUVs in MJ against the number of AUVs in the team when time bound δ is 7 hr.

AUVs, as the size of the team goes on increasing, we can see the distance also increasing to cover the entire area of deployment for choosing the AUVs. Thus, it can be inferred that the formation of a glider team is a more localized problem than that of formation of an AUV team, which is cased by the fixed velocity of gliders.

6. CONCLUSIONS

We presented a framework that allows us to compare the energy efficiency of a team of gliders and that of a team of propeller-driven AUVs for a given mission. We compared them using three different criteria: i) the variation in energy of the team of gliders as compared to that of the team of AUVs as the time bound increases, ii) the energy of team of gliders and AUVs based on the team size, and iii) the maximum distances from which the gliders and AUVs

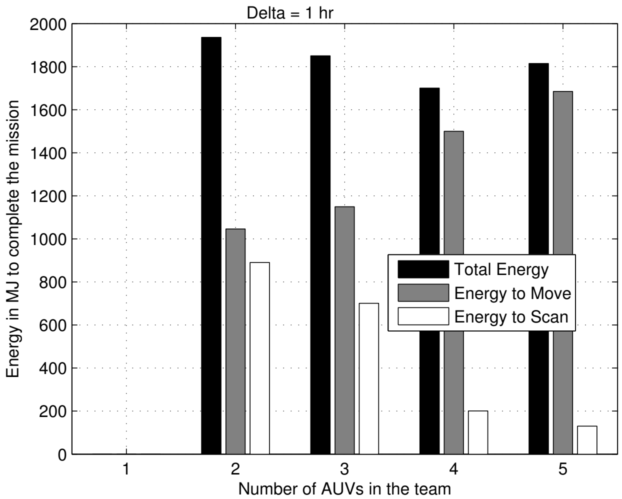

Figure 13: Total energy of team of AUVs in MJ against the number of AUVs in the team when time bound δ is $1\ \mathrm{hr}$.

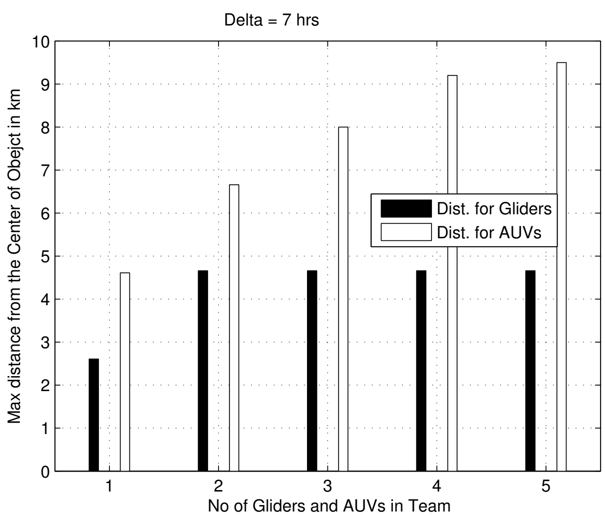

Figure 14: Maximum distance in km from which the gliders and AUVs are selected in the team against the team size when δ is $7\ \mathrm{hr}$.

are chosen respectively to form teams as the size of the team increases. The important conclusion is that the optimization solution derived in this paper is not only giving the best possible solution, but also a valid solution which may be obtained through distributed or localized heuristics. In addition, even if the distributed solution shows suboptimal results, it can still provide a feasible solution from the available set of AUVs or gliders. We showed that a trade off exists between time and energy: in case of missions with long length, gliders should be preferred because of their higher energy efficiency; on the other hand, in case of short-length missions, a team of AUVs can still complete the mission within the delay bound, whereas gliders may not, at the price of higher cost and energy.

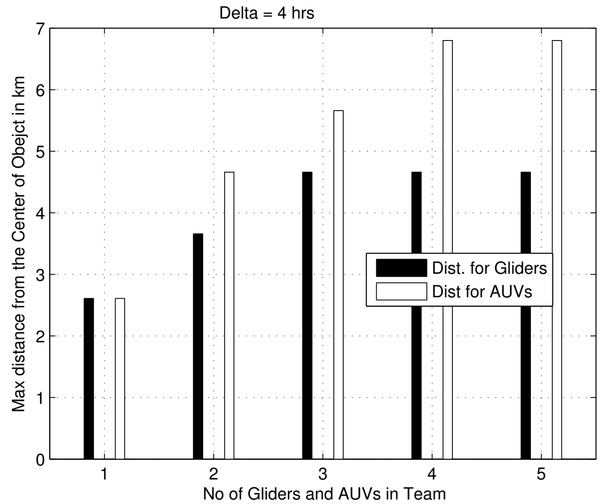

Figure 15: Maximum distance in km from which the gliders and AUVs are selected in the team against the team size when δ is $4\ \mathrm{hr}$.

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