Energy-Optimal Data Collection and Communication Using a Group of UUVs

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Abstract

There has been a growing interest to incorporate Unmanned Underwater Vehicles (UUVs) in various military applications. UUVs can be easily deployed in an area of interest such as offshore fleet operating regions and littoral penetration zones to collect critical data. In many military scenarios, collected sensor data have to be transmitted to a host station which could be a land base station, a host surface ship, a communication relay aircraft or a satellite. Since these types of missions require considerable on-station time, it is very important to perform them in an energy-optimal manner. This paper proposes a novel approach that minimizes energy consumption in collecting and communicating sensor data using a group of UUVs. Specifically, our approach determines the optimal mix of communication and vehicle repositioning for a given spatial configuration of UUVs and the location of the base station they must relay their information to. Our goal is to minimize total energy consumption which includes energies spent in underwater communications among the UUVs, the propulsions of the UUVs required to achieve communications and the RF communications conducted by surfacing UUVs to send the sensor data. Integer Linear Programming (ILP) is used to formulate the problem and solve it optimally under performance constraints. Our experiments show that the proposed approach is very effective in reducing energy consumption required for communication activities and the solution times experienced are not excessive.

Introduction

Popularity of Unmanned Underwater Vehicles (UUVs) has been increasing in both military and commercial applications over the past decade, due to the low-risk and clandestine nature of these vehicles. Specifically, a UUV can reach depths which are impossible to dive with a manned vehicle, and are smaller and have better endurance than comparably able manned vehicles. Furthermore, they can achieve their mission without putting human life at risk. UUVs can be employed for carrying out dangerous tasks such as mine neutralization. Their small size and longer endurance make them more suitable for covertly collecting intelligence, or even attacking predefined targets. Detailed survey studies for UUV applications can be found in [1][2][3]. From a military perspective, The U.S. Navy's new UUV Master Plan published in 2004 [4] lists the Navy's view regarding most promising applications of UUVs. Intelligence, Surveillance, and Reconnaissance (ISR), Mine Countermeasures (MCM), and Anti-Submarine Warfare (ASW) are emphasized as the top three missions that require more research and development studies. Lockheed Martin's Sea Talon (Tactical Acoustic Littoral Ocean Network) [5] is an example of a vehicle that can be employed in ISR and ASW applications. Boeing's LMRS (Long Term Mine Reconnaissance System) [6] is an example of a mine hunting system and Lockheed Martin's AMNS (Airborne Mine Neutralization System) [7] uses STN Atlas Elektronik's Seafox UUV [8] in a state-of-the-art mine neutralization system.

As an area of common concern for both military and commercial companies, harbor protection represents an important application domain that has increasing potential for UUVs. Kermorgant [9] studied harbor protection with AUVs. Bovio conducted a detailed sea experiment using Ocean Explorer [10] and REMUS 100 [11] for port protection [12], which emphasized the man-power efficiency and usefulness of the employment of UUVs for harbor protection. Oil and gas companies are also potential users of the UUVs to conduct deep sea oil and gas related surveys. An example study for this application area can be found in [13].

In this paper, an energy-optimal data collection and communication scenario employing a group of UUVs is considered. In this scenario, the data required to be collected depends largely on the application. Potential applications include multibeam bathymetry or imagery data, or side scan sonar data. There are *N* UUVs which are assigned to perform a specific task in a given underwater area. The operation area is assumed to be a three-dimensional grid. Each conjunction point on the grid is assumed to be the center of an eligible survey area that can be assigned to a UUV. Not all points have to be occupied by a UUV. A point in this three-dimensional space is represented by its three coordinates. For instance, a point A is denoted by A(i,j,k), where i is the x dimension coordinate, j is the y dimension coordinate, and k is the z dimension coordinate of the point. We assume and use the grid conjunction point as the communication point for each UUV regardless of its current location in its assigned area.

Distances between each pair of points on this three-dimensional grid are calculated as Euclidean Distances. A

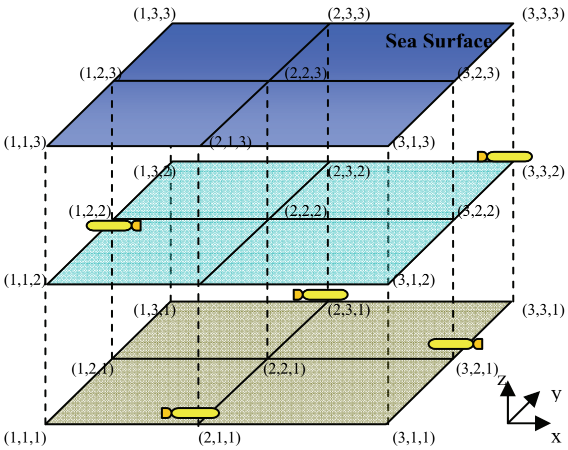

Figure 1: An example 3x3x3 grid with 27 conjunction points. Five UUVs are located on different points of this grid.

sample 3x3x3 grid illustration with five UUVs in it is given in Figure 1. Note that the top layer of the grid is assumed to be the sea surface.

The deployment platform of UUVs can vary. They could be launched from an appropriate submarine (e.g., SSN 688 and NSSN class submarines), as is in LMRS [6]. They could also be deployed from appropriate surface ship(s). In our case, we assume that several fast surface ships deploy the UUVs to the operation area and leave. Upon deployment, UUVs submerge, proceed to their assigned survey area, and begin to collect the data of interest using their (potentially) different types of sensors (e.g., forward looking sonar, side-look sonar, imaging camera, etc.). After a predefined amount of time, the collected sensor data have to be transmitted to the host station. The host station in our case is a land base station 20 Nm away from the operation area. Our goal in this scenario is to ensure that the data collected by UUVs are communicated to the host station with *minimum energy consumption*, which includes the energies spent in UUV movement within the three-dimensional grid, inter-UUV (acoustic) communications, and UUV-host station (RF) communications. The entire scenario briefly explained above is formulated using Integer Linear Programming (ILP). After running our ILP formulation, the ILP solver can generate either of two types of solutions. In the first case, all UUVs are assigned as slave UUVs. Hence, all UUVs must surface and each UUV transmits its own data to host station via RF independently. In the second case, UUVs are put into two different groups: master UUVs and slave UUVs. The ILP solver determines both the optimal number of masters and slaves to minimize the total energy consumption which in turn maximizes the availability of UUVs for future data collections. Further, a subgroup of UUVs is assigned as slave UUVs for each master UUV, and each slave UUV in the subgroup has to send its data to its designated master UUV. Moreover, if a UUV is selected as a master UUV, it first collects the entire data from its slaves, then it surfaces, and finally it transmits all collected data (its own data plus the data received from its slaves) to the host station via RF.

Our ILP solver captures three types of energy consumption values in order to find the optimal number of masters and the data transmission schedule for the UUVs. The first one captures the energy spent in underwater communications

	(1,1,1)	(1,1,2)	(1,1,3)	(1,2,1)	(1,2,2)	(1,2,3)	(2,1,1)	(2,1,2)	(2,1,3)	(2,2,1)	(2,2,2)	(2,2,3)
(1,1,1)	0.00	120.00	240.00	120.00	169.71	268.33	120.00	169.71	268.33	169.71	207.85	293.94
(1,1,2)	120.00	0.00	120.00	169.71	120.00	169.71	169.71	120.00	169.71	207.85	169.71	207.85
(1,1,3)	240.00	120.00	0.00	268.33	169.71	120.00	268.33	169.71	120.00	293.94	207.85	169.71
(1,2,1)	120.00	169.71	268.33	0.00	120.00	240.00	169.71	207.85	293.94	120.00	169.71	268.33
(1,2,2)	169.71	120.00	169.71	120.00	0.00	120.00	207.85	169.71	207.85	169.71	120.00	169.71
(1,2,3)	268.33	169.71	120.00	240.00	120.00	0.00	293.94	207.85	169.71	268.33	169.71	120.00
(2,1,1)	120.00	169.71	268.33	169.71	207.85	293.94	0.00	120.00	240.00	120.00	169.71	268.33
(2,1,2)	169.71	120.00	169.71	207.85	169.71	207.85	120.00	0.00	120.00	169.71	120.00	169.71
(2,1,3)	268.33	169.71	120.00	293.94	207.85	169.71	240.00	120.00	0.00	268.33	169.71	120.00
(2,2,1)	169.71	207.85	293.94	120.00	169.71	268.33	120.00	169.71	268.33	0.00	120.00	240.00
(2,2,2)	207.85	169.71	207.85	169.71	120.00	169.71	169.71	120.00	169.71	120.00	0.00	120.00
(2,2,3)	293.94	207.85	169.71	268.33	169.71	120.00	268.33	169.71	120.00	240.00	120.00	0.00

Table 1: Communication energy values for an example three-dimensional grid (2x2x3) with 12 nodes. Each entry in the table gives the communication energy consumption between the two corresponding points in Watts. (Two neighboring points are assumed to be 10 meters apart from each other).

among the UUVs; the second one is due to the propulsion energy of the UUVs to surface; and the third one is because of the RF communications conducted by surfacing UUVs to send the sensor data. The propulsion energies needed to surface from each point on the three-dimensional grid are calculated as the product of the distance between each point and the surface and the propulsion energy consumption value of the UUV. We use the energy consumption characteristics of the REMUS 600 AUV [14], as it is one of the most widely-used UUVs in both military and commercial applications. REMUS 600 can be employed up to 600 meters depth and can endure up to 70 hours of operational time, depending on the speed and sensor configuration. The propulsion energy consumed by a REMUS 600 (also used in our experiments) is 28 watts per second at the optimal speed of 3 knots. Similarly, underwater communication energies are calculated as the product of distance between two points on the grid and the energy consumption value of the acoustic modem. We assume LinkQuest UWM3000 [15] for the acoustic modem embedded on our experimental UUVs due to its popular usage in the AUV/UUV based-systems and its high reliability. The working range of UWM3000 is up to 5000 meter, and it can be employed up to 7000 meters in depth. Its energy consumption for transmitting data is measured as 12 watts [15]. A sample communication energy consumption input data table for an example 2x2x3 grid is given in Table 1. The value 207.85 marked with orange is the calculated as follows. If we look at Figure 1, the distance between the UUV at the point (1,2,2) and the UUV at the point (2,1,1) is the diagonal of the cubic part of the grid. Even though the length of 10 meters for each edge on the 3D grid is clearly not realistic, it is used here for the sake of illustration. Since the communication energies are calculated as the product of distance between two points and the communication energy consumption value of the acoustic modem (in our case, it is 12 watts for LinkQuest UWM3000, as mentioned above), the communication energy ($CME_{i,j,k,a,b,c}$) needed to send data packet from point (2,1,1) to (1,2,2) can be calculated as:

$$CME_{2,1,1,1,2,2} = 12 watts * \sqrt{10^2 + 10^2 + 10^2} \cong 207.85. \qquad (1)$$

The propulsion energy consumption table is prepared in the same fashion, but only the values between each point and the surface is calculated. We assume that a UUV surfaces on the same z axis where it was initially on (if desired, our ILP formulation can be modified to drop this assumption). Finally, for RF communication, since we assume that the host station is 20 Nm away from the operation area, in order to reach such a far point, the output power of the RF modem and transmitter needs to be adjusted to (potentially) a high value (in our case, it is 6 watts for Military Navigator II VHF/UHF modem [16]). With this output power, there will not be a significant energy consumption difference for communicating between the host station and the nearest or farthest surface points. Therefore, we assume that the energy consumption to transmit data to the host station is identical from all surface points of the grid, and set this as the energy consumption of the RF modem and transmitter. We further assume that each UUV is equipped with a Military Navigator II VHF/UHF modem [16], which has a maximum range of 60 miles. This modem uses Frequency Hopping Spread Spectrum (FHSS) and its output power with transmitter is 6 watts. All these energy consumption values are calculated based on the grid size considering the length of each edge on the grid, and are then given to the ILP solver as input data.

Most of these studies explained earlier focused on UUV design issues and their usage in specific application domains. We are not aware of any study that aims at minimizing energy consumption in a multi-UUV execution scenario. Related energy consumption efforts are mostly covered in the context of adhoc/sensor network applications. For instance, in [17], a well-studied energy optimal communication data transmission algorithm has been proposed for mobile adhoc/sensor networks. But in that work communication schedule is assumed to be known in advance and, according to the schedule, mobile nodes are assigned to move and/or send their data to the intended destination node(s). On the other hand, Draper Laboratory has been working on a combined battlespace scenario (Risk-aware Mixed-initiative Dynamic Replanning (RMDR) Program [18]), which uses both UUVs and Unmanned Air Vehicles (UAVs) to gather intelligence data to relay to a host station. In RMDR, certain number of UUVs is assigned to either survey a given area or track the target(s). Upon collecting intelligence data, they surface and send the collected data to a host station directly, or using relay UAV(s) or satellite. RMDR is a good example of a potential application area of our work, which aims at minimizing the energy consumption by determining the optimal communication scheme. Maximizing the endurance of the UUVs in such an application provides longer mission durations to collect more intelligence which in turn supplies better battlespace operational understanding to the host station.

The main contribution of this paper can be summarized as follows: Considering the all energy needs to transmit the data to host station (acoustic transmission, propulsion, RF transmission) and the distances among the UUVs, an optimal communication topology and data relay schedule are found to minimize the total energy consumption. In order to do that, the ILP solver determines optimal number of master and slave UUVs. In this work, we employ "minimum energy consumption" as our objective function, and then we evaluate our ILP formulation under different scenarios, and finally report experimental data. Note that our ILP formulation can be adopted to work with other objective functions as well.

Problem Formulation

Our goal in this section is first to give the nomenclature used in the rest of the paper, then explain the major definitions we make, and finally, present the ILP formulation of the scenario by considering the specified requirements. Unless otherwise stated, all costs mentioned below are energy consumption costs.

Nomenclature

Indices:

i, a	=	x dimension indices
j, b	=	y dimension indices
k, c	=	z dimension indices
v	=	Vehicle index

Constants:

N	=	Number of UUVs
DX	=	Length of x dimension
DY	=	Length of y dimension
DZ	=	Length of z dimension
GR_UNT	=	Unit size of each edge on 3D Grid
PR_PWR	=	Propulsion power needed to proceed one meter under water (in Watts)
AC_PWR	=	Power needed to transmit via Acoustic (in Watts per meter)
RF_PWR	=	Power needed to transmit via RF (in Watts)
$INIT_{i,j,k}$	=	Shows if there is a UUV at point (*i*,*j*,*k*) at the beginning
$CME_{i,j,k,a,b,c}$	=	Communication cost to transmit from point (*i*,*j*,*k*) to point (*a*,*b*,*c*)
$SRE_{i,j,k}$	=	Surfacing cost of a UUV at the point (*i*,*j*,*k*)

Variables:

$com_{i,j,k,a,b,c}$	=	Binary assignment variable for a UUV at point (*i*,*j*,*k*) to transmit to a UUV at point (*a*,*b*,*c*)
$mas_{i,j,k}$	=	Binary assignment variable for a UUV at point (*i*,*j*,*k*) to be a master
$sla_{i,j,k}$	=	Binary assignment variable for a UUV at point (*i*,*j*,*k*) to be a slave
$sur_{i,j,k}$	=	Binary assignment variable for a slave UUV at point (*i*,*j*,*k*) to surface
$m\_sur_{i,j,k}$	=	Binary assignment variable for a master UUV at point (*i*,*j*,*k*) to surface
kk	=	shows optimal number of master UUVs

Objective Function:

ttl_enrgy	=	Cost function

Definitions and ILP Formulation

As mentioned earlier, our target scenario contains a group of UUVs in a given search area in which each UUV conducts searches and collects data. The data collected by each UUV have to be transmitted to the host station periodically. In order to do this, master and slave UUVs have to be identified. The ILP formulation given below determines the optimal number of master and slave UUVs as well as the optimal communication schedule to keep the total energy consumption to a minimum, including both propulsion energy and data transmission energy.

In our problem formulation, the constants, presented in the following subsection, are the input to our ILP solver. Using these inputs, our ILP solver returns the values of the result variables (output) based on the objective function described in the subsection called "Objective Function".

Constants. *N* UUVs are located on a three-dimensional grid (*DX* x *DY* x *DZ*), and their initial locations are given by $INIT_{i,j,k}$, where $i = 1 \ldots DX$; $j = 1 \ldots DY$; $k = 1 \ldots DZ$. The size of each edge of the grid (i.e., the distance between any neighboring points) is given by *GR_UNIT* and can be tuned according to the mission requirement. For instance, if it equals to 100 meters, size of a 3x3x3 grid would be 300m x 300m x 300m. The energy needed to transmit data from a point (*i*,*j*,*k*) to a point (*a*,*b*,*c*) is denoted by $CME_{i,j,k,a,b,c}$ and equals to the product of the distance between two points and the transmission energy consumption value of the acoustic modem (*AC_PWR*). Similarly, surfacing energy of each point of the grid is calculated in the same fashion as the propulsion energy consumption, and stored in $SRE_{i,j,k}$. Finally, the RF transmission cost from all surface points (top level of the grid) is assumed identical and denoted by *RF_PWR*. All these energy consumption values are calculated as explained in the introduction, and then stored in tables such as Table 1, which are fed into ILP solver as input data.

Variables. Upon solving the energy minimization problem, our ILP solver assigns some of the UUVs as masters ($mas_{i,j,k}$), and some other as slaves ($sla_{i,j,k}$). If a UUV is assigned as master, it needs to surface ($m\_sur_{i,j,k}$) after collecting the data coming from its assigned slaves. Consequently, a slave UUV at a point (*a*,*b*,*c*) needs to transmit its data ($com_{a,b,c,i,j,k}$) to its assigned master at a point (*i*,*j*,*k*). If no UUV is assigned as master by ILP solver, it means that the minimal energy consumption to relay sensor data to host station will be obtained by all UUVs. In this case, all UUVs are assigned as slaves ($sla_{i,j,k}$). They first need to surface ($sur_{i,j,k}$) and then transmit their own data independently.

Constraints in our ILP Formulation. After defining the constants and variables, we can now give the details of our ILP formulations.

1. If there is a UUV at a given point (*i*,*j*,*k*), it must be either a master UUV or a slave UUV.

$$mas_{i,j,k} + sla_{i,j,k} \geq INIT_{i,j,k} \quad (2)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

2. If the UUV at the point (*i*,*j*,*k*) is a master UUV, it must surface and use RF communication.

$$mas_{i,j,k} \leq m\_sur_{i,j,k} \quad (3)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

3. There must be *kk* master UUVs to have the optimal energy consumption ($kk = 1 \ldots N$).

$$\sum_{i=1}^{DX} \sum_{j=1}^{DY} \sum_{k=1}^{DZ} mas_{i,j,k} = kk \quad (4)$$

4. If the UUV at point (*i*,*j*,*k*) is a slave, then it must either send its collected data to its assigned master UUV or surface. (Note that a slave UUV can only surface if there is no master).

$$\sum_{a=1}^{DX} \sum_{b=1}^{DY} \sum_{c=1}^{DZ} com_{i,j,k,a,b,c} + sur_{i,j,k} \geq sla_{i,j,k} \quad (5)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

5. Each slave UUV at a given point (*i*,*j*,*k*) can transmit its sensor data only once.

$$\sum_{a=1}^{DX} \sum_{b=1}^{DY} \sum_{c=1}^{DZ} com_{i,j,k,a,b,c} \leq 1 \quad (6)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

6. If a UUV transmits from its initial point (*i*,*j*,*k*), it must send the data to the master UUV at point (*a*,*b*,*c*).

$$com_{i,j,k,a,b,c} \leq mas_{i,j,k} \quad (7)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$; $a = 1,\ldots,DX$; $b = 1,\ldots,DY$; $c = 1,\ldots,DZ$.

7. If at least one UUV is assigned as the master, the other (slave) UUVs cannot surface.

$$mas_{i,j,k} \leq 1 - sur_{a,b,c} \quad (8)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$; $a = 1,\ldots,DX$; $b = 1,\ldots,DY$; $c = 1,\ldots,DZ$.

8. A UUV cannot send data to itself.

$$com_{i,j,k,i,j,k} = 0 \quad (9)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

9. A UUV can be a master, only if it initially occupies a point in the three-dimensional grid.

$$mas_{i,j,k} \leq INIT_{i,j,k} \quad (10)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

10. A UUV can be a slave, only if it initially occupies a point in the three-dimensional grid.

$$sla_{i,j,k} \leq INIT_{i,j,k} \quad (11)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

11. A UUV can surface, only if it initially occupies a point in the three-dimensional grid.

$$sur_{i,j,k} \leq INIT_{i,j,k} \quad (12)$$

for $i = 1,\ldots,DX$; $j = 1,\ldots,DY$; $k = 1,\ldots,DZ$.

Objective Function. Based on the definitions and constraints presented above, there are two different ways to send data to the host station:

1. Each slave UUV surfaces and transmits its data to host station via RF independently. This is the case if no master UUV is determined by ILP solver. Total surfacing energy consumption equals to the sum of each slave UUV's surfacing cost and it can be expressed as follows:

$$S = \sum_{i=1}^{DX} \sum_{j=1}^{DY} \sum_{k=1}^{DZ} sur_{i,j,k} * SRE_{i,j,k} \quad (13)$$

2. Master UUVs are determined and surface. Then, each master UUV transmits its own data plus the received data from its assigned slave UUVs to the host station via RF individually. Consequently, total surfacing cost for the master UUVs becomes:

$$M = \sum_{i=1}^{DX} \sum_{j=1}^{DY} \sum_{k=1}^{DZ} m\_sur_{i,j,k} * SRE_{i,j,k} \quad (14)$$

In case of determining optimal number of master UUVs to surface, each slave UUV needs to send its data to its assigned master UUV. Upon completing the data transmission among the master and slave UUVs, each master UUV surfaces and sends the received data to the host station via RF. The following formula expresses the total underwater communication cost when considering all slave UUVs:

$$C = \sum_{i=1}^{DX} \sum_{j=1}^{DY} \sum_{k=1}^{DZ} \sum_{a=1}^{DX} \sum_{b=1}^{DY} \sum_{c=1}^{DZ} com_{i,j,k,a,b,c} * CME_{i,j,k,a,b,c} \quad (15)$$

Finally, we can write our objective function as sum of the costs explained above plus the number of UUV (*N*) times the RF communication cost, which gives us the total RF communication cost. It is added here, since no matter what results are returned by the ILP solver, the total amount of data that have to be delivered to the host station is the same (either by master(s) or by slaves themselves) and results in the same cost (we assume that from any surface point, RF communication cost to transmit data is the identical). Therefore, objective function can be expressed as:

$$ttl\_enrgy = S + M + C + (N * RF\_PWR) \quad (16)$$

and our optimization problem can be defined as one of *ttl_energy* under the constraints listed earlier.

Experimental Evaluation

We used *Xpress-MP* [19] to formulate and solve our ILP problem. We used Intel Xeon 3 Ghz processor with 2 GB of RAM for running the ILP solver. A 4x4x3 grid is considered with the edge size of *GR_UNT* = 100 meters (400m x 400m x 300m). Based on these dimensions, the underwater communication energies ($CME_{i,j,k,a,b,c}$) and the surfacing energies ($SRE_{i,j,k}$) are calculated, as explained in the introduction and stored in an input file. We assumed all UUVs are REMUS 600 AUVs and used its technical specifications in all our calculations. The propulsion energy (*PR_PWR*) is set to 28 watts, which is consumed by a

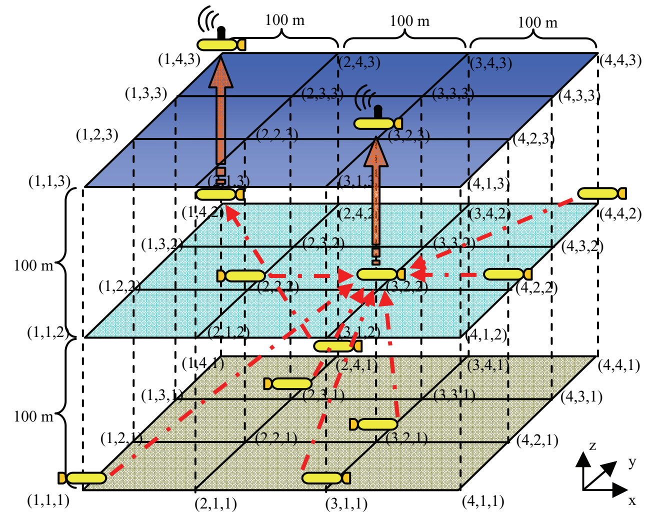

Figure 2. Illustration of the master UUV assignment and data communication schedule involving 10 UUVs on a 4x4x3 grid.

Number of Master UUVs (*kk*)	Total Energy Consumption in Watts
0	42060.0
1	22191.7
2	20355.3
3	20472.0
4	20829.6
5	22429.6
6	25835.5
7	29357.1
8	33260.0
9	37660.0
10	42060.0

Table 2: Energy consumption values for different number of master UUVs *(kk)*.

REMUS 600 for each meter. Similarly, the LinkQuest UWM3000 is selected as our experimental acoustic modem and we set the underwater acoustic communication energy consumption (*AC_PWR*) to 12 watts per meter, which is the output power given in the technical specifications of the modem. Finally, the *RF_PWR* is set to 6 watts considering both the output power of Military Navigator II VHF/UHF modem (4 watts) and the transmitter.

We performed our first set of experiments assuming the deployment points of UUVs on the grid given in Figure 2. After running the program, the ILP solver assigned two UUVs as master, whereas other eight UUVs were assigned as slaves in the energy optimal solution. In the third formula given in constraints subsection, *kk* is introduced as the optimal number of master UUVs to minimize the energy consumption. In order to show that the result returned by the ILP solver is optimal, instead of making the optimal number of master UUVs (*kk*) a variable (an output value of ILP), we can set it as an input (to determine the minimum energy consumption under different number of masters). Considering the same scenario, (with 10 UUVs given in Figure 2), we ran our formulation for each value of *kk* from 1 to 10, and obtained the corresponding total energy consumptions. According to the results given in Table 2, the minimum total energy consumption is obtained in the case that *kk* equals to 2, the value determined by our solver. One can also make several other observations from these results. First, since five of the UUVs are located on the second layer of the grid (z = 2), the energy consumption values for up to 5 master UUVs are similar. This is because all UUVs on the second layer are closer to the surface compared to the ones residing on the bottom layer (z = 1). However, beyond 5 master UUVs, some UUVs have started to come from the bottom layer which in turn increased the total surfacing energy consumed by masters, and ultimately, the total energy consumption as well. Another point we want to emphasize that, the results for kk = 0 and kk = 10 are identical, since there is no difference between having 10 masters and having 10 slaves. In both the cases, each UUV has to surface and transmit its own data to the host station independently. As another example scenario, we studied the deployment of 15 UUVs on a 6x6x4 grid. This time, 4 UUVs are assigned as masters and the remaining 11 UUVs are selected as slaves, by our ILP solver.

	10 UUVs	15 UUVs	20 UUVs
4 x 4 x 3 Grid	0.125	0.172	0.203
6 x 6 x 4 Grid	1.062	1.093	1.140
8 x 8 x 3 Grid	1.891	1.922	2.062
8 x 8 x 6 Grid	7.469	7.609	7.859

Table 3: The times (in sec) the ILP solver took to solve the formulation for various grid sizes with various numbers of UUVs.

Table 3 shows the times the ILP solver took to solve our formulation for various grid sizes and different UUV counts. Note that increasing number of UUVs for a particular grid size affects the solution times only slightly. In comparison, as the grid size increases (no matter how many UUVs are used), the solution times also increase. For example, even though the time difference between the experiment carried on 4x4x3 grid and the one carried on 6x6x4 grid with 20 UUVs is less than one second (0.937 second), if we double the grid size from 4x4x3 to 8x8x6, the solution time difference becomes 7.656 seconds. Even though it seems high, this difference is not important considering the two major application-specific issue of the scenario we assumed in this paper. First, since the UUVs are very slow vehicles, they do not have to respond very quickly, unlike groups of Unmanned Air Vehicles (UAVs) carrying out a strike mission using self-task assignment. Therefore, consuming 7.656 seconds to generate the communication schedule is not significant at all in our considered scenario. Second, since we are not trying to find the optimal locations of the UUVs, only their optimal communication scheme given their locations, the grid size is determined by the number of UUVs employed. In common littoral applications, this would not require the grid to be very large, as the number of potential deployment depths would not be very large. In fact, if we use 8x8x3 grid instead of 8x8x6, as shown in Table 3, the solution time difference in moving from a 4x4x3 grid to a 8x8x3 grid (with 20 UUVs) drops to only 1.859 seconds. Consequently, we believe that the ILP solution times to generate our energy-optimal results are not excessive.

We also performed additional experiments capturing a different situation in which it is assumed that there are four UUVs located at the furthest corners of the grid given in Figure 2, namely, at points (1,1,2), (1,4,2), (4,1,2), and (4,4,2). In this case, our ILP solver assigned all UUVs as slaves and sent all of them to the surface. Similar to the previous experiment, if we force the ILP solver to assign master(s); for kk = 1, total energy consumption becomes 15115.2 watts; for kk = 2, it is 12824.0 watts, and for kk = 3 it is 12024.0 watts, whereas for kk = 0 and for kk = 4 it takes the optimal value of 11224.0 watts. The main reason for this, choice of our solver is because the communication among UUVs in this case is very costly due to the large distance. Consequently, all UUVs are assigned as slaves and forced to surface without any inter-UUV communication.

Conclusions

This paper presents an ILP formulation that determines the energy-optimal data reporting scheme of a group of UUVs (i.e., UUVs that will communicate with the host station) located at predetermined locations on a three-dimensional grid. We take into consideration the underwater communication energy, RF communication energy and propulsion energy. To test our ILP formulation, we implemented it using a commercial solver and performed several experiments. The results collected clearly show that our formulation is effective, and the ILP solution times experienced are negligibly short.

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